Title

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Semiconductor Production Equipment, Linkages, and the Limits to International Trade

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Introduction

The deteriorating technological and market leadership of U.S. producers of semiconductor production equipment is undermining the already precarious position of U.S. chip producers and of virtually every American firm that produces a microelectronics-based product.1 Indeed, recent data suggest that U.S. firms have lost market share in the equipment industry even faster than they have lost it in the chip industry, dropping from an 85 percent share of the world market in 1978 to barely 50 percent in 1987. Still, the scope of the competitiveness problem--whether it will be confined to the relatively small $5 billion equipment market or magnified to include the entire half-trillion dollar market for final electronic systems--depends critically on the nature of the technical linkages between semiconductor equipment development and prowess in semiconductor production. If those technical linkages are sufficiently loose, then purchases of foreign equipment can substitute for interactive equipment development on the part of U.S. semiconductor firms and their domestic equipment suppliers. As this study argues, however, equipment development and manufacturing prowess are tightly linked, representing a capability embodied in people and organized in firms, but not tradeable across national boundaries.2 A failure to capture the benefits of such linkages domestically will not be compensated by the purchase of advanced production equipment from abroad. A decline in the U.S. semiconductor equipment sector will instead rend the fabric of technological connections that now sustains innovation and growth in the American economy.

The semiconductor equipment sector is "strategic" in the sense that it provides extensive positive spillover effects through R&D and innovation to the semiconductor device sector, and through that sector to the rest of the economy.3 Because of these spillovers, the decisions of particular firms, and of governments, can powerfully influence the competitive opportunities facing other firms in the industry. When technical advantage moves decisively from the firms of one nation to those of another, those firms and that nation may come so to dominate a stream of product and process innovations that future competition from others is severely circumscribed. In the case of semiconductor equipment, the exchange of technological leadership is already well underway. Judging from recent trends in market performance by U.S. firms and evidence of a substantial decline in the U.S. industry's overall technological edge, patterns of production organization built up during the last two decades have not enabled U.S.

producers of semiconductor equipment to meet the twin challenges of costly increases in technological complexity and vigorous competition from Japan.4 By the same measure, and in sharp contrast, Japanese institutions, industrial structure, and corporate strategy have proven quite compatible with the new realities of international competition.

The organizational linkages between semiconductor makers and their equipment suppliers matter in part because of the increasing importance of technical linkages between semiconductor manufacturing and the development of semiconductor production equipment. Increasing interdependence results as semiconductor production and design become increasingly automated, capital intensive, and computer-driven. Moreover, as devices take on the characteristics of electronic systems they generate the need for strategic coordination between chip producers and the growing array of downstream industries that use semiconductors in their final products. That list now includes computers, industrial equipment like robots, telecommunications, consumer electronics, aerospace, automobiles, and defense. Consequently, for firms within this entire complex of industries, the know-how gained through managing the process of equipment development constitutes a strategic source of competitive advantage.

As this study demonstrates, the short-term, arms-length relationships which have traditionally existed among U.S. producers of semiconductors and semiconductor equipment mitigate against the pursuit of just this sort of advantage while the close, enduring relationships characteristic of Japanese device and equipment firms make the pursuit of such an advantage possible. The extent to which positive spillovers can be captured by U.S. firms and made the basis of a national competitive advantage in microelectronics thus depends on the extent to which closer technical, financial, and strategic ties can be generated between U.S. semiconductor producers and their domestic equipment suppliers. The form such ties should take is a matter of some contention. But evidence from Japan does not support the view that policy interventions should encourage straightforward vertical integration. Rather, the Japanese structure contains elements of both market and ownership. Unlike classical vertical integration, partial ownership ties require equipment divisions to compete against outside vendors for a substantial portion of the parent firm's business--a spur to continued innovation. But they also avoid the uncertainties of a pure market relationship, thus enabling the development of a long-range competitive strategy. In an American context, such semi-market, semi-ownership ties might preserve some of the benefits of dynamic entrepreneurialism characteristic of the existing structure while creating a new atmosphere of trust and cooperation between device makers and their equipment suppliers. Such an atmosphere would seem to be a prerequisite to the appropriation, by domestic firms, of the economic benefits that accrue from innovation and learning in the equipment development process.

Development, Diffusion, and International Trade: Some Broader Issues. A case study of international competition in the semiconductor equipment sector would be interesting and significant in and of itself due to the strategic nature of microelectronics worldwide. But it is also a useful case in point for examining some broader issues. These include the historic role of the capital equipment sectors in inducing development and expansion in a wide range of manufacturing industries, the routes by which innovations diffuse among firms and between nations (with particular focus on the organization of inter-firm linkages), and the ways in which the inhibition of such diffusion--whether planned or not--may create real and lasting competitive advantage for a firm, an industry, or an entire national economy. This last issue is especially contentious in light of traditional theories of international trade and development which tie comparative advantage to relative factor endowments. These theories deny the possibility that government policies or domestic structures can be fashioned strategically in ways that improve aggregate national welfare.5 But to some extent the geographic diffusion of knowledge about a production process is channelled by the structure of inter-firm linkages and the character of the labor market. To the extent that such knowledge is actually embodied in people, as a consequence of learning by doing, the skill level of the labor force (relatively immobile across national boundaries) becomes a primary determinant of national competitive advantage.

Innovations by firms producing production equipment have sparked many of the critical technological advances of the past two centuries.6 With the growing specialization of industrial activity, technological progress in manufacturing sectors has become increasingly yoked to technological developments in the sectors from which manufacturers buy their capital goods. Put another way, productivity increases by firms in the manufacturing industries have come to depend increasingly upon skills and resources located in their supplier firms. For example, textile firms that once produced their own machines turned to an increasingly independent set of specialized machinery producers as the market for such machinery grew and the machines themselves became increasingly complex.7 Chemical firms that used to design their own production facilities came to rely increasingly on specialized contractors for the construction of new plants.8 In these instances, skills and resources that were once internal to the manufacturer became external; they may have also become, over time, increasingly unfamiliar.

A limited conception of inter-firm and inter-industry linkages hampers our understanding of the ways in which innovation in the capital goods sector can spur technological development and productivity growth in the manufacturing sector. Linkages are typically defined, broadly, as "the contacts and flows of information and materials between individuals, firms, industries, and sectors in an economic system."9 Conventional linkage analyses trace these contacts and flows as they are revealed in monetary transactions, a convention that has contributed to the popularity of input-output analysis at the sectoral level. An input-output matrix enables us to view each sector simultaneously as both producer and consumer; it therefore provides a wealth of information on the structural interdependencies--the inter-sectoral flows--that characterize an economic system at a single point in time. But not all important elements of linkages can be captured by tracing monetary transactions. Input-output analysis cannot, by itself, explain why certain contacts and flows induce not only economic growth, but also economic development, an enhanced capacity for internally-generated growth.10

Following Schumpeter, the French economist Francois Perroux investigated the range of mechanisms through which an innovative firm or industry--a propulsive unit--induces growth and development in other parts of an economy. Perroux's "propulsive unit" is in many ways similar to our notion of a strategic sector which, in Perroux's words "manifests itself in points or `poles' of growth, with variable intensities; it spreads by different channels with variable terminal effects for the economy as a whole."11 The different channels include the familiar Leontieff input-output relationships through which expansion in one sector creates multiplier effects in other sectors of an economy, as well as Keynesian processes by which new investment in one sector generates economy-wide multiplier and accelerator effects. They encompass what Scitovsky called "pecuniary external economies," that is, increased profits in one sector due to the expansion of other industries that it supplies or that supply it.12 Finally, they include the stimulant effects of innovation and imitation identified by Schumpeter.

Perroux understood, unlike many who later adapted his ideas, that these growth forces may be felt both inside and outside a national territory. "The national economy in growth," he writes, "no longer appears simply as a politically organized territory in which a population lives, nor as a supply of factors of production the mobility of which stops at the frontiers."13 It is, rather, "a place of passage for forces."14 Whether those propulsive forces can be bottled up and harnessed to the competitive advantage of the national territory depends in part on the influence of domestic structures on the rate at which those forces diffuse internationally. Cohen and Zysman contrast, for example, the American and Japanese environments for technological diffusion:

> The technology pools in each country are not equally open. The United States is a fast-diffusing environment that is quite open to outsiders because of the quite special role of university research and the mobility of engineers among companies. Japan, by contrast, is a slow-diffusing setting; and in addition, the diffusion there appears to take place chiefly within the country and only with difficulty spreads outside.15

Indeed, the pace of technological diffusion between capital goods sectors and final producers often varies both intra- and internationally with the organization of linkages among manufacturing firms and their equipment suppliers. A sector dominated by large, vertically integrated producers will tend to internalize many linkages, with firms choosing to undertake many of the steps of the manufacturing process by themselves. A more fragmented, less integrated industrial structure will tend to leave manufacturers more technologically dependent upon inputs purchased from outside suppliers. Manufacturers will be more able to capture the economic benefits of innovation and learning in the former case; the latter case provides a faster route of diffusion among firms and, when suppliers include foreign firms, between nations.

The character of such inter-firm linkages matters powerfully when officials attempt to transform market advantage for a set of firms into trade advantage for an entire national economy. Recent trade theory has highlighted the competitive advantage that can accrue to producers whose internal organization enables them, among other things, to slow down the diffusion process, to appropriate the benefits stemming from the innovative capacities of their suppliers.16 Indeed, where innovation and various learning processes are the major source of economic growth, different national patterns of production organization influence long-term development prospects by varying the extent to which strategic gains due to technical innovation, learning, and other positive spillovers can remain "bottled up" within the national economy.

As Giovanni Dosi has noted, the fundamental properties of conventional trade theory would not be significantly challenged in this instance if (a) learning were to occur in areas largely independent from production activities, (b) technological knowledge were simply information, and (c) this information were largely a public good.17 In this case, firms and nations could gain access through the market to future opportunities for learning; price signals would do the job of alerting them to their chance. But what happens when, as Cohen and Zysman put it, "the object that is sold, whether a machine tool or a refinery, does not embody the whole of the technology"?18 When, in Dosi's terms, learning is a sort of "joint production" that arises from engaging in a manufacturing process over time? In this case, part of the learning, the understanding of how a product or process was developed and how it can be used and modified, remains off the market. The know-how is itself "untraded information, embodied in people and organized in firms."19 It remains within the network that developed the technology, the network that applies it. These networks are fundamentally national in character, in part because technological diffusion is conditioned by the organization of linkages among firms, their suppliers, and their customers. These linkages are organized differently among firms of different national origin.

In these cases, purchases of a foreign-developed technology cannot substitute for a domestic sector's intimate involvement in the process by which that technology has been developed. The degree of sustitutability between foreign and domestic equipment depends ultimately on variations in the geographic diffusion of manufacturing knowledge gained during the process of technological development. Following Krugman, we can identify two extreme cases of geographic diffusion.20 At one, we find a type of highly specific production knowledge that barely diffuses at all. This is knowledge which can be internalized by an individual firm. This is the case, in fact, when knowledge gained through experience with high-volume production (the fabled "learning curve" effect) is so specific that it is often slow to diffuse among plants within a single firm, much less across firms. Because of its resistance to diffusion, this sort of knowledge provides the plant or firm that possesses it with a distinct competitive advantage. At the other extreme, however, there are innovative, but easily copied features actually embodied in products, and thus capable of being imitated by anyone with the appropriate skills, anywhere in the world. These are cases in which even relatively loose inter-firm linkages can lead to a significant amount of international knowledge diffusion, as evidenced by the frequently successful practice of reverse engineering. Within certain acceptable price and performance parameters, purchased equipment will substitute for equipment developed in-house. The knowledge it embodies imparts no particular competitive advantage, though it may be essential to competitive survival.

In between the two extremes, however, there is a gray area of knowledge, where understanding is diffused by word of mouth or individuals moving about, and thus tends to be more limited in its geographic spread. This is precisely the type of knowledge that is often gained during the equipment development process, knowledge that can escape the confines of a single plant or firm, but which cannot be fully embodied in the equipment itself. Put simply, it is a product of the interactions between particular people and particular machines and thus is contained at least partially within the minds of an industry's labor force. It can be spread by individuals moving about within a group of affiliated firms, like the Japanese keiretsu, or by people traveling among the highly-mobile labor markets and informal communications networks common to high tech agglomerations in the United States, like Silicon Valley or Route 128. But it rarely transcends national boundaries.

Consequently, if the knowledge obtained by individuals and firms during the process of developing semiconductor production equipment cannot be fully embodied in the equipment itself, then the purchase of foreign equipment will not adequately substitute for interactive equipment development by domestic semiconductor producers and their domestic equipment suppliers. There are certainly indications already that, viewed from an American strategic perspective, Japanese equipment would imperfectly substitute for domestic equipment development by U.S. semiconductor producers and their domestic suppliers. Japanese firms typically have less extensive training and maintenance networks in the United States than in Japan. The dearth of Japanese language skills among U.S. managers and engineers obstructs their ability to assess Japanese product offerings, Japanese production organization, and Japanese technical practice. Finally, given the structure of close inter-firm linkages that exists in Japan, it might be in the competitive interest of Japanese equipment producers to engage in strategic technology hoarding, refusing or obstructing the sale of their most advanced equipment to U.S. semiconductor firms. In each case, the technological head-start referred to earlier is compounded by additional factors which would have the effect of delaying equipment delivery or impairing the actual performance of Japanese equipment exported to the United States.

I have suggested, however, that the ultimate competitive impact of inter-firm linkages, in this case links between semiconductor producers and their equipment suppliers, originates in the equipment development process itself, prior to marketing. Equipment development represents a store of knowledge that cannot be readily purchased from firms or individuals of different national origin.21 Yet the historical record suggests that the American industry is much more likely than the Japanese industry to try to "commodify" such knowledge. It is organized in a way which encourages the transformation of all inter-firm linkages into loose, input-output relationships. This enables Japanese firms to purchase access to innovations and learning that would otherwise constitute a source of distinct national competitive advantage for the United States. Equipment development and manufacturing prowess are by their very nature tightly linked, spatially bound. If American firms do not develop these links domestically, they will not be able to purchase the know-how that would be gained thereby from Japanese, European, or Korean firms--American know-how will lag behind or not develop at all. The developmental effects of a decline in one nation's semiconductor equipment industry depend on the degree to which organizational linkages among semiconductor equipment and device producers capture technical linkages that are non-substitutable, that is, not tradeable as commodities, because they represent a source of manufacturing knowledge that does not transcend national borders.

A comparative decline in American equipment technology, and the subsequent disappearance of many American equipment suppliers, could well be disastrous for U.S. semiconductor producers and their larger clients downstream. To the extent that American chipmakers continued to buy their equipment from domestic sources, they would be relying on inferior technology from firms in chronically precarious financial condition. To the extent that U.S. producers then turned to their Japanese competitors' equipment affiliates for the latest manufacturing technology, they would be buying equipment that had already been jointly developed and implemented into manufacturing by their fiercest rivals, the Japanese semiconductor-computer conglomerates. For policymakers, corporate officials, and others interested in the continued competitiveness of U.S. semiconductor equipment and device firms, this study can be read with an eye toward identifying ameliorative actions that might still enable this critical industry to reverse course.

Overview. Essentially this study consists of an attempt to understand how the U.S. and Japanese semiconductor equipment sectors developed the structural attributes that each brought with them to the international competition that began in the early 1980's, and how those attributes are shaping the outcome of that continuing competition. Sections I and II outline the evolution of each national industry with an eye toward identifying the unique historical circumstances that attended the development of important structural differences. The outline of each industry's development will then serve as a basis for examining, in Section III, how international competitive dynamics are being influenced by the structural differences that have come to distinguish each nation's domestic sector. Section IV will include some observations about the prospects of efforts currently underway in the United States to alter some of those domestic structures. It will be my contention, in the end, that the chronically short-term, arms-length relationship that exists between U.S. semiconductor producers and their equipment suppliers--a legacy of the industry's historical development--now places those firms at a profound disadvantage relative to their Japanese competitors in adapting to the new technical and economic realities of the international marketplace.

I. Evolution of the Industry in the United States

Origins (1958-1965). During the early days of semiconductor manufacturing, device makers built their own production equipment. Semiconductor producers purchased general-purpose machinery and instruments from established suppliers of analytical and scientific equipment, and company technicians then modified or re-configured the equipment--electronic measuring devices, optical apparatus, gas and vacuum control equipment--to meet their own processing requirements. Since there was as yet no independent supply of dedicated semiconductor equipment, these initial arrangements grew up as much out of necessity as out of choice. Early on, internal equipment development manifested the U.S. semiconductor industry's autonomous capacity for basic technological innovation.

Advances in production equipment have always moved in step with advances in circuit design. During the mid-1950's, equipment requirements began to change radically as producers of solid-state transistors shifted their attention to the more complex task of manufacturing integrated circuits. Jack Kilby built the first, crude integrated circuits at Texas Instruments in 1958; almost simultaneously, Fairchild's Bob Noyce discovered the key to their commercial production in a technical adaptation of a recent discovery by another of Fairchild's founders, the physicist Jean Hoerni. Hoerni's "planar" process was a method of oxidation and heat diffusion that resulted in the formation of a perfectly smooth insulating layer across the surface of a silicon wafer. As Noyce soon perceived, this meant that if several transistors and other circuit elements were embedded directly in silicon, then they could be isolated electrically between a series of these insulating layers; otherwise, as Kilby had found, the elements would have to be cut apart physically and wired back together. Using the planar process, ultimately thousands of electronic devices could be manufactured together with the wires that connected them, all in a single batch. By making higher-volume batch production feasible, development of the planar process thus cleared a technical path for the commercial manufacture of integrated circuits.22 It simultaneously created the demand for an entirely new class of production equipment, machines designed to conduct precise layer-by-layer deposition and diffusion processes plus instruments built to ensure the correct alignment of circuit patterns between the layers.

With the main technical stumbling block to commercial production thus removed, it still remained for the Pentagon and NASA to convince the scientific and industrial communities that volume production of integrated circuits might be profitable. Military performance specifications for miniaturization, low heat and low power consumption had already resulted in development of silicon-based devices; now, product and process innovation continued to be driven by highly centralized and technologically sophisticated government demand. Government procurement provided both Fairchild and Texas Instruments with an initial, successful demonstration market for IC's: for Fairchild, it came in the form of a guidance computer for the Apollo spacecraft; for TI, a missile guidance system for the Minuteman II.23

State procurement spurred market growth and expanded production volumes; since military performance requirements overlapped with the needs of civilian markets, military demand for integrated circuits accelerated their diffusion into civilian uses. Growing production volumes pushed U.S. firms down the learning curve earlier and faster than their foreign competitors, teaching them how to achieve lower prices through higher production yields and more consistent performance. Increasingly, such achievements required the development of production equipment dedicated specifically to the manufacture of semiconductor devices, and the scope of government procurement reflected this fact. Included in the Air Force's December 1960 award to Texas Instruments was a $2.1 million contract to support the development of "production processes and special equipment dedicated to the fabrication of IC's in bulk quantities."24

Enlarged by the initial demands of the defense and space programs, these "special" equipment needs began to spawn a small set of independent, specialized equipment suppliers. Materials Research was founded in 1957 to specialize in the manufacture of high-purity metals; soon the company was manufacturing sputtering equipment for the application of thin metal and ceramic films to silicon substrates. In 1959, prior to the commercial diffusion of Fairchild's planar process, a small firm called Kulicke & Soffa was asked by Western Electric to solve the problem of placing wire on silicon. The project culminated in the first commercial wire bonder. That same year, a one-year-old company known as Geophysics Corporation of America (GCA) acquired a small manufacturer of comparators called David W. Mann, and began to build on Mann's precision motion capability to tackle the problem of precisely aligning circuit patterns between successive layers of a silicon wafer. Its first and most successful product, during the 1960's, was a step-and-repeat camera, the Photorepeater. 1962 witnessed the creation of Thermco, which quickly became a leading producer of diffusion ovens.

The structural impact of early government procurement grew out of several environmental factors that were unique to the U.S. domestic market. Chief among these were the ready availability of venture capital, the high mobility of technical personnel between firms, liberal licensing policies by pioneering semiconductor firms, and, most important, anti-trust contraints on potential entry by electronics giants IBM and ATT into the open market for semiconductor devices. In combination, these factors contributed to a uniquely dynamic competitive environment that was unusually conducive to entrepreneurial ventures. Unlike integrated circuit production in Europe and Japan, which was dominated by large, vertically integrated electronic systems manufacturers, IC production in the United States came to be dominated by a set of independent "merchant" firms whose primary business was the manufacture and open market sale of semiconductor devices. Well after government procurement ceased to account for a predominant proportion of total semiconductor sales, competitive rivalry between the merchant firms, as well as between the merchants and more established systems houses like RCA, Westinghouse, and General Electric, continued to push the pace of technological advance and accelerate the diffusion of integrated circuit technology throughout the domestic economy.

Perhaps the clearest case of diffusion, with respect to production equipment, was the series of public seminars given by Motorola in 1963. Motorola apparently decided that it had to do something dramatic in order to establish a reputation within the emerging semiconductor industry for IC technology it considered to be every bit as good as TI's or Fairchild's. Ultimately, over 1,000 engineers attended the Motorola presentations; they also toured the company's manufacturing facilities. Out of those tours came requests by current and potential device makers to purchase some of Motorola's fabrication and test equipment. By 1964, Motorola was selling not only integrated circuits, but also semi-automatic test instruments, IC cap welders, and scribers, making it one of the first open-market vendors of semiconductor production equipment.

Between 1963 and 1965, the average selling price of integrated circuits dropped from $50 to below $9; total IC production mushroomed, from $4 million to $80 million; and government's share of the IC market dropped from 95 percent to 75 percent.25 The conditions for continued innovation and growth became progressively less tied to government support. Indeed, they were becoming internalized in the competitive structure of the industry itself. Growing competition pushed the pace of product and process innovation; new merchant firms entered the IC market and older electronics systems producers--RCA, Sylvania, Motorola, Westinghouse, Raytheon--began to move, slowly but surely, into volume IC production. Each new round of competition lowered the cost and improved the performance of integrated circuits, soon sparking the interest of U.S. computer and telecommunications equipment producers.

Thus, two historical developments, one technological and one economic, set the stage for the evolution of an independent, entrepreneurial semiconductor equipment industry in the U.S. First, development of the planar process for manufacturing integrated circuits created a new set of demands for dedicated production equipment, that is, machinery and instruments designed specifically for use in the manufacture of semiconductor devices. Second, the subsequent development of a unique segment of "merchant" device producers, sheltered by government anti-trust laws and nourished by state-of-the-art military procurement, fragmented the primary market for that new equipment. The small size and financial vulnerability of the newer merchants combined with the rapid pace and growing expense of technological advance in circuit design and processing to encourage specialization in both products and production processes. By the mid-1960's, most semiconductor producers still built their own production equipment, but the success of a small set of highly specialized, independent equipment suppliers, combined with the response to Motorola's early informational seminars, indicated a growing market for sophisticated production equipment that most merchant semiconductor producers could not afford to build on their own.

Spin-offs and Start-ups (1966-1972). Between 1966 and 1972, U.S. production of integrated circuits more than doubled. The IC industry's extraordinary growth rate reflected its growing synergistic relationship to the computer and telecommunications industries, both of which pursued competitive advantage through the rapid introduction of state-of-the-art semiconductor capabilities. Growing markets for both mainframe and minicomputers fed and fed off the rapid expansion of IC production. Advances in IC design progressed from the implementation of basic logic functions in silicon to the construction of entire computer sub-systems on a family of chips. At the same time, ever more sophisticated integrated circuits were creating demands for ever more sophisticated "custom" production equipment. The newer IC's presented stringent requirements for clear resolution, narrow line widths, and correct alignment between layers of the silicon wafer that semiconductor producers attempted to meet often by tinkering with equipment that had been designed to process previous generations of semiconductor devices. High growth rates and recurrent cash flow crises among merchant start-ups had them looking for other firms with which to share the costs of financing and manufacturing the increasingly expensive equipment. Both independent equipment start-ups and large, established analytical and scientific equipment firms came forward to fill the vacuum.

The biggest chip producers--IBM, Fairchild, Texas Instruments, ATT--continued to build production equipment internally. Increasingly, however, the majority of merchants simply did not have the financial wherewithal to develop new production equipment themselves. Thirty new firms entered the semiconductor device competition between 1966 and 1972. Vigorous price competition during this period meant that profits per unit of sales were decreasing even as sales volume increased. The capital constraints which rapid growth placed on company resources meant that firms often had to choose between expanding capacity and developing new products. The rapidity of technological innovation in the external environment meant there were always a dozen promising avenues left unexplored by any individual firm. This led to a high degree of frustration among talented employees who were constrained from developing their new ideas in-house. Confident of their own technological prowess and emboldened further by the ready availability of venture capital for start-ups (at least until the 1969 changes in the capital gains tax), a steady flow of entrepreneurial engineers quit during the 1960's to start their own chip firms--and an independent equipment industry.

The intensely innovative technological environment, increasing competition in the device sector, and the shifting structure and composition of semiconductor demand during this period all placed severe strains upon the organizational capabilities of small firms, despite their considerable internal capacity for innovation and adaptation to changing market conditions. Solutions to recurrent financial crises were conditioned by the historically-specific organization of industrial structure. The chip and equipment sectors were soon marked by an extraordinary degree of "commoditization"--the open-market exchange of every imaginable link in the production chain, from people and technology to entire firms, including not only materials and production equipment, but also engineering services, product and process licenses, and intellectual property rights. Linkages between semiconductor producers and their suppliers were, in a phrase, permanently contingent, based on a series of separate market transactions that might be repeated between particular pairs of firms over time, but were truncated, always, by considerations of competitive secrecy. Cooperation was minimal and trust fleeting because device makers could never be certain that their equipment suppliers were not also selling state-of-the-art machines--and perhaps some of their manufacturing secrets--to a competitor; under normal circumstances cooperative strategic planning was out of the question.

As in the device sector, new equipment ventures were often started by defecting executives from chip houses or other equipment firms. This fact, by itself, mitigated against the development of detailed, highly personalized interaction between firms and their suppliers. Technical knowledge was highly prized; but no firm could be sure that it alone would reap the benefits of that knowledge in the marketplace. A second factor accounting for the lack of development of stable communications linkages was the widespread availability of requisite technical skills. With the important exception of microlithography equipment, many technicians and engineers possessed the expertise necessary to put together a working piece of semiconductor production equipment. Once they had bought a new machine, semiconductor firms could, and often did, modify and re-configure the equipment themselves. The equipment firms could not benefit, then, from any monopoly of scarce technical or engineering skills. Their task was rather to create exciting new products--new ways of doing old things or ways of doing intriguing new things--and to convince equipment buyers that it was in their competitive interest to buy them. The attitude of equipment buyers was like the attitude of the citizen from Missouri: "Show me."

By the end of the 1960's, widespread skills, low entry costs and plentiful venture capital had enabled the creation of many small start-ups. Generational crises were frequent, but not unexpected, since they tended to follow equivalent crises in the device industry. By this time, the low entry costs were also attracting a set of larger companies which had previously produced scientific instruments or manufacturing equipment for older-generation electron tubes. New divisions of such established firms positioned themselves--often by acquiring struggling start-ups--to share or shoulder the development costs of new capital goods that most merchant chip producers could not afford to develop internally. A good example is Varian Associates, one of Silicon Valley's founding firms, which entered the semiconductor equipment business by way of the wafer coating business in which it was already competing. Varian's initial emphasis was on vacuum-related equipment; through a series of acquisitions beginning in the mid-1960's, Varian became a factor in sputtering equipment and then a leading producer of ion implanters.

Larger firms soon benefited from economies of scale in marketing. Unlike their smaller counterparts, who often had to rely on independent sales representatives or trading companies to sell a handful of incredibly specific machines, large equipment firms attempted to develop diverse product lines--what economists refer to as a strategy of horizontal integration--while establishing stable marketing networks. Diversity in the product line enabled the larger firms to spread their risks; quite often, such firms would introduce half-a-dozen failures for every big winner. The salesperson for a full-line firm had at least a fighting chance of parlaying successful sales of one type of equipment into companion sales of complementary product lines. Just as important, larger firms were more likely to provide dependable after-sales service and a ready supply of replacement parts. With semiconductor production engineers desperate to avoid equipment down time, the availability of regional service technicians capable of quick response constituted another significant competitive advantage for the larger equipment firms.

The larger firms also benefited from some limited economies of scale at the product level, particularly in the area of vacuum control equipment (etch, deposition, and ion implantation systems). Evidence for these economies includes the fact that a great many firms provide equipment for two or all three of these equipment sub-segments. In general, however, the production process for semiconductor production equipment resists routinization. Production costs do not tend to decrease with increases in unit production. Indeed, when comparing the production process of a full-line equipment company to that of a single-line specialist, the most significant differences are typically quantitative--more people, more types of equipment--not qualitative.

The manufacture of semiconductor production equipment can best be described as a job shop operation. The production space is clean, uncluttered, and well-lit. The incidence of automation or mechanization is rare; no assembly lines, no conveyor belts. Instead, skilled technicians and engineers tinker with complex parts and sub-assemblies, fine-tuning here, re-configuring there, focusing their efforts on meeting a particular customer's technical specifications. This organization of work reflects the character of demand for the equipment company's product.

The overriding competitive consideration is not cost, but performance: getting the equipment to perform properly at the user's wafer fabrication facility. Thus, an enormous measure of time and resources are spent in equipment development, the quasi-scientific, quasi-artisanal process by which highly-paid, super-skilled engineers "tweak" a piece of equipment until it does what it is supposed to do. Because of the particular competitive structure of the industry in the United States, this process typically takes place almost entirely in the equipment maker's plant. We shall see later that this process is very different in Japan, where equipment and device makers have less reason to worry about sharing proprietary information. There, most equipment development occurs at the user's production site.

Economies of scale in marketing, combined with some limited scale economies at the product R&D level, privileged the emergence of a relatively stable set of larger equipment firms, including Varian, General Signal, and the persistent market leader, Perkin-Elmer. Organizational size and product diversity fed financial stability; expanded resources translated into expanded R&D and expanded product lines. Each new generational crisis brought with it a new crop of innovative start-ups. Some succeeded on their own, most failed, and many were acquired by the larger firms, still seeking to diversify their product lines in order to take advantage of scale economies in marketing and development. In 1970, the Semiconductor Materials and Equipment Institute was founded to provide technical standards for the burgeoning array of independent equipment firms. As device makers readied for the next phase in their own competitive evolution, signalled by Intel's introduction of the microprocessor in 1971 and the industry-wide move toward large-scale integration, a separate semiconductor equipment and materials infrastructure had clearly emerged.

The High-Tech Cottage Industry (1973-1981). The emergence of a separate semiconductor equipment industry in the United States can be traced symbolically, if not precisely in fact, to the commercial introduction of Perkin-Elmer's Micralign projection aligner in 1973. Once again, DOD procurement seems to have provided a critical launch market for working out the bugs and bringing down the costs. Perkin-Elmer, the world's largest supplier of analytical instruments, began development of the system around 1969, after the company had contracted with Wright Patterson Air Force Base to provide a scanning alignment system using a refractory lens. Introduction of the company's commercial version, the Micralign, in 1973, marked the first real shift of momentum for technical innovation in equipment away from the large semiconductor producers and toward the larger, independent equipment houses.

The Micralign had a profound impact on the entire semiconductor production chain. Device makers experimenting with the Micralign were finding that masks which previously had to be replaced after as few as 150 contacts now lasted for as long as a year. As word spread, more and more semiconductor producers turned to the new machine, and the Micralign began to send shock waves through the entire network of materials suppliers. Suddenly, mask-substrate manufacturers had to provide flatter substrates; wafer manufacturers had to provide flatter wafers; and mask makers had to supply virtually zero-defect masks. The masks cost device makers up to $1,000 each, but their improved durability, due to Perkin-Elmer's projection aligner, justified the investment. The Micralign also paved the way for the introduction of the first E-beam systems (developed by TI and IBM around 1975) which could be used to make higher-quality masks. The Micralign, which has been updated several times, remains the single most successful line of semiconductor production equipment ever produced.

Throughout the early 1970's, most semiconductor equipment manufacturers were still small, undercapitalized niche fillers, highly vulnerable to the economic and technological fortunes of the device industry. Communication continued to be poor; semiconductor makers feared compromising proprietary secrets and so withheld vital information. They even declined to explain their expected equipment requirements, preventing equipment firms from planning with any certainty. Things began to improve during the hectic build-up of 1973 and early 1974, as the shift to large scale integration (LSI) and the use of new MOS circuits in computer main memories sparked the growth of a new mass market for IC's. The technological prowess of American semiconductor firms, sparked by early military support and fired by the synergistic integration of semiconductor production with applications in global computer, consumer, and industrial markets, positioned the industry to dominate the emerging mass markets.

But, like all component industries, the semiconductor industry's fortunes are tied to market demand for the final systems in which their products are used. As the economy hit the rocks in the mid-seventies, so, for the first time, did the American semiconductor industry. And so did the already tentative relationship between device makers and equipment suppliers. Semiconductor producers had overestimated demand and with it their ability to pay for new equipment; quick to double-order in boom-times, they moved even faster to cancel during the bust. Equipment houses struggled to stay alive by selling equipment for new R&D work; products that were not highly advanced or that merely increased capacity remained unsold.

With the recovery beginning late in 1976, renewed confidence in the market sparked a wave of mergers and acquisitions in both the device and equipment industries. Badly burned in 1974, however, the equipment firms were slow to respond to new orders from merchant chipmakers. The atmosphere remained one of mutual mistrust and antagonistic independence. In addition, generational instability in both the device and equipment sectors meant that it was unwise, in any event, for equipment producers to build up substantial inventories. With technical progress so dramatic, the useful life of most capital equipment was typically five years or less, and semiconductor equipment producers remained cautious about trusting the upturn.

By the period 1977-78, it had become clear to equipment suppliers that the recovery was for real; but by then order backlogs were enormous, and delivery schedules stretched out for months. Understandably, American equipment firms gave delivery priority to their primary customers. Foreign customers were often left in the lurch. This was particularly true in Japan, where the government's VLSI project was even then strengthening technical capabilities and organizational ties among newly-formed domestic equipment firms and vertically-integrated systems and semiconductor producers. Long delivery lags, combined with normal delays due to distance and poor communications, badly weakened the stronghold U.S. equipment manufacturers had established in the Japanese market, just as Japanese chipmakers were gearing up for their successful assault on the high-volume markets for semiconductor memories.

The relationship between chip and equipment firms was shifting, in general, because of fundamental changes in the cost and complexity of semiconductor equipment. As circuit line-widths shrank, equipment development costs soared. So did prices. The price of coaters climbed from $20,000 to $100,000 to $300,000. Prices for projection aligners, ion implanters, and diffusion systems often reached $500,000, while prices for next-generation systems like E-beam lithography equipment approached the $2 million mark. The IC equipment business was still relatively small and immature, but big-money transactions such as these began to bestow equipment suppliers with some real clout. So did their increasing technical sophistication. By the late 1970's, it could no longer be said that the technical know-how for building a state-of-the-art piece of equipment was widespread. Large equipment firms were devoting considerable time and resources to the development of proprietary innovations; GCA's introduction of a commercial wafer stepper in 1978 was perhaps the most spectacular of these.

Merchant chip firms had neither the space nor the resources to develop their own equipment; increasingly, they bowed to the growing expertise of their suppliers and gritted their teeth through the long delivery times. Although giant systems producers and a few of the largest merchant firms--the IBM's and the TI's--continued to build much of their own production equipment, even they were shifting more and more toward purchasing the increasingly sophisticated equipment available from independent suppliers. The normal structure of inter-firm linkages was still contingent, purely a series of market transactions. But the equipment industry had begun to evolve a set of informal "listening posts," so that it could better anticipate the current and future needs of device suppliers. These included such things as trade association meetings and industry conventions, technical seminars and publications, plus the information that diffused inevitably through the normal interaction between user and supplier in the process of developing a complex piece of equipment and "tweaking" it to meet the customer's particular requirements.

The large firms continued to get larger, swelled by increased sales and acquisitions. By 1979, Perkin-Elmer's equipment business exceeded $100 million in sales, making it the first semiconductor equipment supplier to break that barrier. That year, the company acquired Etec, the leading producer of E-beam systems for mask making. Other large firms continued the acquisition wave. General Signal also bought into the E-beam market, as well as the markets for etch, diffusion, and resist processing systems, automated assembly equipment, and wafer steppers. Varian bought Extrion, a leading producer of ion implanters. Applied Materials, started in 1967 and traditionally the leading supplier of epitaxial reactors, began its own attempt to become a multi-product supplier when it introduced its phenomenally successful dry etcher in 1981; by the mid-eighties the company was poised to enter the markets for ion implantation and chemical vapor deposition equipment.

The expanding equipment business also began to capture the attention of non-electronics giants looking for a way to diversify into the electronics business. The largest of these was Eaton, traditionally a supplier of auto and truck parts. In 1978, Eaton acquired Cutler-Hammer, a Milwaukee-based equipment company with extensive--though largely unproven--holdings in photoresist processing, wafer alignment, plasma etching, ion implantation, and memory test systems. The biggest prize in this acquisition was Nova Systems, the high-current ion implant systems maker founded by the former manager of Varian's Extrion division. Buoyed by its acquisition of Nova, Eaton soon entered the ranks of the top ten semiconductor equipment suppliers.

Summary. During its first twenty years, the U.S. semiconductor equipment industry evolved in a highly entrepreneurial, technologically volatile environment in which the manufacturing needs of its primary customers, the merchant semiconductor producers, were driven by the demands of electronics-systems firms that used semiconductors in their final products. Just as the large systems houses increasingly turned to captive production of the semiconductor devices on which so much of their competitive advantage had come to depend, so the large semiconductor firms continued in-house production of sophisticated semiconductor production equipment. Given widespread know-how in the U.S. electronics industry about how to design chips and build the equipment needed to make them, competitive advantage for the merchant chip and equipment firms came to rest on product or process specialization--many small firms were started for the express purpose of developing a single, highly specialized piece of equipment. This had two primary consequences: (1) the development of a highly fragmented industrial structure populated by hundreds of small, independent equipment firms and a dozen larger multi-product enterprises all highly specialized in the manufacture of semiconductor production equipment; and (2) the creation of an equally fragmented market structure characterized by arms-length relationships between equipment makers and most merchant semiconductor firms.

The equipment industry did share some important attributes with the device sector that spawned it: a high rate of new venture formation, high labor mobility among technical personnel, idiosynchratic corporate cultures and incentive structures, rapid intra-industry diffusion of technological innovation, and recurrent generational crises. With the significant exception of the Defense Department's VHSIC program beginning in 1980, cooperation between government and industry remained limited. Private R&D expenditure remained high, but highly volatile; most basic research was conducted in the nation's universities.

The U.S. equipment industry exhibited several competitive strengths. The large pool of mobile, entrepreneurial talent formed a solid base for continuous technological innovation; the ready availability of investment financing for start-ups accelerated the translation of innovative ideas into marketable products. Moreover, the independence of semiconductor equipment firms enabled them--indeed, required them--to sell their most advanced machines to all potential users, a fact which led routinely to the rapid diffusion of state-of-the-art processing equipment. Independent equipment firms also retained the ability to discontinue production of obsolete equipment, thereby forcing some users to migrate to newer process technologies faster than they might have done otherwise.

These characterstic competitive strengths were reflected in characteristic competitive strategies. Most U.S. equipment firms emphasized development of state-of-the-art equipment (new product development), rather than the constant refinement of existing machines. Marketing centered around the development of strong, reliable installation and maintenance programs, plus on-site user training, rather than on continuous feedback during equipment development or on-site testing prior to marketing. In foreign markets, marketing was generally organized around the establishment of joint ventures for sales and technical support rather than through the formation of wholly-owned manufacturing subsidiaries.

As long as all of the equipment firms were American, these strengths and strategies tended to hide a host of potentially serious competitive weaknesses that also derived from the equipment sector's particular market and industrial structure. The most serious of these involved the lack of any close working relationship between users and producers of semiconductor production equipment. This contributed both to unstable equipment demand patterns and a persistent gap between equipment capabilities and user requirements. Installed equipment often required frequent adjustments in order to bring it up to spec. Indeed, new equipment often could not meet the specifications claimed for it, if it was really available at all. The lack of support given older equipment often led to declining market share, yet high development costs meant that research results were not rapidly translated into new commercial products. Indeed, persistent order backlogs meant that research priorities were often subordinated to production priorities. Finally, as with most American firms, quarterly management accountability to stockholders mitigated against a longer-term strategic perspective.

The vulnerabilities of this system remained hidden as long as U.S. equipment firms dominated the international market and continued to control the development of new production technology. Once this was no longer the case, the entire equipment industry was suddenly threatened with extinction, and with it the domestic semiconductor industry it supplied.

II. Evolution of the Industry in Japan

The Japanese Context. Japanese semiconductor device and equipment makers recognized their dependence on American technology early on and, with considerable assistance from the Japanese Ministry of International Trade and Industry (MITI) and NTT, Japan's quasi-public telecommunications monopoly, they organized themselves to turn this apparent weakness to their advantage. Through marketing agreements and joint ventures, Japanese firms initially emphasized the rapid acquisition and adaptation of semiconductor production equipment developed in the United States. Subsequently, a government orchestrated R&D program underwrote the cooperative development and diffusion of an indigenous technology base. During both periods, government policy and certain characteristics of Japanese business structure worked in concert to insulate domestic producers from foreign competition.

Government efforts during this period were concentrated on limiting foreign competition in the domestic market while promoting the acquisition and rapid diffusion of foreign technology and know-how. With regard to semiconductor equipment, Japan's giant trading companies continued to serve as an essential link between the insulated domestic economy and its external sources of supply. Until the late 1970's, in fact, Japanese markets for semiconductor fabrication and test equipment were almost entirely supplied by U.S. firms via special marketing arrangements with Japanese firms. The most important of these was Tokyo Electron Ltd. or TEL. Unlike most of its domestic rivals--affiliated companies of large general trading companies or of the combined semiconductor-computer manufacturers--TEL began life in 1963 as an independent trading company specializing in semiconductor production equipment. The largest share of TEL sales came from the marketing of diffusion furnaces, which TEL had first imported from the U.S. firm Thermco in 1964.

Like its domestic competitors, TEL organized for rapid technology acquisition first through marketing agreements, then through joint ventures with U.S. manufacturers. Indeed, TEL's experience with an early joint venture served to demonstrate some of the advantages of domestic manufacturing to other Japanese equipment firms. Like those other firms, TEL had already constructed complete maintenance and service facilities in Japan for users of the equipment it imported. Then, in 1968, Kokusai Electric attempted to enter the Japanese market for diffusion furnaces on the basis of lower prices. TEL's response, thought daring by some at the time, was to form a joint venture with Thermco in order to commence complete domestic production for the Japanese market. Within a short time, TEL had recovered its dominant market share, and, eventually, Thermco would be incorporating lessons learned at its Japanese manufacturing facility into its parent plant back in the United States.26

Although the proliferation of such joint ventures would soon make TEL the largest manufacturer of semiconductor equipment in Japan, the company remained the exception rather than the rule. Most Japanese equipment firms were close affiliates of, even partially owned by, the combined Japanese semiconductor-computer firms. Equally important, the traditional structure of Japanese business provided a context for close collaboration between semiconductor device and equipment producers. Although the "Zaibatsu" inter-company group linkages that developed before World War II were dismantled during the American occupation, groupings based on old Zaibatsu ties reemerged during the postwar period, now organized around common ties to a few large banks (keiretsu).27 As has been pointed out elsewhere in the literature, keiretsu ties come in several forms, ranging from close operational ties to loose, basically financial arrangements. Whatever one's view of the significance of kereitsu ties, however, the fact remains that most company stock in Japan is held by other companies or by banks. Thus, like so many of the country's smaller firms, many of Japan's fledgling semiconductor equipment companies became linked as a matter of course to the larger semiconductor-computer companies, as suppliers or subcontractors or partially-owned affiliates. The major links:

Hitachi, which also manufactures photolithography equipment is linked to Shinkawa, a manufacturer of assembly equipment, and Kokusai-Electric, a producer of etch, deposition, and ion implantation systems. Fujitsu owns part of Advantest (formerly Takeda-Riken) a leading maker of test equipment. NEC owns Ando-Electric, another test equipment producer, and is linked to both Anelva, a producer of etch and deposition equipment, and Kaijo-Denki, a manufacturer of etch and assembly systems. Toshiba is affiliated with Toshiba-Machine, which makes lithography equipment, Toshiba-Seiki, which produces assembly equipment, and Tokuda-Seisakusho, a manufacturer of etch and deposition systems. Mitsubishi has ties to Nikon, the giant lens maker and now leading producer of photolithographic systems, plus JEOL, a manufacturer of leading-edge lithography, etch, and diffusion systems. Matsushita is affiliated with Ulvac, also a leading manufacturer of etch, deposition, and ion implantation systems.

During the period of technological catch-up, most Japanese equipment and device firms were intent on simply keeping up with the latest American advances in semiconductor design and manufacturing. Only in the area of semiconductor assembly equipment did Japanese firms provide any hint of an indigenous capacity for technological innovation, a capacity otherwise obscured by the massive transfers to Japanese firms of technologies invented abroad. By the early 1970's, semiconductor assembly still constituted the most labor-intensive segment of the production process and consequently the least technically sophisticated segment of the semiconductor equipment market. But government policy soon combined with characteristic differences in corporate strategy between Japanese and American semiconductor firms to create an opportunity for Japanese producers of semiconductor assembly equipment.

In response to domestic competition during the 1960's, American semiconductor firms had bifurcated the overall production process, keeping capital-intensive design and fabrication in the United States, but moving labor-intensive assembly, and later, test operations offshore in search of cheap labor. Constrained by government policy and the domestic industry's inter-linked structure, Japanese chipmakers decided to keep leading-edge device production fully integrated at home. Because Japanese wages were considerably higher than those obtaining in the rest of Asia, this created a demand in Japan for more highly automated semiconductor assembly equipment. U.S. assembly equipment producers reacted slowly, the bulk of their business coming from sales to the U.S. merchants' less-automated Southeast Asian assembly plants. They failed to develop more sophisticated machines in time to satisfy the growing Japanese demand. It was left for Japanese firms to fill the void. And fill it they did. Shinkawa invented an automatic wire bonder in 1972, thereby equalling in sophistication the best machines produced by U.S. firms. Disco, an independent Japanese firm, quickly mastered the technology of dicing saws. Once America's technological lead in assembly equipment vanished, so did American domination of the Japanese market, a portent of things to come. In short order, Disco and Shinkawa were able to expand their overseas sales as well, penetrating the U.S. market for the first time in 1975 and 1976, respectively.

Despite these limited successes in the early 1970's, most Japanese equipment firms remained engaged in the importation, marketing, and maintenance of foreign-produced machines. At best, they participated in joint ventures formed to organize the assembly in Japan of production and test equipment developed elsewhere. Unlike their American counterparts, sparked by the demands of an expanding computer sector and fired up by the entrepreneurial drive of the semiconductor merchants, Japanese equipment firms--with the exception of producers of assembly equipment--faced no dynamic expanding demand for products more sophisticated than the ones they were currently marketing. For, through the early 70's, Japanese semiconductor firms remained substantially dependent on the production of discrete circuits for consumer electronics products. Production of integrated circuits accounted for only about one-fourth of total semiconductor production. Significant basic research was being carried out in government and NTT laboratories, but private R&D spending by Japanese semiconductor companies was not on par with spending by U.S. firms. Indeed, by the early 1970's, Texas Instruments was spending more on semiconductor R&D than Fujitsu, Hitachi, and NEC combined were spending on both semiconductor and computer research.28 If Japanese firms were to generate the product and production strengths necessary to compete in the rapidly expanding world markets for semiconductors and semiconductor-based systems, business as usual would clearly have to change.

The State and the State of the Art: Government Promotion in the 1970's. The strategy of technological diffusion and limited market access enabled Japanese semiconductor-computer firms to roughly mimic technological developments in the United States throughout the 1960's.29 By the end of the decade, however, demands from America's rapidly expanding computer sector were accelerating the pace of semiconductor innovation, and Japan's semiconductor-computer firms were lagging farther and farther behind. At the same time, Japan's relative weakness with regard to LSI technology and the shift offshore of major U.S. semiconductor and consumer electronics producers were also beginning to erode traditional Japanese strengths in international consumer electronics markets.

So it was that, in 1971, when the Japanese government introduced a series of measures aimed at promoting advanced technology industries, MITI planners chose to promote the development of LSI technology through a thorough reorientation of domestic semiconductor production. Under government tutelage, LSI development was geared toward the more sophisticated needs of Japan's fledgling computer industry. Together with Japan's Electronics Industry Association, MITI formed an LSI cartel among the country's ten major semiconductor producers for the purpose of standardizing LSI device structures and manufacturing processes. The program was also set to include the development of LSI test equipment.

Between 1971 and the end of 1975, these coordinated, government-subsidized R&D efforts worked with the shifting composition of consumer demand to change the nature of semiconductor production in Japan. The proportion of total semiconductor production accounted for by integrated circuits rose from 27 percent to about 42 percent.30 Again, although government policies were critical, the driving force behind this growth was domestic competition in a protected and rapidly expanding Japanese market. By 1976 Japanese semiconductor-computer companies dominated that market for all but the most advanced IC devices, and their share of the domestic installed base of general purpose digital computers had climbed to over 60 percent.31

Still, the combined efforts of Japanese government and industry had not been enough to get ahead of the international market. By the mid-1970's, the introduction by U.S. computer companies of low-cost, LSI-based plug-compatible mainframes had reinforced IBM's international dominance in software and consolidated for U.S. firms precisely the LSI-based computer market segment toward which Japanese development efforts had been aimed. If Japanese companies were going to break into the international market for computers, they were clearly going to have to do so on the basis of the next generation of semiconductor-computer technology.

In mid-1975, MITI and NTT agreed to unite parts of their separate LSI research and development projects into a joint program aimed at developing the next generation of semiconductor device technology, very large scale integration, or VLSI. Phase I of the so-called VLSI project funneled approximately $132 million of MITI funds (in the form of interest-free loans which are now being repaid) and $191 million provided by participating electronics firms into a special research association which coordinated the development of IC fabrication and testing systems, in addition to crystal cultivation and semiconductor device design. The VLSI project resulted in about 1,000 patents between 1976 and 1979.32 Semiconductor equipment developed through work with the MITI labs included Nikon's wafer steppers, Canon's projection aligners, and E-beam lithography equipment developed by Hitachi, Toshiba, and JEOL. Cooperation with the NTT labs resulted in Advantest's (Takeda Riken's) state-of-the-art testers, Ulvac's ion implantion systems, Nikon's first X-ray aligners, and Dai Nippon Printing's X-ray masks. It was also in the context of the VLSI project that certain Japanese semiconductor manufacturers began their patronage of various semiconductor equipment firms--Hitachi with Kokusai Electric for deposition and etch systems and ion implanters, Toshiba with Tokuda for dry etching, NEC with Ando Electric for testers.

Rapid technical improvements on the part of Japanese manufacturers resulted from the combination of several factors. These included the wholesale transfer of American technology, a change in the nature of technological advance from generational to incremental innovation, and tactics of internal production organization designed to encourage the constant adoption and incremental improvement of new manufacturing methods, the last made possible by the remarkable degree of cooperation between semiconductor producers and their equipment suppliers.

First, between one-third and one-half of the VLSI project's funds were used to purchase advanced U.S. production equipment.33 Although some of this equipment was clearly used for the production of semiconductor prototypes, much was simply dismantled and analyzed by manufacturing technicians in an effort to fabricate production equipment equal or superior in performance to that provided by U.S. firms. Similar efforts at reverse engineering characterized the involvement of Japanese firms in joint ventures with U.S. firms that produced equipment for the Japanese market.

Second, the Japanese were able to close the process gap so rapidly, in part, due to a change in the nature of the technological advancements that characterized semiconductor equipment development during the late 1970's. All of the standard front-end processes presently in use--ion implantation, dry etching, step and repeat microlithography, E-beam mask generation--were developed by 1978. True to their history of competition through product innovation, American firms continued to invest in the new generations of microlithographic equipment (wafer steppers, direct write E-beam, focused ion beam, and X-ray systems) that were expected to become necessary as the level of chip integration increased and device line widths shrank. But Japanese firms chose a different strategy, working instead to extend the capabilities of existing lithography equipment based on visible and ultraviolet light.34 This strategy emerged logically from established Japanese manufacturing practice, though it was reinforced, as we shall see, by the failure of U.S. equipment firms to supply their Japanese customers on time with new equipment. In any event, Japanese efforts to extend the life of existing equipment soon combined with their successes in markets for high-volume semiconductor memories to slow the pace of technical innovation by American firms even further, greatly simplifying the efforts by the Japanese to overtake the technological leaders.

Third, and most important, the VLSI project provided a context in which semiconductor and equipment firms could work together to organize a production system geared toward the constant introduction and refinement of new manufacturing techniques. Because it was understood that involvement in the VLSI project would provide all major firms in the industry with a common technical base, competition between semiconductor firms would have to center on improving quality and/or lowering costs through constant refinement of the manufacturing process. Semiconductor producers thus had a clear strategic incentive to cooperate closely with their equipment suppliers, and in the context of the VLSI project, that cooperation was remarkable indeed. Overall development costs were shared. Equipment needs were jointly defined by the device and equipment firms, with chip producers using their own prototype wafer fabrication lines as development laboratories for the equipment producers' systems integration and quality improvement efforts. Cooperating chip producers, NTT, and MITI's electrical labs provided equipment firms with a guaranteed internal market through which to gain essential production experience. And the entire process proceeded under the direction of the very production engineers that would ultimately be responsible for implementing the new equipment into the manufacturing process.

Conquering the Domestic Market. By 198O, the VLSI project had resulted in the development of an indigenous semiconductor technology base in Japan. But unlike the case of the computer market of the mid-seventies, developments in the international market were soon to play right into Japanese hands. Japanese semiconductor firms had decided--correctly, as it turned out--that economies of scale would be crucial to the success of their aggressive market-penetration pricing strategies in high-volume semiconductor markets. Thus, despite a massive recession in 1981-82, Japanese semiconductor firms continued to invest heavily in huge, increasingly automated mass production chip fabrication facilities. Consequently, while the American market for semiconductor equipment grew only 10 percent between 1980 and 1982, the Japanese market exploded, growing a phenomenal 66 percent. U.S. equipment firms, mostly dependent on Japanese trading firms for feedback on the Japanese market, were caught unprepared. As delivery delays lengthened, Japanese semiconductor producers switched rapidly to their domestic equipment suppliers, and the U.S. share of Japanese equipment markets declined rapidly for every category of equipment.

The success of Japanese semiconductor firms in world markets for memory devices depended critically on tactics of production organization developed through the decades of technology transfer and perfected through the cooperative relationships they had developed with their equipment suppliers during the VLSI project. Japanese chip producers led their U.S. merchant competitors in the introduction of the state-of-the-art 64K dRAM device, not by being more innovative in design, but by pursuing their usual strategy of constant introduction and incremental refinement of new manufacturing techniques. Japanese semiconductor firms chose, essentially, a straightforward scale-up to 64K of their 16K dRAMs, which were based on U.S. merchant Mostek's industry standard 16K design. This is in stark contrast to US producers who, following their historical strengths in innovation, adopted a range of novel approaches to the 64K device (such as redundancy, self-refresh) which made their development times longer and their production problems greater than those experienced in the straightforward Japanese effort.

Most important for our purposes, Japanese firms achieved the scale-up through incremental improvement of older photolithographic techniques, in particular proximity aligners, which few U.S. firms believed capable of reaching the 2-3 micron design rules of the 64K device. U.S. firms, by contrast, moved to projection aligners and wafer steppers--new equipment they believed would be necessary to produce the next generation of dRAMs, the 256K. The newer process techniques required a much longer period for acquisition and debugging, and this accounted, at least in part, for the costly delays in production of the 64K dRAM experienced by U.S. semiconductor firms.

Unlike their American counterparts, Japanese device makers were able to input specific requirements for new production equipment. They rarely purchased standard equipment or installed it in their plants without modification. The structure of ownership ties between many device and equipment producers enabled semiconductor manufacturers to permit scientists and technicians from their tool-making affiliate to have access to their wafer fab facilities for extended periods of time without fear of losing proprietary secrets. Equipment could then be modified during the process of development as the equipment vendor's familiarity with the device manufacturer's particular process environment enabled him to make timely suggestions for reducing contamination and improving production yields. The technological feedback thus provided to the equipment maker resulted in the development of manufacturing equipment that better met the production needs of the semiconductor manufacturer and allowed for a better integrated--and more readily automated--production line. With these and other competitive advantages flowing from the close cooperative ties between Japanese device and equipment producers, it is little wonder that Japanese companies locked up nearly three-quarters of their domestic equipment market during the early 1980's.

Summary. During the 1970's, a series of government-orchestrated R&D projects enabled Japan's semiconductor equipment industry to achieve state-of-the-art capabilities in both semiconductor test and assembly and most parts of the wafer fabrication process. These projects reinforced the tactics of production organization which Japanese semiconductor device and equipment producers had instituted during the 1960's to encourage the rapid diffusion and adaptation of production technologies developed elsewhere, mostly in the United States. Just as in the U.S., domestic competition in a rapidly expanding domestic market drove the growth of the industry. Unlike the U.S. case, Japanese competition was structured by government policies designed to insulate the domestic market from foreign competition while providing all major firms in the industry with a common level of technical expertise.

With that common base of technical expertise in place, competition among Japanese semiconductor firms focused on constant refinement of the manufacturing process to boost quality and lower costs. This facilitated two important conditions with respect to Japan's semiconductor equipment industry: (1) the development of a fairly concentrated industrial structure in which semiconductor firms--the equipment users--fostered close, sometimes ownership ties with equipment producers; and (2) the creation of a similarly concentrated market structure in which chip producers and government laboratories routinely provided equipment firms with a guaranteed internal market on which to build production volumes and manufacturing expertise prior to engaging in international competition.

The Japanese equipment industry exhibited several competitive strengths, all flowing from the characteristically close relationship between user and producer. First, device makers most often took the lead in promoting or introducing new equipment into the manufacturing process. Thus, government-orchestrated cooperative R&D projects helped forge a structure of close operational links that facilitated continuous feedback between semiconductor device and equipment producers during the equipment development phase. Second, manufacturing engineers and scientists employed by the device makers worked closely and routinely with their equipment suppliers to adapt equipment to the actual production environment in which it was expected to operate prior to marketing the product, a practice known in the industry as beta-site testing. Third, financial and ownership ties among semiconductor device and equipment firms, device and systems producers, a set of industrial groups and their affiliated banks, meant there was a larger pool of capital available for equipment development and marketing than was generally the case among independent equipment firms in the United States. Riskier projects were subsidized through government-orchestrated cooperative efforts or quasi-public institutions such as NTT.

Just as in the United States, the Japanese industry's characteristic competitive strengths were soon reflected in characteristic competitive strategies. But, since the strengths differed, so did the strategies. For example, rather than emphasize new product development, most Japanese equipment firms focused on the interactive introduction of new equipment or, more often, incremental improvements in the operation of existing equipment (through the evolution of cleaner environments or better production controls--particularly statistical quality control--overseen by highly-skilled equipment operators). Prior to achieving state-of-the-art capability, Japanese equipment firms would typically make extensive use of reverse engineering. Manufacturing would often target low-end technology equipment to facilitiate learning and to gain market entry. Marketing would typically center not on on-site user training but on continuous feedback between user and producer during equipment development or on on-site testing prior to marketing. In foreign markets, Japanese equipment firms emphasized the early establishment of sales and distribution networks and training facilities, plus the development of strong installation and maintenance programs.

The Japanese equipment industry was not without its weaknesses. Start-ups were difficult to establish. Domestic market options were limited, since semiconductor producers were likely to be wary of purchasing equipment from firms affiliated with one of their competitors. Similarly, equipment firms were generally not in a position to benefit from exposure to technological advances made by their domestic competitors outside the context of a government-sponsored cooperative project. Still, the protected domestic market provided an insulated base within which Japanese firms could reach scale economies, improve quality, reduce costs below world levels, then enter competition with U.S. and European firms.

With the shift in semiconductor technology from large-scale to very-large-scale integration, escalating equipment costs began to outstrip the ability of semiconductor firms to finance new equipment purchases out of chip sales. This was a consequence, in part, of Japanese successes in flooding world markets for certain types of high-volume semiconductor memories. Still, as the 1980's progressed, the new technological and market environment trained a bright spotlight on the Japanese equipment industry's characteristic competitive strengths--while simultaneously casting a harsh glare at the U.S. industry's comparative weaknesses.

III. International Competition in Semiconductor Production Equipment: A Comparison of Strategy and Structure in the U.S. and Japan

The Interaction of Strategy and Structure. In 1975, U.S. firms supplied nearly 80% of the Japanese market for semiconductor production equipment. Ten years later, the numbers had almost completely reversed: 75% of all semiconductor production equipment sold in Japan in 1985 was manufactured either by Japanese companies or by joint-ventures between Japanese companies and American equipment suppliers.35 Operating from this secure domestic base, Japanese firms entered international markets for advanced lithographic, process, and test equipment, markets previously dominated, if not monopolized, by American firms.

Although the dynamics of individual market segments easily muddle in the swamp of equipment types and the wide and sometimes overlapping mix of players involved in selling them, the competitive outcome overall is increasingly clear. Since about 1981, American producers have been steadily losing market share, and Japanese firms gaining it, in nearly every category of semiconductor production equipment. In 1986, U.S. firms actually lost world markets for optical lithography and automatic test equipment. More important, however, is the competitive situation in markets just beginning. For a wide array of critical next-generation technologies, the initiative for real innovation in both products and production processes has shifted rapidly, and decidedly, to Japan.36

In this section, I will argue that Japanese successes in adapting to world market conditions stem from two core structural attributes which the Japanese industry possesses and the U.S. industry lacks. One is the government's capacity to orchestrate cooperative, commerically-oriented R&D projects involving all the major firms in the industry. The other is the network of close and enduring linkages that characterizes semiconductor producers and their affiliated equipment suppliers. The competitive outcome is not determined by the development of these particular structures. Those structures have become decisive, however, due to a couple of fortuitous events. Japanese market entry was faciliated by simultaneous economic and technological developments--the emergence of a high-volume commodity-product market, in the form of random-access memories, and the shift from large-scale to very-large scale integration. These developments shifted the terms of competition to favor the typical strengths of large, integrated firms: capital investment, mass production, and marketing.

The deteriorating position of U.S. equipment firms can be traced in large part to the declining competitiveness of the U.S. merchant semiconductor producers who are their major customers. This decline traces most directly to the merchants' losses in the high-volume markets for several types of random-access memory. Japanese semiconductor device and equipment firms began to compete internationally just when escalating capital costs were beginning to outstrip the ability of each new generation of chip sales to pay for each new generation of production equipment. They responded, in part, by choosing competitive strategies aimed at maximizing market share in the commodity memory segment. Since maximization of market share required a production strategy based on mass production of memory chips, Japanese device firms and their equipment suppliers were encouraged to take a holistic view of the semiconductor production process. This meant that introduction of new equipment, already an interactive process between Japanese semiconductor producers and their affiliated equipment suppliers, was done with an eye toward integrating (and automating) the entire production line. It was on this basis that Japanese semiconductor producers entered world markets for memory chips in the late 1970's, and trounced the American merchants.

Merchant losses in world markets for standard, commodity products like dRAM's undermine the American equipment sector in two ways. First, as market shares decline, U.S. semiconductor producers buy less capital equipment for both production and R&D. Faced with financial catastrophe in the short-term, the merchants are unwilling to invest in long-term cooperative equipment development. Second, due to the rapid increase in demand for memory chips during the past decade, merchant losses in that market have shifted the chief source of demand for leading-edge production equipment from the U.S. to Japan. Given the close ties between semiconductor device and equipment producers in Japan, this is a fact of paramount importance.

Expenditures for semiconductor equipment in Japan pulled ahead of U.S. expenditures in 1983.37 By the beginning of 1987, Japan's demand for fabrication equipment (excluding test and assembly) stood at about 35% of the world total (as compared to 23% in 1979); equivalent demand in the U.S. had shrunk from 67% to 57% during the same period.38 These figures reflect both the rapid increase in Japanese semiconductor production and the high and growing level of capital expenditures by Japanese chipmakers, measured as a percentage of semiconductor production.39 For example, despite Japan's smaller share of the worldwide semiconductor market in 1985, the Japanese spent 12% more for capital equipment that year as compared to U.S. firms.40 Capital spending by Japanese chipmakers amounted to 31% of the value of production that year; equivalent spending by U.S. firms amounted to just 21%.41

Part of this reflects keiretsu ties between semiconductor equipment and device makers, between device and systems manufacturers, and between all of these firms and an affiliated bank. Such ties provide the individual firms with a larger and more patient pool of capital than that which is typically available to U.S. equipment producers. Unlike their Japanese counterparts, U.S. semiconductor equipment makers have had to make a number of risky investment decisions without much financial or strategic assistance from their compatriot semiconductor producers. This has led to a number of false starts.

Determined, for example, not to repeat the mistakes that had cost them so dearly during the mid-seventies downturn, U.S. equipment firms continued to build heavily during the recessionary period of 1981-82. When the upturn came, however, they were in for another rude shock. U.S.

semiconductor makers had reacted to Japanese seizure of commodity memory markets by shifting their product emphasis toward more complex chips. Not only did the renewed emphasis on comparatively small-scale, batch production of innovative chip designs require a shift to a whole new generation of production equipment; it also reinforced the U.S. industry's habit of introducing new production equipment in piecemeal, process-by-process fashion, just as the Japanese were reaping the benefits of more integrated and automated fab lines. Thus, equipment makers who had built up large inventories during the 1981-82 recession found themselves stuck with large stocks of machines that were suddenly technologically obsolete. "We thought people were adding capacity," said GCA's vice president for marketing at the time, "but they were adding capability. We were caught."42

Ironically, it was sales to the booming Japanese equipment market that kept many U.S. equipment firms afloat during the early 1980's. Soon after that, the chip boom of 1984--fed by real and anticipated sales of personal computers for homes and offices--encouraged several new U.S. equipment start-ups and a host of ambitious expansion plans. Meanwhile, the Japanese kept busy consolidating their home market advantage--meaning the Japanese market would not be available to bail U.S. equipment firms out of the next slump. They also set about building extensive sales and distribution networks in Europe and the United States. The prolonged semiconductor slump beginning in 1985--and the attendant financial debacle for independent U.S. equipment firms--gave better-financed Japanese firms the opening they needed to enter the American market. By 1986, when chip producers were buying equipment only for R&D and advanced prototype production, Japanese firms were able to seize U.S. and European markets for leading-edge optical lithography and automatic test equipment. This is higher-volume equipment whose development and modification stems most directly from experience gained in the mass production of cutting-edge memory devices.

An examination of these cases will be most instructive. The competitive consequences of structural differences between the U.S. and Japanese equipment industries can be seen most clearly in the equipment markets most directly affected by American losses in the memory chip markets. Memory chips encourage maximal exploitation of scale economies, automation, and new equipment. Their geometrically regular architecture means that competitive advantage derives more from integration levels, reliability, and low cost than from functional capacity. What is more, their commodity-product character facilitates high-volume mass production, providing the range of production experience that is necessary to propel their producers quickly down the learning curve for both chips and equipment. These factors, in combination, make memory production ideal for the introduction and perfection of advanced lithographic, processing, and test equipment. That equipment can then be applied to the fabrication of more complex logic, custom, and semicustom circuits.43

Thus, it is surely no accident that the strongest Japanese companies in the U.S. market currently are Nikon (in wafer steppers) and Advantest (in automatic test equipment); each competes in a market whose cutting-edge products are honed on the mass production of semiconductor memories. By examining the competitive evolution of wafer steppers and automatic test equipment, products introduced and, for most of their history, manufactured and marketed primarily by American firms, we will be able to gain a clearer understanding of how structural differences between the U.S. and Japanese equipment industries affect competitive outcomes in practice.

Lithographic Equipment.44 GCA was still a small atmospheric instrumentation company known as the Geophysical Corporation of America when it developed a precision map-making technology that could also be applied to the problem of aligning masks during photolithography. Direct wafer steppers actually eliminate the need to generate a mask, achieving high resolution instead by moving step by step across a silicon wafer to project circuit patterns directly onto individual chips. GCA moved quickly to commercialize its innovation, introducing the first commercial wafer stepper in 1978. Major semiconductor producers were just as quick to recognize the stepper's potential advantages over existing equipment.45 Early GCA customers included IBM, ATT, Fairchild, National Semiconductor, and Siemens, among many others, and the company's revenues exploded, growing from $62 million in 1978 to $309 million in 1984.46

Meanwhile, Nikon and Canon had begun their long march. During Japan's VLSI project, both firms formed close ties with Japan's major semiconductor makers in the process of developing equipment to meet their needs. It was during this same period that Japanese chip manufacturers were gearing up for a massive assault on the world market for 64K memories, thus promising a large potential market of great interest to the two giant optics firms. Of great importance is the fact that Nikon and Canon did not initially compete with each other; they concentrated their initial efforts in different areas of the market, Nikon on wafer steppers, Canon on older-generation projection and contact/proximity aligners. Both Nikon's steppers and Canon's projection aligners emerged through work with the MITI labs.

As I mentioned in Section II, Japanese chipmakers depended initially on incremental improvements of older lithographic techniques, in particular contact or proximity aligners, in order to reach the 2-3 micron design rules of the 64K device.47 In contrast, their U.S. counterparts were turning to new processing techniques like projection aligners and wafer steppers. The Japanese chipmakers' strategy presumably aided Canon, whose task was made easier because the Japanese chipmakers had adopted a straightforward scale-up to 64K of their 16K dRAMs, also in contrast to U.S. firms who were then adopting a wide range of novel design approaches.

The task was also made necessary, because U.S. equipment producers, including GCA, were caught short by the demand surge that preceded the recession in early 1981, and gave delivery priority to their U.S. customers. The absence of close ties between GCA and its customers prevented the equipment firm from designing an appropriate production schedule in advance. In contrast, Japanese semiconductor producers benefitted from both a simpler design strategy and the opportunity to develop and improve their existing equipment with help from their affiliated equipment suppliers. With Japanese chip producers and the MITI labs providing a guaranteed internal market, Japanese equipment makers gained valuable time and resources to develop their own state-of-the-art steppers (Nikon) and projection aligners (Canon). U.S. chipmakers were still waiting delivery or working out the bugs in theirs. This is one of the reasons the Japanese were able to beat their U.S. competitors into the 64K dRAM market.

Both the timing and the resources were crucial. Japanese semiconductor producers continued to expand manufacturing capacity during the 1981-82 recssion while U.S. firms were either delaying or cutting back their own expansion plans. Moreover, the Japanese concentrated on bringing production costs down by automating their 64K dRAM production process. The ability of Japanese semiconductor and equipment firms to sustain their level of investment during this period reflected their access to larger pools of capital, as well as the longer time horizon of Japanese financial institutions. Their ability to automate production depended crucially on guaranteed stable access to a rapidly growing domestic market for 64K memories, access they had due to the substantial portion of each firm's output that was either used internally or sold within the essentially captive market of the firm's own keiretsu.48 Japanese chip producers seized 70% of the world 64K memory market in 1981 and their high quality, automated mass production orientation shifted the market for wafer steppers, and the incentive and resources for continued innovation, directly to Japan. By the end of 1984, the Japanese stepper market was bigger than its U.S.

counterpart; some 55% of the 1,088 units sold throughout the world went to Japan, which meant that Japanese chip producers bought more steppers that year than the rest of the world combined.

It was in this atmosphere of rapidly accelerating domestic demand that Nikon entered the Japanese stepper market in 1981, snatching GCA's big NEC and Toshiba accounts, and ramping up production as fast as it could. Initially, Nikon attracted customers by producing a higher resolution lens than GCA offered; not used to the competition, GCA was slow to match that development and upgrade its basic machine. Indeed, as long as no other company was manufacturing a wafer stepper in Japan, GCA was content to avoid the tremendous investment required to build indigenous manufacturing capacity. GCA chose to import American engineers as needed for technical support, even after signing up the giant Japanese trading company Sumitomo to market its basic American machine. Sumitomo is a member of NEC's keiretsu. Meanwhile, Nikon equipment builders were honing their production skills in NEC semiconductor plants.49

Back in the U.S.A., GCA had other problems. Company sales plummeted 50% during the recession of 1981-82. But GCA benefitted from the fact that most equipment operators in the U.S. had been trained on GCA steppers. Many American engineers wanted to experiment with other steppers, but with turnover high and flexibility low due to the limited skills of most equipment operators in most U.S. wafer fab facilities, the installed base apparently fed on itself.50 GCA was able to reestablish itself with a number of major customers, including ATT and Advanced Micro Devices; by 1983, GCA was on the rebound in the United States.

The situation in Japan, however, was quite the reverse. By 1983, GCA's share of the Japanese stepper market had declined from 68% in 1981 to approximately 45%. Belatedly awakened to the Nikon challenge, GCA responded by attempting to improve its technical support to Japanese customers. To do this, GCA upgraded its relationship with its distribution agent, Sumitomo, establishing a 50-50 joint venture, Sumitomo-GCA. Sumitomo-GCA set up a new distribution system, built a testing and assembly plant, hired Japanese engineers for the first time, and began to purchase subassembly equipment from Japanese vendors with the goal of manufacturing entire systems. At the same time, Nikon made its initial move into the American market, not through a joint venture, but through a wholly-owned subsidiary, Nikon Precision, Inc., established in Silicon Valley in August 1982. Drawing on its experience in Japan, Nikon consciously set about establishing a good service network in the United States before attempting to sell its steppers in volume.51

Back at corporate headquarters in Bedford, Mass., GCA's managers moved to diversify. Despite signs of an impending slowdown, the company invested heavily in new fields, particularly robotics, doing everything, it seems, to erase its reputation as a one-product company competing in a single market. GCA launched, then abandoned, several new equipment projects--a deposition system, an ion implanter, a dry-etching system, an electron-beam project. The company also shifted its marketing strategy for wafer steppers in early 1985, announcing a new low-end stepper (the Model 5000) targeted at applications in 2- or 3-micron high volume chip production.52 By 1985, most such production had shifted to Japan, where GCA's market share had stabilized at approximately 30%.

GCA's new corporate strategy clearly reflected management optimism about the pace of IC automation, an optimism not shared by most industry observers, but not surprising given GCA's lack of interaction with its major customers. The diversification undermined the company in two ways. First, and most simply, the company entered new businesses that were subject to the same business cycles as the semiconductor business on which it relied most heavily for funds. Second, the company diverted precious R&D resources, both money and talent, away from its primary wafer stepper business. In 1983, for example, the company invested some 25% of its $38 million R&D budget on its Industrial Systems group, the division responsible for developing robotic-based handling and control systems for use in automotive, aerospace, and other heavy manufacturing applications. That year, Industrial Systems accounted for only 7% of GCA's total sales.53 Finally, GCA managers simply underestimated the severity of the semiconductor slump of 1985. The lack of any strategic ties to its primary customers meant that the company never had enough information, far enough in advance, to develop a capacity to adjust to any wild fluctuations in demand for its basic product. In any event, GCA geared up to sell between 500 and 600 steppers in 1985 at more than $1 million a piece; when actual orders barely reached 100, the downhill slide began for real. GCA lost $94 million.

The diversion of R&D funds to peripheral ventures combined with the company's severe overproduction to stall the development of the company's newest product, the high-end Model 8000, a 5X reduction stepper meant to compete with Canon, Censor, and Nikon.54 By the beginning of 1986, GCA had abandoned the low-end Model 5000, concentrating all of its resources on getting the 8000 ready for shipment. But the financial drain was already too great. Major suppliers, like Zeiss the lens maker, stopped delivering critical components due to GCA's unpaid bills; Nikon, which makes its own lenses, would never face a similar problem. GCA was even barred for a time from bidding on government contracts because a company executive boasted of having seen a competitor's sealed bid on a $50 million contract with the Environmental Protection Agency. After "the sudden departure of [the company's] chairman, two successive presidents (including one who lasted only eight days), two chief financial officers, the entire board of directors, and GCA's top technical wizard," one of GCA's major lendors, Mellon Bank, finally brought in outside management. So far, GCA's new managers have sold off several GCA subsidiaries and reduced the payroll by 70%. But the company's arms-length relationship with its major American customers continues to cast a long shadow across the company's future prospects. Indeed, the company's financial survival will depend, in part, on bringing in Sumitomo--read NEC--as a significant minority holder of GCA stock.55

Although major American customers, including IBM, have been trying to lend a hand with some quick cash, the chipmakers are understandably hedging their bets. IBM reportedly also ordered 20 new wafer steppers from Canon, which entered the U.S. stepper market in 1984, while Texas Instruments has turned to Nikon, after being favorably impressed by Nikon equipment in one of its Japanese plants.56 AMD, one of GCA's biggest customers, did not include GCA in the competition for a next-generation stepper order for its Austin, Texas plant, and Nikon was reported to have the inside track.57 Nikon also clearly benefitted from GCA's failure to bring out the Model 8000 on time, thrusting itself into a long-running stepper evaluation by Intel.58 A survey taken by VLSI, the market research firm, indicates that American chipmakers now prefer Nikon, even though GCA machines have better uptime in the U.S. This finding coincides with earlier research done by Japan's Nomura Research Institute (NRI). According to an NRI official, Japanese chipmakers do not seem to think that Nikon steppers are any more dependable than GCA steppers. "Reliability is the same...Japanese users are very skilled, so usually they can get the same results from Nikon and GCA."59 The reasons for Nikon's recent successes in the U.S. seem to relate more to firm reputation. According to VLSI's Dan Hutcheson, "The reason is apparently Nikon's experience in consumer [cameras] and their reputation for high-quality lenses."60

With its growing installed base in the United States--IBM, ATT, Intel, RCA, Texas Instruments, and some U.S. subsidiaries of Japanese firms--Nikon is clearly the firm to beat in the market for 1- to 1.25 micron steppers. Canon has had trouble entering the stepper market (Fujitsu sent their Canon steppers back in Japan due to reliability problems), as has equipment giant Perkin-Elmer, which bought the Lichtenstein stepper-maker Censor in 1984, despite Censor's troubled marketing history in the U.S. Some observers look favorably on the joint stepper venture between ASM America (Advanced Semiconductor Materials) and its Dutch compatriot, the electronics giant, Philips--"if," Hutcheson cautions, "they can really demonstrate the specs they claim."61 One American chipmaker that apparently has confidence in the ASM stepper's specifications is Cypress Semiconductor, which specializes in state-of-the-art process niches and recently delivered five CMOS memories with line-widths of 0.8 microns.62 Most industry observors doubt, however, that ASM has the service and support networks it needs to sustain its equipment in this country. Nevertheless, there is no disagreement on a central fact: GCA's losses to Nikon, Canon, and ASM mean that the center for the development of next-generation stepper technology has already slipped offshore.

Automatic Test Equipment.63 When Schlumberger, the diversified French/American producer of oilfield equipment, bought Fairchild in 1979, sales by fast-emerging Japanese tester makers were already eroding the company's market-leading position. Unique among the semiconductor merchants, Fairchild had entered the production equipment business and had built a dominant worldwide position in markets for automatic test equipment, not only for semiconductors, but for printed circuit boards as well. But Fairchild's unique position among American firms as an integrated device/tester producer provided no particular advantage in Japan, where tester producers Advantest and Ando were both owned, in part, by giant, integrated chip and systems producers. Fujitsu owns 21% of Advantest; Ando Electric is 51% owned by NEC.

Fairchild's hold began to slip in the early 1980s as Advantest (then known as Takeda Riken) emerged from the VLSI project (specifically, the NTT labs) with the most sophisticated memory tester on the market. This occurred just as Japanese memory makers were winning the worldwide dRAM market from American merchants. Memory testers play the same role in the tester market as memory chips do in spurring equipment technology overall. First, the machines are more profitable than other tester types; the market's large size means that a single basic model can create large volume sales which can then be used to fund the next round of technological innovation. Second, semiconductor memory testers typically serve as seedbeds for trying out the most advanced processes available, first for memory production itself, and subsequently for testing of logic and VLSI logic circuits.

The Japanese quickly achieved technological parity, if not leadership, in tester hardware. Building on its cooperative R&D work with the NTT labs, Advantest (Takeda Riken) came out with the first commercial 100 MHz logic tester in 1979, surprising American ATE suppliers who were still debating the merits of building 25-50 MHz testers. The American firms were confident that available equipment was more than adequate for testing the overwhelming majority of devices which typically operated, at the time, at less than 10 MHz.64 In a sense they were right. Takeda Riken's 100 MHz logic tester was not a commercial success at the time; there was not yet a large enough market for it and the company provided inadeqate technical support. But the 40 MHz testers that followed benefitted from the company's reputation as the 100 MHz developer. More importantly, the virtual withdrawal of the U.S. semiconductor merchants from memory and other technology-driving markets soon removed both the incentive and the financial ability for many U.S. semiconductor ATE firms to advance the state of the art in testable clock rates and pin counts.

Ando and Advantest benefitted mightily from their ties to NEC and Fujitsu. These and other major Japanese semiconductor makers quickly switched their preferences to the Japanese ATE suppliers, and as their consumption of ATE skyrocketed so did the world market share of Japanese ATE firms. Japan's share of the worldwide market for memory testers jumped from about 30% in 1978 to approximately 45% in 1985. Hitachi, by then the leading dRAM producer worldwide, became a major Advantest customer, though by 1985 it was following traditional Japanese practice and developing a memory tester of its own.

The Japanese tester firms also benefitted, initially, from targeting different segments of the tester market, just as Nikon and Canon had initially targeted different segments of the market for optical lithography equipment. Advantest initially targeted top-of-the-line memory testers while Ando pursued a broad-based position in logic, memory, and eventually, VLSI logic testers. By 1986, Advantest and Ando were estimated to have locked up about 80% of the Japanese tester market, with Advantest alone accounting for over 50%.65

Unlike relations between their quasi-integrated Japanese counterparts, relations between U.S. ATE producers and American semiconductor merchants have been typically short-term and arms-length. American ATE suppliers were generally cautious about developing new equipment capable of handling the higher speeds of new devices, particularly in view of the tremendous investment required compared to the uncertain size of the market for specific pieces of equipment. Device makers, in turn, complained about ATE firms "dragging their feet" in producing new hardware and software tools for testing complex VLSI circuits. Of course, there is bound to be some lag between device availablity and tester availability; the users want equipment to test new devices, but the testers need sample devices to place in their equipment so that it can be designed to do the testing. This would seem to be obvious, but the fragmented competitive structure on both sides of the U.S. market gets in the way. The chipmakers jealously guard their new device designs, refusing to share their development work with ATE suppliers who would most likely try to sell the resulting testers to the chipmakers' competitors.

The semiconductor merchants have also long criticized what they perceive as a lack of sufficient built-in upgradeability in testers offered by American ATE firms. Combined with 2-5 year equipment development schedules, the resulting technical rigidity means the equipment is often functionally obsolete by the time it is finally delivered. Nevertheless, the merchants have not usually responded to this dilemma by offering to help defray development costs or by working more closely with the tester makers to get them pointed in the right technological direction. Rather, they have been increasing expenditures for designing additions to test systems in-house (designing networks and interfaces; adding signal processing and multiplexing) in order to extend the useful life of obsolete equipment. Since the chipmakers under most pressure to do this are precisely those on the cutting edge of device technology, the result has typically been a cutback on purchases of the most sophisticated software and hardware from U.S. ATE suppliers. This situation obviously reinforces the tendency of ATE suppliers to be ultra-cautious about developing next-generation testers.66

Amongst all the bickering, Fairchild's financial problems were providing an opportunity for aggressive market entrances by other American firms. By the end of 1983, Fairchild was already two years late in delivering its new VLSI tester. GenRad entered the market in 1981, although it misjudged development costs and almost had to drop out. (GenRad tried to develop a general-purpose VLSI tester at the same time it was building a hybrid-circuit tester for IBM.)67 Teradyne, on the other hand, decided to leave board testing to GenRad and LSI circuit testing to Fairchild, concentrating its resources and coming on strong with a cutting-edge VLSI tester in 1983.68

Operating from their secure domestic base, Japanese ATE firms were by this time accelerating their efforts to sell overseas, especially in the U.S. Concentrating on memory and logic testers, Advantest chose to target Fairchild customers in the U.S. as the one-time market leader was slipping. Advantest built U.S. sales to about $30.4 million in 1985, almost double its U.S. sales in 1984.69 Overseas sales have become even more important to Advantest as its R&D costs have risen; by the beginning of 1987, exports accounted for about 40% of its tester sales.70

Ando emphasized logic, VLSI logic, and linear testers. Most important, it pursued a strategy of following its parent NEC to production sites overseas, a strategy that should give pause to anyone who believes that the recent increase of Japanese chip fabrication facilities located in the U.S. will necessarily benefit American equipment suppliers. Ando's U.S. subsidiary now assembles, sells, and services its IC testers in the United States, and will soon open a U.S. software center. On the other hand, the core hardware still comes from Japan, a fact which has led some U.S. semiconductor firms, like ASIC maker VSLI Technology, to stick with U.S. vendors, such as Megatest.71 VLSI does not see the Japanese moving very fast in terms of offering links to CAE (computer-aided engineering) either, something Teradyne has done since 1984, when it set up a Design and Test Automation Group to sell software that the company had already designed for internal use.72

Faced with increased Japanese competition world-wide and at home, U.S. tester companies have recently begun seeking alternatives, including up-front development money from device makers, purchase orders signed in good faith many years before equipment can actually be available, and increased government funding.73 Yet, although a closer relationship may be developing between chipmakers and ATE suppliers, the disaggregated nature of both industries continues to create considerable obstacles. Tester makers point out that each major semiconductor maker uses different speeds, pincounts, and other parameters for the devices they are currently making or have under development. Thus, although the idea of general test equipment seems sensible to many--a way to keep tester costs down through large-scale sales of standard equipment--the fact that each chipmaker is more concerned with having its own requirements met means, instead, increased customization on the part of tester makers, who do not have the financial wherewithal to do both.74

Overall, the response of U.S. ATE firms to Japanese competition and the shift to VLSI has been characteristically both spirited and uncoordinated. New entrants continue to pop up. Building on its dominant position in linear circuit testers, LTX/Trillium has attempted to diversify by entering the market for VLSI logic testers, winning a major contract with Intel. Doubts persist, however, about the $145 million company's financial staying power in the face of rivals twice its size; LTX forecast a loss for fiscal 1986 and had to cut its workforce by 37%.75 Similar doubts plague the VLSI tester efforts of Tektronix and venture-capital-backed firms like Megatest and Semiconductor Test Solutions.76 Financial troubles also plague more established players like GenRad, whose high-end Model GR180 is targeted on devices in the Pentagon's Very High Speed Integrated Circuit (VHSIC) Program, and Schlumberger's Sentry, the latest incarnation of Fairchild's formerly dominant ATE division. GenRad spent nearly $50 million on development of its VLSI tester; the company lost $52.3 million in 1985 alone and fired 500 employees.77 And by the time Sentry's flagship Model 50 finally made it to market, potential users found that it was built with what many regard as an obsolete architecture.78

In the Japanese market, only LTX/Trillium has had any success in selling a new generation tester; its 1986 sale of one 256-pin, 60 MHz Arraymaster system to Mitsubishi clearly reflects its present lead in developing testers for complementary metal-oxide (CMOS) chips. LTX/Trillum will probably target "second-tier" Japanese accounts, such as Ricoh and Sony, companies whose systems people are now doing more circuit design work on their own and may thus be more open to buying American equipment.79 Sentry ended its relationship with its Japanese distributor Tokyo Electron Ltd. in 1982 and has attempted to go into direct sales and service; but Sentry's share of Japan's memory tester market still stood at less than 5% by the beginning of 1987.80 Neither GenRad nor Megatest operates a Japanese subsidiary; GenRad continues its joint marketing venture with Tokyo Electron Ltd. while Megatest is represented by Japan LSI.

Clearly, the U.S. firm with the best prospects--both in and outside Japan--is Teradyne, which introduced the industry's first megabit memory tester in 1986. Teradyne operates a wholly owned subsidiary in Japan staffed by 200 Japanese nationals. Yet even Teradyne, which through its Japanese subsidiary is attempting to break the tight buyer-seller union forged between Japanese tester suppliers and memory makers, is a relatively undiversified, $400 million independent company in a business notorious for chewing up capital. Teradyne is the only U.S. firm attempting to compete in the market for next-generation megabit memory testers, and with three of the four Japanese producers of megabit RAM testers owned in part or in whole by the very Japanese semiconductor producers most likely to dominate the world's 1 Mb RAM markets, it is going to be difficult for Teradyne's tester to emerge on top.

Other Processing Equipment. The structural characteristics which have advantaged Japanese equipment firms in international competition in memory-specific equipment sectors advantage them as well in less mature, lower volume sectors still dominated, for the most part, by American suppliers. Having taken the lead in optical lithography and automatic test equipment, Japanese equipment firms are now working with Japanese chipmakers in government-orchestrated projects aimed at the development of state-of-the-art equipment for the other front-end processing steps. Although the U.S. currently maintains a slight technological lead over Japan in established processing areas (ion implantation, thin film epitaxy, deposition and etch), access to the growing Japanese market for these systems has steadily diminished as Japanese firms have achieved rough technological parity. In sector after sector, government-assisted R&D, kereitsu ties, and joint ventures with U.S. firms enable Japanese firms to catch up with or surpass American firms technologically, diminish access for American firms to a growing Japanese market, then compete directly with American firms in Europe and the United States. Experts agree that, as a result of these efforts and the lack of anything comparable in the U.S., the Japanese could become major suppliers of deposition and etch systems by the early 1990's.

For instance, the U.S. still dominates the equipment market and research in reactive ion etching.81 The world market leader, Applied Materials, introduced its reactive ion etcher batch system in 1981, and has maintained a world market share of between 25% and 35% in what most market analysts consider to be a still immature market.82 (The leader in in-line systems is Tegal, now a unit of Motorola; at $46 million in sales in 1984, Tegal was the second largest worldwide supplier of dry etch systems.)83 Yet despite American world market and technological leadership, major Japanese semiconductor firms have fostered their own dry etch equipment makers and have been able to lock up their home market. NEC's Anelva held on to between 60% and 70% of Japan's dry etch market in 1981; although its share slipped to about 30% in 1984, it lost most of that ground to Hitachi, which brought its internally-developed etcher to the open market that year and captured about 24% of sales.84 By contrast, Applied Materials' Japanese subsidiary held only about 22% of the Japanese market in 1984.85 Indeed, by 1983, Japanese dry etch equipment makers were secure enough in their domestic base to launch their first full-scale attack on the American market.86

The Japanese seem perfectly willing to admit when they are not yet on par technologically with U.S. firms; as long as there is still no comparable Japanese supplier, Japanese firms will contract with U.S. vendors to develop equipment jointly. Japanese equipment firms do not work with American equipment firms, however; American equipment firms work with Japanese chipmakers or with NTT. The technological expertise is thus built up by the users of the new equipment, which enables them, eventually, to share that knowledge later with Japanese equipment suppliers, something U.S. vendors would be justifiably reluctant to do.

For example, as in the case of dry etching equipment, the United States continues to lead the world in materials and physics research related to basic implantation processes. This lead is reflected in the area of ion implantation equipment for conventional applications, low/medium and high current.87 Japanese firms are increasingly competitive in the maturing markets for low- and medium-current ion implanters.88 Ulvac, a Matsushita affiliate, developed its ion implanters in cooperation with the NTT labs during Japan's VLSI project; Hitachi's affiliate Kokusai Electric is also a minor producer. Still, Eaton/Nova remains the clear technological and market leader in high-current systems, even in Japan.89 Thus, Eaton/Nova has been contracted by NTT's research labs to develop a new high-current oxygen implanter.90 Foreshadowing future competitive developments, perhaps, is the fact that Eaton's other high-current implanters are manufactured and sold in the Japanese market by Eaton's Japanese joint venture partner, Sumitomo Heavy Industries, a member of NEC's keiretsu.

Similarly, NTT has signed an agreement with Varian to develop new sputtering systems for depositing thin films.91 Varian continues to be a leading producer of sputtering equipment worldwide, but faces increasingly stiff competition from Anelva, an NEC-affiliate which began as a joint venture between NEC and Varian.92 Under the recent agreement, Varian and NTT will refine processes based on planarization methods developed by NTT, with the techniques incorporated into Varian's sputtering equipment.93 It may be important to note, again for future reference, that Varian's sputtering equipment is sold in Japan through Varian's Japanese joint venture partner, Tokyo Electron Ltd. (TEL).

The relative advantages and disadvantages of joint ventures versus wholly-owned subsidiaries have been hotly debated. A significant amount of technology transfer to Japanese firms has occurred through the operation of joint ventures between Japanese firms and U.S. firms producing equipment for the Japanese market. As previously noted, Anelva started life as a joint venture between NEC and Varian; today, Anelva is Varian's strongest competitor in the market for sputtering equipment. Tokyo Electron Ltd. (TEL) has become Japan's leading vendor of semiconductor production equipment on the basis of its joint ventures with Thermco (diffusion/oxidation furnaces, CVD equipment), Varian (ion implanters, sputterers), TRE (wafer steppers), GenRad (VLSI testers), and Lam Research (plasma etchers).

In the case of Thermco, a California-based subsidiary of Sunbeam that was bought in 1981 by Allegheny International, the relationship with TEL has been highly beneficial. TEL-Thermco has built all of the company's diffusion/oxidation furnaces sold in Japan since the early 1970's. The company's experience in building diffusion/oxidation furnaces has also helped it to build a strong position in the market for low-pressure chemical vapor deposition (CVD) systems. By 1983, TEL-Thermco's 40% Japanese market share was actually outperforming Thermco's market share in the U.S., where the company was second to Bruce Systems, with a little more than 25% of the market.94 TEL-Thermco's successes stem from the sophistication of its customers; Japanese chipmakers have demanded highly automated equipment and have even funded TEL-Thermco's development or modification of equipment to meet their needs. Ironically, the same factors that are responsible for TEL-Thermco's success in Japan may have impeded Thermco's efforts somewhat back in the U.S. According to the company's president, "U.S. device manufacturers aren't ready to use such expensive, specialized equipment. We are marketing and promoting it [in the U.S.], but it isn't being bought [in the U.S.] like it is in Japan."95

It should be kept in mind that TEL-Thermco's successes have come in the markets for a maturing technology. The Japanese are probably not too worried about the continuing success of an American firm in a market that promises little future growth. Another dynamic has operated when different technological standards among U.S. and Japanese equipment users have attended joint venture efforts between U.S. and Japanese firms in cutting-edge equipment areas. For example, TEL-TRE was formed in July 1981 to manufacture the U.S. company's wafer steppers in Japan, but TEL apparently thought that TRE's machines were not sophisticated enough to compete with Nikon technology. Recall that Nikon took the Japanese market by storm in 1982 offering a very high performance stepper that was also lower in price than TRE's product. The TEL-TRE partnership is now thought to be dead, for all intents and purposes. Moreover, joint ventures can cost U.S. firms sales in Japan since the U.S. firm has no local manufacturing/distribution networks to fall back on if its Japanese partner starts causing difficulties. For example, Perkin-Elmer reportedly suffered from a strained relationship with its Japanese distributor Kanematsu. (Japanese chipmakers also reportedly found Perkin-Elmer's complex etch and deposition equipment difficult to automate).96 And TEL itself has been facing competitive difficulties of late; the top management team was recently fired, personnel defections are reportedly high, and customer regard for TEL is reportedly wavering. The difficulties at TEL may force several U.S. companies to change their distribution channels in Japan. Lam Research, for example, recently terminated its manufacturing/marketing joint venture with TEL and will now use a Japanese start-up distributor headed by TEL's ex-president.97

Clearly, the most successful foreign firms in the Japanese market have been those which have been able to open wholly-owned Japanese subsidiaries. These include Advanced Semiconductor Materials (ASM), the Dutch equipment manufacturer which dominates the world market for plasma-enhanced CVD reactors,98 and Applied Materials, ASM's top American competitor in that market, also the world leader in equipment for dry etching and epitaxy, and a new entrant in the market for high-current ion implanters. (Recall that Teradyne, the only U.S. automatic tester maker competing in the tester market for 1Mb memories, also runs a wholly-owned Japanese subsidiary). Again, the Japanese government seeks to exploit U.S. technological leadership where it exists, and independent American firms have been happy to oblige in return for at least a small protected foothold in the Japanese market. Thus, the Japanese technology center opened in 1984 by Applied Materials became, in 1985, the first wholly foreign-owned company to receive funding--in this case, a $3.4 million loan--from the Japanese Development Bank, a government agency charged with fostering industrial development within Japan.99

Sometimes noticing which advanced foreign technology the Japanese are not interested in obtaining can be as illuminating as noticing how the Japanese go about obtaining the technology they do want. For example, to date, Japanese chipmakers have shown little interest in epitaxial growth technology. Applied Materials holds a dominant position worldwide in epitaxial growth equipment, having sold $66 million worth of epi reactors in 1984, compared to $19 million for its closest competitor, Gemini Research.100 American chipmakers have become increasingly interested in epi reactors, in part, for avoiding the problem of "latch-up" in making CMOS chips.101 Latch-up refers to the potentially fatal condition in which excess stray current builds up, creating a voltage that causes chips to burn out. But Japanese chipmakers have been slow to respond. One reason is the cost of the process; it can add up to 5% to the cost of the finished wafer. A more significant reason may lie, however, in the Japanese chipmaker's more precise manufacturing process. Apparently latch-up has not yet posed a major problem for Japanese chipmakers, though analysts contend that even the Japanese will turn to epi processing with the onset of 4-megabit memories.102

Emerging Technologies. As ominous as these trends appear for U.S. firms competing in a range of current generation front-end process equipment markets, worse may be in store based on comparisons of on-going U.S. and Japanese research and development efforts aimed at commercializing emerging technologies. Japan is already considered to be leading in the development of a wide range of new technologies, including microwave plasma processing, laser assisted processing, compound semiconductor processing, and 3-D device structures. Not surprisingly, Japanese firms are concentrating efforts in the area of high resolution lithography, where researchers are developing increasingly efficient focused ion beam systems and high-throughput electron-beam systems and are making a large commitment to X-ray lithography. Once again, Japanese equipment makers are able to use the prototype wafer fabrication facilities of Japanese semiconductor producers, MITI, and NTT as developmental laboratories for their newest processes, and a guaranteed internal market for building up revenues and manufacturing expertise.

Submicron lithography will be dominated by some combination of three technologies: electron-beam systems for mask making and/or direct-writing, focused ion beam direct-writing, and X-ray lithography. In the area of electron-beam direct write equipment, nearly half-a-dozen American firms have already competed themselves out of the business, a bit like over-heated booster-rockets taking off individually and colliding in mid-air. Unfortunately, the main carrying vehicle--in this case the E-beam market itself--is still counting down on the launch pad.103 Meanwhile, three Japanese firms--Hitachi, Toshiba, and JEOL (an affiliate of Matsushita)--have unveiled proprietary direct-write systems, after first acquiring E-beam technology from American suppliers, then in effect creating their own internal markets for the equipment. This enabled them to master the technology through use. Today, JEOL has even begun marketing a system in the United States, although, ironically, U.S. chipmakers are reportedly reluctant to buy such a complex and "unproven" system from a Japanese supplier.

In stark contrast, only one American firm, Perkin-Elmer, still has an E-beam system under development for sale on the open market.104 The company has been able to stay in the market, moreover, primarily due to its involvement in the Pentagon's VHSIC (Very High Speed Integrated Circuit) Program. DOD picked up about 40% of the $20 million development cost of Perkin-Elmer's AEBLE 150, with the rest split between Perkin-Elmer and its VHSIC partner, Hughes Aircraft.105 Indeed, most of Perkin-Elmer's sales have been to various VHSIC contractors, like TRW, and IBM has also been a major customer.106 Dependence on the military market has created some production delays for the AEBLE 150; performance problems with Hughes' prototype were traced to contamination of both the building and the equipment in which the system was being tested, something that might have been avoided had the tests been done on the Japanese model--in the clean room of a semiconductor firm.107 But Pentagon funding appears to be the only game in town. As indicated before, five other independent U.S. equipment firms--Varian, GCA, Veeco, General Signal, and CDC/Microbit--all began and then cancelled major R&D efforts in electron beam etching for direct writing and/or mask making.108 By mid-1985, these firms had simply written off their losses, which totaled in excess of $100 million.

Although the Japanese now dominate the direct writing technology for circuit fabrication, the U.S. (Perkin-Elmer) holds onto the major market share of the E-beam mask making technology. This is fast becoming ironic, since purchasing decisions by merchant U.S. chipmakers have contributed to the near-demise of the U.S. mask making sector.109 Three Japanese firms--Dai Nippon, Toppan, and Hoya--entered the $230 million world mask making market in 1985, taking significant market share away from 15 undercapitalized U.S. start-ups. That same year, Intel reportedly switched its purchases from a combination of seven U.S. suppliers to a new combination of two U.S. and two Japanese suppliers. Other merchants apparently followed suit, encouraging a ruinous round of price competition among the underfunded U.S. start-ups. Dai Nippon and Toppan claimed annual revenues exceeding $50 million, while the largest American supplier reported 1984 revenues of just $16 million. Others, including Micro Mask and Master Images, reported operating losses in 1985.

There can be little doubt that the Japanese mask making firms will slowly substitute domestic E-beam systems for Perkin-Elmer's, taking away a downstream market that may one day be critical to the competitiveness of U.S. chipmakers in mask-intensive ASIC markets. In the meantime, of course, Perkin-Elmer has been perfectly willing to sell its equipment to any Japanese mask maker willing to buy it. It should also be noted, in passing, that U.S. losses in mask making have already registered further upstream in the production chain, where maskmakers must buy supplies of extremely high-quality glass. During the 1970's, the dominant supplier was America's Corning Glass; today, it is Hoya, the Japanese firm which also competes in mask making.

In the area of focused ion beam equipment, the Japanese seem once again to have seized the initiative.110 U.S. observers have remarked on the widespread use of focused ion beams in advanced circuit and process development in Japanese laboratories; in all, there are about 30 commercial finely tuned ion beam systems in use, most spectacularly at MITI's Optoelectronics Joint Research Laboratory. By contrast, there is little applied ion microbeam research going on in the United States and only three underfinanced U.S. start-ups have gotten into the business. They have shipped only a few systems, mostly to Japan. Only Japan's JEOL, drawing on its considerable experience in e-beam lithography, seems to be succeeding at selling its systems worldwide.

In the area of X-ray lithography, still thought to be roughly a decade away from large-scale commercialization, U.S. firms appear to have lost the initiative to Japan and West Germany for the development of commercial equipment.111 Current X-ray lithography tools are based on a conventional source (as used in the X-ray stepper being developed by Perkin-Elmer for the VHSIC program) or a plasma source (to be used in an X-ray system being developed by yet another U.S. start-up, Hampshire Systems). X-ray techniques will be increasingly favored for mass production of design dimensions of 0.5 microns and below. But both of the technologies now in use by the two U.S. firms mentioned are considered less powerful than computer-controlled, superconducting X-ray synchrotrons, which may be capable of superior resolution down to the sub-0.1 micron range.112 They are also expected to cost between five and ten million dollars each.

German firms have already announced the commercial availability of both synchrotrons and X-ray steppers; a consortium including Siemens, Philips, Telefunken, and Eurosil is conducting development work on a more powerful synchrotron X-ray source.113 In Japan, MITI and MPT are co-sponsoring a consortium of 13 Japanese electronics firms aimed at developing an X-ray system based on an advanced synchrotron source; the project is estimated to cost $100 million.114 NTT also has its own ongoing synchrotron project, involving Hitachi, Toshiba, and Mitsubishi. In contrast, there is currently no joint U.S. project in this area, although such a project is under discussion by the Departments of Energy and Defense. IBM is the only major American semiconductor producer experimenting with a synchrotron source. ATT's Bell Labs recently announced it was scaling back its X-ray lithography program to concentrate on mask making technology that can be licensed; ATT has stated that it cannot independently fund development of a synchrotron source.115 Several U.S. equipment firms, including Varian, have completely cancelled their X-ray lithography efforts.

By some estimates, West Germany and Japan have a two or three-year lead over the U.S. in advanced synchrotron radiation development, due to government-sponsored efforts in those countries. By contrast, the storage ring at the University of Wisconsin at Madison was not made available to U.S. experimenters until November 1985, and the University had to contend with some serious bureaucratic bickering before being guaranteed continued financial support through the National Science Foundation in May 1986.116

Summary. Between the mid-1970's and the mid-1980's, market dynamics in the semiconductor industry drove competitive strategies in both the semiconductor and semiconductor equipment sectors. These strategies were mediated significantly by characteristic differences in market and industrial structure, as well as in government policy, between Japanese producers and the U.S. merchant sector. Japanese entry was facilitated by simultaneous economic and technological developments--the emergence of a high-volume commodity-product market, in the form of random-access memories, and the shift from large-scale to very-large-scale integration. These developments shifted the terms of competition to favor the typical strengths of large, integrated firms: capital investment, mass production, and marketing. But the Japanese were particularly advantaged by two core structural attributes that the U.S. industry lacked--the government's capacity to orchestrate cooperative, commercially-oriented R&D projects and the network of close, enduring linkages between semiconductor producers and their equipment suppliers.

The initial technology base for the development of semiconductor equipment was devised and diffused in a cooperative R&D project orchestrated and subsidized by the Japanese government. Subsequent equipment development has been financed by banks affiliated with the same equipment suppliers, the linked semiconductor-computer producers, and their broader industrial groups. Unlike their U.S. counterparts, Japanese chip producers often take the lead in creating new equipment, financing equipment development out of their own sales. When equipment development is too risky, or when the technology is so fundamental that the government can obtain the cooperation of every major firm in jointly developing a common technical base, research and development is subsidized through the involvement of government labs. In either case, Japanese government policy or inter-firm ties explode the constraints on capital availability that menace competing U.S. equipment firms.

Continued high levels of investment during the 1981-82 recession enabled Japanese equipment firms to catch up technologically in memory-driven lithography and test equipment sectors. Continued investment during the slump beginning in 1985 has brought the Japanese to the verge of technological leadership in etch and deposition equipment, and has enabled them to open a widening lead in a broad range of crucial next-generation processes. The strategic benefits conferred by inter-firm financial ties and government subsidized R&D increase when competitive advantage in a new product generation begins to depend powerfully on competitive outcomes in markets for the current product generation. Competitive advantage is no longer temporary; it is cumulative. GCA's losses in the market for wafer steppers leave the company unprepared to finance development of next-generation e-beam equipment; Eaton's development efforts are similarly impeded by a slow market for its top-selling ion implanters; Sentry's losses in the memory tester market help delay its introduction of a next-generation VLSI logic tester until it is thought to be already functionally obsolete by the time the product makes it to market. The loss of one market battle leaves each independent equipment firm technically and financially unprepared for the next. But many Japanese equipment firms do not face that problem. Teradyne's struggle to succeed with its lone American 1 Mb RAM tester arises, for example, from the fact that its three Japanese competitors are owned by the very semiconductor producers certain to dominate world markets for 1 Mb devices.

Strategic advantage in equipment markets also derives from close marketing ties to the device sector. If GCA had enjoyed closer ties to its major customers, perhaps it could have anticipated and thus stabilized the demand for its major product. At the other extreme, Ando and Anelva are so closely tied to NEC that they follow the company to its new production sites in the United States, a fact that should give pause, as I said before, to those who think that U.S. production by Japanese semiconductor firms will necessarily benefit domestic equipment and materials suppliers. Indeed government policy need not take a leading role in protecting the Japanese equipment market from foreign competition (though it has clearly played a critical role in creating the very market/industry structure that enables Japanese firms to attain technological parity, a fact which may now make overt protectionism unnecessary). Given a highly concentrated, integrated industrial and market structure, partial or even total market closure can occur spontaneously.

As the previous paragraphs illustrate, industrial groups in Japan have many incentives to buy only from themselves and each other. By buying domestically, Japanese electronics producers can enjoy earlier access to next-generation semiconductor equipment than the U.S. merchant chipmakers, permitting them to be first to market with the latest generation of chips, and first to market with the final products that contain the chips. Where U.S. leadership still exists in mature, slow growth markets, the Japanese will buy the product from a U.S. firm, as they do buy diffusion ovens from Thermco. Otherwise the Japanese may purchase American equipment, work in Japanese subsidiaries of U.S. firms, or engage with U.S. firms in joint manufacturing ventures in order to gain access to American know-how prior to manufacturing the equipment themselves. It is in the individual, short-term interest of each American firm to make these deals, though it may spell disaster in the long run, both individually and in the aggregate. But once the Japanese achieve technological parity--or even a bit before, since Japanese users are highly skilled and can elicit superior performance from inferior equipment--they begin to exclude imports automatically.

When entering competition, either domestically or internationally, Japanese equipment firms derive competitive advantage from concentration as well as integration. Higher concentration facilitates efficient market targeting and coordinated entry: recall the different product emphases that characterized the initial entrance of Nikon and Canon into the markets for optical lithography equipment, or Ando and Advantest in automatic test equipment. Note also the scale at which the Japanese have typically entered each equipment niche, generally two or three firms at most as opposed to the dozen or more entrants usually fielded on the American side.

Finally, Japanese equipment firms gain strategic advantages from their close technical links to semiconductor producers. Japanese personnel in both chip and equipment firms build critical production skills while honing new production equipment on integrated and increasingly automated mass production fabrication lines. Requests from the chip producers for equipment improvements emerge from an intimate knowledge of the capacities of their equipment suppliers. Suggestions from suppliers derive from an intimate knowledge of the needs and capacities of the semiconductor producers. It is the kind of knowledge that may tend to pass around from firm to firm as individuals work together, change jobs, attend formal industry gatherings or meet colleagues informally. It is the kind of knowledge, however, that tends not to transcend national boundaries, and thus constitutes a distinct source of national competitive advantage.

The entrepreneurial independence characteristic of the U.S. semiconductor and equipment sectors has continued to facilitate rapid introduction and diffusion of product and process innovations. However, this same structure has also caused U.S. firms to respond to the growing Japanese challenge in ways that actually accelerate the rate of Japanese penetration in both the device and equipment sectors. Continued innovation in product design depends ever more heavily on continued mastery of the complex semiconductor production process. That mastery was traditionally gained (and financed) through experience in mass producing the most sophisticated versions of current-generation memory devices. Thus, Japanese inroads in both the memory device and production equipment sectors are threatening to sap the U.S. industry of its greatest remaining competitive strength--technological leadership in complex product design.

In the United States, alarm bells have been sounded first and most harshly by integrated producers like IBM and other non-commercial entities which have, for their own institutional reasons, much longer time horizons than the merchant chip producers and their independent equipment suppliers: the CIA and the Department of Defense. The fear is that, for all the reasons I have just detailed, U.S. semiconductor and semiconductor equipment producers will not survive in their present form--perhaps not in any form--against a structurally-superior Japanese industry. Blinded by their fragmented industrial structure and their chronically short time horizons, most U.S. chipmakers have been slow to respond as Japanese chip and equipment firms pursue several aggressive, government-orchestrated, industry-wide efforts to surpass their American counterparts in every category of semiconductor design and manufacturing.

In the final section, I will discuss a set of political responses which, combined with emerging patterns of production reorganization by individual firms, are leading to the evolution of a new industrial structure in the United States that may or may not achieve more success in competition with the Japanese. The fact remains, however, that in mid-1987, U.S. merchant semiconductor firms are only just beginning to look over their shoulders to perceive the damage being done to them in the equipment sector. They are looking in the wrong direction. The Japanese have already leapt over their heads.

IV. Creating Advantage: Policies and Prospects

The U.S. semiconductor industry has advanced two major political responses to the competitive dilemma it faces in the late 1980's. The first has been to lobby for fair trade legislation; the second has been to promote the idea of a $1.5 billion, government-assisted R&D consortium (Sematech) aimed at restoring U.S. superiority in semiconductor manufacturing technology.117 True to form, the chip industry has been slow to consult its equipment suppliers in the process of drafting these responses. As a result, both responses may end up confusing the competitiveness issue rather than resolving it.

For example, almost as soon as the U.S. and Japanese governments reached a semiconductor trade agreement in 1986, U.S. semiconductor equipment producers joined many U.S. chip users in criticizing the pact. The agreement implemented price protections against certain Japanese chips imported into the United States, while promising greater access for U.S. firms to the Japanese semiconductor market. Along with other chip users, American computer manufacturers quickly protested that they would now have to pay higher prices for many of the chips they buy in the United States. Producers of semiconductor production equipment had a different worry: the potential further loss of Japanese sales. Since the U.S. government calculates fair market value on the basis of the costs incurred by Japanese firms in producing the chips they wish to export to the United States, U.S. equipment producers have contended that the pact creates an incentive for Japanese firms to produce chips using older, lower cost equipment in older, lower cost plants. In addition, to the extent that Japanese chipmakers respond to the pact by building chip manufacturing facilities in the United States, the pact may not have the anticipated effect of creating new Japanese customers for U.S. equipment suppliers. Rather, it may simply create new U.S. business for Japanese equipment suppliers, who often follow their chip-making patrons across the Pacific to their new U.S. production sites. Thus, although the trade pact may aid U.S. chipmakers in the short run, it may ultimately do more harm than good if it ends up further undermining the domestic equipment sector. Once again, a fragmented industrial structure has kept U.S. semiconductor makers from taking the needs of their equipment suppliers into account--and from understanding the extent to which their equipment suppliers' continued competitive health is essential to their own.

It is the close, interactive relationship between Japanese semiconductor producers and their equipment suppliers that forms the core of their competitive advantage over the U.S. industry. That is why Sematech will not be sufficient to solve the industry's problems either, especially to the extent that it is viewed as a technical fix. The Japanese advantage does not inhere in better equipment; it derives from the interactive process of equipment development and the character of the production process in which the equipment is used. Equipment needs are jointly defined by equipment suppliers and the manufacturing engineers actually responsible for implementing the equipment into production. The chip producers' own prototype and production lines serve as the development laboratories in which the equipment is pieced together. Moreover, the success of Japanese semiconductor producers in achieving high yields is due less to superior machine technology than to superior inspection, cleanliness and production controls, and the use of highly trained equipment operators, in many cases, engineers.118 Indeed, Japanese chipmakers typically endure only half as much downtime for unscheduled maintenance as U.S. semiconductor firms on the same U.S.-made machines.119

Competitive advantage derives as much from the manufacturing firm's working relationships with its equipment and component suppliers as from the quality of the equipment and components themselves. Thus Sematech cannot solve the chip industry's problems simply through the development of state-of-the-art equipment in a prototype semiconductor plant any more than General Motors has been able to solve its competitive problems through the construction of automated automobile factories. GM seems to be learning its lesson, rationalizing its supplier network on the model of the less automated GM-Toyota joint venture in California. The evidence so far indicates that the Sematech consortium has not yet taken the same lesson to heart.

Indeed, the consortium did not initially consider a practical means for integrating the equipment industry into its plans, assuming, incredibly, that the various independent equipment suppliers would somehow integrate horizontally.120 Instead, the larger equipment manufacturers began approaching Sematech individually with their own proposals for direct participation. Smaller equipment firms followed suit, fearing a lockout similar to that which occurred during the Pentagon's Very High Speed Integrated Circuit (VHSIC) Program, in which only the largest equipment firms participated directly. The problem of working with each of more than a dozen competitors in each equipment category was finally solved on the initiative of the Semiconductor Equipment and Materials Institute, which will participate in Sematech through a chapter membership which only U.S.-based companies may join. Requests for new equipment and materials will be submitted to the chapter; members will then have the opportunity to assess the requirements and bid for Sematech contracts individually or in teams.121

In its development Sematech has already proved to be a useful vehicle for building cooperative relationships between merchant semiconductor firms faced with a formidable competitive challenge that none of them can meet alone. If it is to create a real structure for continued competitiveness, however, it must do more than advance the state of the art of manufacturing technology for all of the major firms in the industry. It must do that, but it must also serve as a vehicle for building cooperative relationships between semiconductor producers and their equipment suppliers. The technical, financial, and strategic benefits of such cooperation have been amply demonstrated in this study. But attitudes born of a fragmented industrial structure continue to feed an atmosphere of antagonism and mutual mistrust. And those attitudes result from a developmental history that traditionally rewarded entrepreneurial independence.

The particular advantages of the industry's traditional industrial structure should not be forgotten, however, in a rush to judgment about that structure's evident disadvantages for withstanding both the Japanese challenge and the sky-rocketing equipment costs associated with the shift to very large scale integration. The existence of a volatile, aggressively independent, merchant equipment sector--no less than the existence of a merchant semiconductor sector--has played an essential role in the development and diffusion of microelectronics technology worldwide. It has promoted both regular leaps of innovation (due to vigorous product competition) and rapid technological diffusion (because, as independent companies, the equipment firms have been constrained to sell their most advanced machines to any and all semiconductor producers willing to pay the price). Unfortunately, at least from an American strategic perspective, many of their most consistent and attentive customers have been Japanese.

The challenge then, is for American semiconductor equipment and device producers to evolve a new industrial structure that creates some of the advantages of inter-firm linkage enjoyed by the Japanese while maintaining the advantages of entrepreneurial independence so characteristic of the U.S. industry. A manufacturing consortium like Sematech would seem to be an essential ingredient, providing all the major firms in the device industry with a common level of manufacturing expertise, thus enabling them to concentrate on their traditional strengths in semiconductor design. Beyond that, semiconductor equipment and device firms in the United States should take a closer look at the semi-market, semi-ownership ties that characterize the relationships between their Japanese counterparts. As Cohen and Zysman have argued, there are great advantages to structural arrangements with elements of both market and ownership.122 Unlike classical vertical integration, semi-market arrangements--e.g. the buying of equipment and services by groups of companies with partial ownership of their suppliers--avoid the rigidities of purely bureaucratic procurement between protected divisions of a single organization. Equipment divisions must still compete against outside vendors for a substantial share of the parent firm's business--a spur to continued innovation. But they also avoid the uncertainties of a pure market relationship. And diminished uncertainty enables the development of a long-range competitive strategy.

Such semi-market, semi-ownership ties are not without precedent in the American context. The relationship between IBM and Intel offers a prime example. And if equipment development and manufacturing prowess are by their very nature tightly linked, spatially bound, then national competitive advantage in microelectronics depends on the development of closer technical, financial, and strategic ties between semiconductor equipment and device firms in the

United States. A failure to develop those linkages domestically will not be compensated by the purchase of advanced production equipment from Japanese, European, or Korean firms.

If U.S. equipment producers are allowed to fail, American semiconductor producers--including captive producers like IBM and ATT--will have two choices. They will bear the expense of building their own equipment, an expense that will be reflected in higher prices for their final products, or they will be forced to turn to their Japanese competitors' affiliated equipment suppliers for the latest manufacturing technology. Either choice leaves American electronics firms extremely vulnerable in international competition. For the American economy, then, the losses are unlikely to be confined to American producers of semiconductor production equipment. They are likely to extend to the electronics industries as a whole, an economic sector that currently ranks as the United States' largest industrial employer.

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1. A nationalistic perspective seems reasonable when the primary object of study concerns the extent to which variation in competitive outcomes traces to different domestic structures and differences in national government policy. Nevertheless, it is important to note that an analysis that focuses on issues of relative national welfare avoids important issues of aggregate welfare, how it is distributed among nations, and how it is distributed among socioeconomic groups within nations.
2. The notion of "tight" and "loose" linkages is introduced in Stephen S. Cohen and John Zysman, Manufacturing Matters: The Myth of the Post-Industrial Economy (New York: Basic Books, 1987).
3. For more on the definition of "strategic" sectors, see Cohen and Zysman (1987), op. cit., and Laura D'Andrea Tyson, "Creating Advantage: Stategic Policy for National Competitiveness," BRIE Working Paper #23, Berkeley Roundtable on the International Economy, University of California, Berkeley, January 1987. The notion can be traced back at least as far as Schumpeter: "Progress--in industrial as well as any other sector of social and cultural life--not only proceeds by jerks and rushes but also by one-sided rushes productive of consequences other than those which ensue in the case of co-ordinated rushes. In every span of historic time it is easy to locate the ignition of the process and to associate it with certain industries and, within these industries, with certain firms from which the disturbances then spread over the whole system." Joseph A. Schumpeter (1939), Business Cycles: A Theoretical, Historical, and Statistical Analysis of the Capitalist Process (abridged edition, New York: McGraw-Hill,

1964) page 76. For an argument that microelectronics, specifically, is a strategic sector, see Michael Borrus, Renewal: Microelectronics and the Restoration of American Autonomy and Growth (Ballinger, forthcoming, 1988) Chapter 2.

4. Recent market trends are reviewed at length in Section III of this study; the deteriorating technological position of U.S. firms in the semiconductor equipment sector is detailed in the report of the National Materials Advisory Board to the National Science Foundation, Advanced Processing of Electronic Materials in the United States and Japan, Washington, D.C., National Academy Press, 1986; and the report of the Defense Science Board to the U.S. Department of Defense, "Report of the Defense Science Board Task Force on Defense Semiconductor Dependency," Washington, D.C., Office of the Under Secretary of Defense for Acquisition, February 1987. The DSB Task Force found that the U.S. maintained a technological lead in only two of more than a dozen areas of semiconductor processing surveyed.

5. For the argument that domestic policies and structures alter the patterns of risk and opportunities confronting firms and nations, consequently permitting the adoption of business and policy strategies that shape international advantage for firms and entire economies, see Borrus, (forthcoming, 1988) op. cit., Chapter 3.

6. See, for examples, Nathan Rosenberg, Technology and Culture (Chicago: University of Chicago Press, 1979) pp. 25-50.

7. See Nathan Rosenberg, "Technological Change in the Machine Tool Industry," Journal of Economic History, December 1963, pp. 418-19; and David Landes, The Unbound Prometheus (Cambridge: Cambridge University Press, 1969).

8. Rosenberg (1979) op. cit., and C. Freeman, "Chemical Process Plant: Innovation and the World Market," National Institute Economic Review, August 1968, pp. 30-1.

9. This definition originated with Philip Shapira of the Office of Technology Assessment, U.S. Congress. On the definition of linkage, see R.J. Blackwell, et al, The Dictionary of Human Geography (Oxford: Blackwell, 1981).

10. Good reviews of the literature on linkages include M.J. Taylor and N.J. Thrift, "Industrial linkage and the segmented economy: 1. Some theoretical proposals," Environment and Planning A, 1982; Allen J. Scott, "Location and linkage systems: A survey and reassessment," The Annals of Regional Science, XVII(1), March 1983; and A.G. Hoare, "Industrial Linkage Studies," in Michael Pacione, ed., Progress in Industrial Geography (London: Croom Helm, 1985).

11. See, for example, Francois Perroux (1955), "Note sur la notion de pole de croissance," translated by I. Livingstone, in I. Livingstone, ed., Development Economics and Policy: Selected Readings (London: Allen and Unwin, 1979).

12. T. Scitovsky, "Two concepts of external economies," Journal of Political Economy (62), 1954, pages 143-51.

13. Perroux (1955), op. cit., page 185.
14. Francois Perroux (1950), "Economic space: theory and applications," in John Friedmann and William Alonso, Regional Development and Planning: A Reader (Cambridge, Mass.: MIT Press, 1964).
15. Cohen and Zysman (1987), op. cit., p. 103.
16. See, for example, E. Helpman and P. Krugman, Market Structure and Foreign Trade: Increasing Returns, Imperfect Competition, and the International Economy (Cambridge: MIT Press, 1985). David Teece uses the term "regimes of appropriability" to refer to environmental factors, excluding firm and market structure, that govern an innovator's ability to capture the profits generated by an innovation. The most important of these, Teece argues, are the nature of the technology and the efficacy of legal mechanisms of protection. See David J. Teece, "Profiting from technological innovation: Implications for integration, collaboration, licensing, and public policy," Research Policy, 15(6), December 1986, pages 285-305.
17. Giovanni Dosi, "Some Notes on Patterns of Production, Industrial Organization, and International Competitiveness," prepared for the meeting on "Production Organization and Skills" at the Berkeley Roundtable on the International Economy (BRIE), University of California, Berkeley, September 10-12, 1987.
18. Cohen and Zysman (1987), op. cit., page 103.
19. ibid.
20. Paul Krugman, "Strategic Sectors and International Competition," paper prepared for the conference on "U.S. Trade Policies in a Changing World Economy," Institute of Public Policy Studies, University of Michigan, March 28-29, 1985.
21. Knowledge embodied in an advanced piece of production equipment can be transformed into a source of distinct, national advantage as well, if the equipment is kept off the international market.
22. The sensitivity of the semiconductor production process to temperature, timing, vibration levels, dust, and the density of chemical solutions creates a particular pattern of learning by doing. The yield of usable chips may be as low as 5% when a new chip design is put into production; over time, the yield will typically rise sharply as trial-and-error methods improve the conditions for production. For more on the early history of the semiconductor, see Dirk Hanson, The New Alchemists: Silicon Valley and the Microelectronics Revolution (New York: Little, Brown, and Co., 1982).
23. For details on the development of the U.S. semiconductor industry, see Michael Borrus, James Millstein, and John Zysman, U.S.-Japanese Competition in the Semiconductor Industry: A Study in International Trade and Technological Development, Policy Papers in International Affairs #17, Institute of International Studies, University of

California, Berkeley, 1982.
24. ibid., page 16.
25. ibid., pages 16-17.
26. Yasuhiro Kishimoto and Takayuki Kitahara, "Perspectives on the Semiconductor Manufacturing Equipment Industry: Case Studies," JST Reports, Vol. 1, No. 2, Autumn 1985.
27. For more on the structure of Japanese business, see James Abegglian and George Stalk, Kaisha, The Japanese Corporation (New York: Basic Books, 1986).
28. Borrus, Millstein, and Zysman (1982), op. cit., page 70.
29. For details on the development of the Japanese semiconductor industry, see Borrus, Millstein, and Zysman (1982), op. cit., especially Chapter 2.
30. ibid., page 72.
31. ibid., page 73.
32. Figures are from U.S. Department of Commerce, "A Competitive Assessment of the U.S. Semiconductor Manufacturing Equipment Industry", prepared by the Office of Microelectronics and Instrumentation (Washington, D.C.: U.S. Government Printing Office, March 1985).
33. Estimate from BRIE's Michael Borrus.
34. See the U.S. Commerce Department's "Competitive Assessment..." op. cit., pages 59-63.
35. Electronics, July 22, 1985, "The Game Could Be Over In Japan Market For U.S. Chip-Equipment Makers," page 26.
36. See, for example, the report of the National Materials Advisory Board to the National Science Foundation, Advanced Processing of Electronic Materials in the United States and Japan, Washington, D.C., National Academy Press, 1986; and the report of the Defense Science Board to the U.S. Department of Defense, "Report of the Defense Science Board Task Force on Defense Semiconductor Dependency," Washington, D.C., Office of the Under Secretary of Defense for Acquisition, February 1987.
37. Electronic News, supplement, March 10, 1986. Chart on page 3, based on data from ICE.
38. Figures for 1979 from U.S. Department of Commerce, Office of Microelectronics and Instrumentation, A Competitive Assessment of the U.S. Semiconductor Manufacturing Equipment Industry, U.S. Department of Commerce, Washington, D.C., March 1985; Table 16, page 35. Figures circa 1987 from VLSI Research, reproduced in Graph 3, page 7, of Michael J. Stark, "Asian Semiconductor Equipment Overview," Robertson, Colman, & Stephens, February 5, 1987.
39. Capital spending includes property, plant, and equipment. Equipment accounts on average for 80% of capital spending; 60% of that goes for fabrication equipment, 30% for test equipment, and 10% for assembly equipment. Electronic News, supplement, March 9, 1987, page 5.
40. In 1985, the Japanese held 40% of the $23.5 billion semiconductor market to America's 47%; but Japanese firms accounted for 46% of the $5.5 billion spent on capital

equipment that year. (U.S. spending accounted for 36%)
41. Electronic News, supplement, March 9, 1987; table on page 5; figures from Dataquest.
42. Electronic Business, May 1, 1983, "GCA learns the hard way," page 126.
43. Production of logic circuits is more likely to drive equipment development in such specific areas as computer-aided design for maskmaking, electron-beam and laser systems for direct writing, and flexible as opposed to dedicated automation systems capable of creating economies of scope (product mix flexibility) as well as scale.
44. The top producers of projection aligners for microlithography are America's Perkin-Elmer and Japan's Canon. The major producers of today's dominant lithographic equipment, direct wafer steppers, are America's GCA and Japan's Nikon. Other players in the wafer stepper market include Ultratech, a subsidiary of General Signal founded in 1981, Perkin-Elmer's Censor, a Lichtenstein manufacturer acquired by Perkin-Elmer in April 1984 after P-E had spent eighteen unsuccessful months attempting to sell Censor's wafer stepper in the U.S., TRE, a U.S. company which survived a disastrous joint venture with Tokyo Electron (TEL) in Japan, Japan's Canon, and the Dutch independent equipment producer ASM (Advanced Semiconductor Materials) whose stepper is a joint venture with the Dutch giant Philips. Eaton's Optimetrix dropped out of the stepper market in the summer of 1986, concluding that the stepper market would probably never be profitable.
45. Wafer steppers, introduced by GCA in 1978, have become the dominant front-end technique in semiconductor fabrication due to their superior ability to produce chips with line widths below 2 microns. Nevertheless, steppers have not completely displaced the once-conventional projection mask aligners, dominated by Perkin-Elmer since 1973, due to the latter's higher throughput rate. The two technologies competed in see-saw fashion during the late 70's and early 80's, as improvements in first one, then the other technology gave each type of equipment advantages that turned out to be transitory. The stepper's low throughput handicap was compensated by its extremely low-defect, high-yield rate; but aligners were improved with the development of pellicles to reduce defect densities, and their usefulness was extended again with the realization that 256K RAMs could be produced with 2-micron geometry rather than with one or less. Thus, the industry seems to have settled, for the time being, on a "mix and match" arrangement, with steppers used for exposure layers in which precise registration is critical and aligners used for less critical work. More and more, however, both steppers and projection aligners in use worldwide are marked "made in Japan." Nikon and Canon are rapidly achieving dominant status, with Perkin-Elmer losing market share and GCA nearly bankrupt. See Electronic News, supplement, March 7, 1983, "Aligner vs.

Stepper Rivalry Winding Down," pages 8, 20.
46. New York Times, Business section, January 19, 1987. "Big Worries Over Small GCA," pages 19-21.
47. Michael Borrus, with James Millstein and John Zysman, Responses to the Japanese Challenge in High Technology: Innovation, Maturity, and U.S.-Japanese Competition in Microelectronics," BRIE Working Paper #6, Berkeley Roundtable on the International Economy, University of California, Berkeley, July 1983. page 71.
48. see ibid., pages 71-74.
49. Meanwhile, Perkin-Elmer was suffering from a difficult relationship with its Japanese distributor, Kanematsu Gosho, and saw its share of the Japanese market for projection aligners drop from 60% in 1981 to just 17% in 1983. Canon was the direct beneficiary of Perkin-Elmer's slide in projection aligners; by 1986, Canon also controlled about 90% of Japanese sales of older-generation contact/proximity aligners.
50. Electronic Business, February 15, 1986, "Slump and missteps realign market for stepper aligners," page 62.
51. Electronic News, supplement, March 7, 1983, "Japan Mfrs. Seek Tech Feedback via U.S. Sales," page 23.
52. This move put GCA in direct competition with Ultratech, the General Signal subsidiary which has emerged as a major supplier of low-end 1:1 machines. Unlike high-end "reduction" steppers, 1:1 machines transfer circuit images from mask to wafer without optically reducing the images. Reduction steppers shrink the image by a factor of 5 or 10 (5X or 10X), so that dust particles will not "print" on the wafer. Ultratech machines receive high marks from technical experts, but most continue to be skeptical that the technology can work once circuit linewidths shrink below 1 micron. See Electronic Business, May 15, 1986, "Ultratech's submicron attack uses one-to-one tactics," pages 94-96.
53. Electronic Business, October 15, 1985, "GCA: Diversification during a slowdown," page 80.
54. Again, reduction steppers shrink the image of the circuit by a factor of 5 (5X) or 10 (10X) so that dust particles will not "print" on the silicon wafer.
55. New York Times, January 19, 1987, op. cit.
56. ibid.
57. Electronic Business, February 15, 1986, "Slump and missteps realign market for stepper aligners," page 62.
58. ibid.
59. Electronic Business, March 1, 1985, "GCA works hard to put on a Japanese face," page 31.
60. Electronic Business, February 15, 1986, op. cit., page 64.
61. ibid.
62. personal communication.
63. The top Japanese producers of automatic test equipment are Advantest (formerly Takeda Riken), in which Fujitsu has a 21% equity, and Ando Electric, 51% owned by NEC. They

compete against several well-established American firms, the most important of which are Schlumberger/Sentry (formerly a subsidiary of Fairchild, the only semiconductor merchant selling capital equipment), Teradyne, and GenRad, plus a number of smaller start-ups, principally Megatest and Trillium, a subsidiary of LTX, itself a Teradyne spinoff.

64. Ando estimates that actual demand now is for testers at 20 MHz and 200 pins in production plants, and 40 MHz and 300 pins in the R%D lab. Both Ando and Advantest have organized task forces to develop logic testers able to handle 1,000 pins at 400-500 MHz. Electronic News, March 9, 1987, "Japanese Aim: Breaking 500-MHz Barrier," page 12.

65. Electronics, March 31, 1986, "Why Teradyne Thinks it can Recapture Japan," page 53.

66. Electronic News, supplement, March 8, 1982, "Firms Turn to Home-Made System Additions," pages 11, 21-23.

67. Electronic Business, October 1983, "GenRad's struggle to test VLSI circuits," page 122.

68. Electronic Business, April 1, 1986, "Alexander V. d'Arbeloff: Concentration for best test," page 38.

69. Electronics, October 16, 1986, "Japanese ATE Makers Still Wait for the 1-Mb RAM Boom," page 112.

70. Electronic News, supplement, March 9, 1987, op. cit., page 12.

71. Electronic Business, March 1, 1987, "Selling VLSI equipment in Japan tests U.S. vendors," page 68.

72. ibid., and Electronic Business, May 1, 1985, "A strategy to smooth the lumps," page 123.

73. Electronic News, supplement, March 10, 1986, "ATE Firms Seek Client Cash to Aid VLSI Effort," page 5.

74. Electronic News, supplement, March 5, 1984, "Semicon, ATE Makers in Talks--Customization is the Rule," page 14.

75. Electronic Business, July 1, 1985, "LTX seeks digital waters as linear seas swell," pages 48-54.

76. Electronics, October 16, 1986, "Is the ATE Market Headed for a Shakeout?" pages 111-12.

77. Electronic Business, October 1983, op. cit., and Electronic Business, April 1, 1986, op. cit., page 38.

78. Electronic Business, March 1, 1987, op. cit. Like GenRad and some of the Japanese tester makers, Sentry's Model 50 uses a conventional shared-resource system in which tester channels share memory and formatting functions. In LTX/Trillium's system, by contrast, each test pin has its own memory, timing, and formatting capability.

79. Electronic Business, March 1, 1987, op. cit.

80. Electronics, January 8, 1987, "Schlumberger Manager Tackles a Tough Market," page 19.

81. An essential part of device fabrication involves etching the circuit design onto a wafer and removing unnecessary photoresist material--the so-called "etch and strip" process. This was traditionally accomplished through "wet" etching (with chemicals) but plasma or dry etching (with reactive gases) is more compatible with the demands of very

large scale integration. Thus, although dry etching is more expensive than wet, there has been a steady shift of etch/strip equipment sales toward dry etch equipment, which accounted for 40% of sales in 1980, 71% in 1983, and was forecast to account for 80% by 1988. Overall, etching equipment of both varieties accounts for about 17% of sales of all front-end wafer processing equipment. U.S. Department of Commerce, A Competitive Assessment of the U.S. Semiconductor Manufacturing Equipment Industry, op. cit., page 25.

82. Applied controlled about 30% of the $380 million worldwide dry etch market in 1986; its 1985 sales totalled $174.6 million, up 4% over 1984. In general, market analysts seem to agree that dry etch is still an immature market. The tremendous array of process problems associated with dry etching, plus the increasingly specialized needs of chipmakers driving toward submicron linewidths, seems to create new niches for start-ups to fill. The worldwide dry etch systems market includes more than 40 players, with three or four start-ups every year taking the place of three or four failures. Besides Applied Materials, U.S. players include independents like Lam Research, Drytek, Plasma-Therm, and Branson/IPC, and major manufacturers of broad lines of semiconductor manufacturing equipment, like Perkin-Elmer, Materials Research Corp. (MRC), GCA, and Varian (through Zylin). Except for Perkin-Elmer, none of the larger firms has had much success in the dry etch market, although market observers note that they are more likely than the smaller independents ($20-$30 million companies) to possess the financial resources to carry through with ongoing development programs. See Electronic Business, August 15, 1985, "The best etch: good growth in a dry market," pages 90-2.

83. Ironically, Applied Materials' etcher is a "batch" system--it etches 10 to 18 wafers at a time--rather than an "in-line," or single wafer system. This is ironic because industry analysts have been arguing for years that batch systems cannot compete with in-line systems which are less expensive, easier to automate, and offer greater wafer-to-wafer process uniformity. NEC's Anelva also offers a batch system. See Electronic Business, August 15, 1985, op. cit., pages 90-2.

84. Hitachi also is linked to Kokusai Electric, a maker of both etching and deposition equipment.

85. Likewise, Branson/IPC remains a leading supplier of plasma etchers, in which the wafers are lined up like dishes in a dishwasher and gased. (Because plasma etchers work isotropically--with no directional control--they are used primarily for stripping or for non-critical etching). Nevertheless, Branson/IPC's 36% share of the Japanese market in 1981 was whittled down to about 15% by 1985. The main beneficiaries were Tokyo Ohka (which also pioneered in-line etchers in Japan), TEL/Lam (the 50-50 joint venture between

America's Lam Research and Japan's Tokyo Electron Ltd.), and Tokuda (a subsidiary of chipmaker Toshiba).

86. Three Japanese firms chose initially to rely on U.S. firms for marketing--Tokuda (first with Koberly & Associates, then with Tylan), Tokyo Ohka with Airco, and Kokusai with Veeco (whose epitaxial reactors are sold by Kokusai in Japan). Their rationale seemed to be that trying to sell equipment directly in the U.S. is too costly and bears too little fruit; with American distributors, however, the Japanese firms would not have to make a big investment--"all we have to do is put the equipment on the ship." Recently, Tokuda appears to have changed its mind; its new U.S. distributor, Tylan, has considered assembling parts supplied by Tokuda and possibly manufacturing Tokuda etchers in the U.S.

Following its affiliate, NEC, Anelva has always been more aggressive, spending half a million dollars to establish a Silicon Valley facility for processing, sales/service, and R&D. Anelva feels it is necessary to do processing or actually demonstrate its dry etchers in the U.S., due, for example, to heavier U.S. demands for bipolar sampling as opposed to large demands in Japan for memory applications. See Electronic News, supplement, March 5, 1984, "Japanese Makers Cautious About Plans for U.S. Market," pages 16-21.

87. Ion implantation equipment bombards a semiconductor wafer with charged particles or "dopant" to create junctions within the silicon that direct the flow of electrical current. Despite the high cost of this equipment--from one-half to several million dollars--use of ion implantation has grown steadily at the expense of diffusion/oxidation furnaces for initial doping depositions prior to diffusion. This is primarily because ion implantation can provide greater precision. Ion implantation equipment is segmented by the maximum beam current or energy available from the system; conventional equipment includes both low/medium current, a serial process, and high current, a batch process which provides higher throughput. New processes include high energy ion implantation, which is used for deeper dopant penetration, thereby eliminating the need for high temperature diffusion, or for forming layers of silicon dioxide beneath the wafer surface. (There is much interest in such silicon-on-insulator [SOI] heterostructures for increased speed and higher densities).

88. In 1984, 61% of Japan's conventional ion implanters were still imported. Eaton/Nova was estimated to have 40% of the Y35 billion Japanese market, TEL/Varian 35%, and Ulvac 13%. Electronics, July 22, 1985, op. cit., page 27. Figures from Nomura Research Institute.

89. Eaton's Nova subsidiary held an estimated 70% of the worldwide high-current systems market in 1985, and 30% of the medium current market. Nova Systems began as a small Beverly, Mass. start-up founded by Peter Rose, the former

manager of Varian's Extrion division. In accounting for Nova's rapid rise, Eaton officials point particularly to the stability of its technical group, men who have worked together for 20-30 years. (Electronic Business, May 15, 1985, "Eaton pieces together an equipment puzzle," pages 92-96.) Eaton competes primarily with Varian's Extrion division, the market leader in medium-current systems. Applied Materials, the world leader in equipment for dry etching and epitaxy, entered the high-current ion implantation market in late 1985. Veeco is another new, relatively small participant in this market. The worldwide market for conventional ion implantation equipment reached about $400 million in 1985.

90. Both the U.S. and Japan are increasingly interested in developing low-energy implantations for the formation of shallow junctions, but while the U.S. has been active in the area of high-energy, low-dose implants, the Japanese seem to have made a clear commitment to the use of high-dose implantations for materials syntheses like the buried insulating layer process. National Materials Advisory Board, Advanced Processing of Electronic Materials in the United States and Japan, op. cit., pages 9-11.

91. Film deposition or metallization involves the depositing of various elements onto the silicon wafer, in the form of thin films or epitaxial (single crystal) growth, in order to impart insulation, conduction, or dielectric characteristics. The equipment used in this activity accounts for about 20% of all equipment expenditures in wafer fabrication. Types of equipment, in order of sales volume, include sputtering or physical vapor deposition (PVD), chemical vapor deposition (CVD)--both low-pressure and plasma-enhanced--and epitaxial growth.

92. Anelva may lead Varian in Japan, where in 1984 it was estimated to hold 35% of the Japanese sputtering market, compared to TEL/Varian's 30%, and Ulvac's 12%. About 49% of the Japanese sputtering market was supplied by imports in 1984. Other suppliers of sputtering equipment include Kokusai and Hitachi, as well as U.S. firms Perkin-Elmer, Machine Tech, and Materials Research Corp. (MRC).

93. Electronic News, May 26, 1986, "Semicon Gear Firms Race to Field New-Generation Etch, Deposition Systems," pages 1 and 60.

94. Kokusai Electric was second to TEL/Thermco in Japan, with about one-quarter of the market.

95. Electronic Business, September 1983, "Crossing the TEL bridge into Japanese markets," pages 164-67. Quote on page 166.

96. Electronic Business, October 15, 1985, "Trauma, meet market leader Perkin-Elmer," pages 74 and 78.

97. "Asian Semiconductor Equipment Overview," February 5, 1987, op. cit.

98. American suppliers of plasma-enhanced CVD systems include Applied Materials and Varian. Japanese suppliers

include Kokusai and Hitachi. The world market for plasma-enhanced CVD was estimated at about $73 million in 1986. It is forecast to reach about $134 million by 1989. In the Japanese market in 1984, ASM held 47% as opposed to Applied Materials 27%.

99. Japan's is not the only government that has been able to coax American equipment firms offshore for research and development activities. For example, Applied Materials was able to limit its risk on entering the high-current ion implantation market by raising about $6 million for early development from the British Government. Applied got into ion implantation in 1980 when it bought the rights to high-current technology developed by Lintott Engineering, a British aerospace and engineering and manufacturing company, which had worked closely with Britain's Atomic Energy Authority and was the Europe's major producer of implanters. Applied's high-current implanter was developed at its British subsidiary, Applied Implant Technology; the grant from Britain's Department of Trade and Industry accounted for about one third of the implanter's total funding. That grant, part of the department's Microelectronics Industry Support Program, stipulated that the company remain in the field of microelectronics and conduct the product's development and three years of manufacturing in the UK. Significantly, most of the company's 125 engineers and support technicians are British. Electronics, September 9, 1985, "Getting R&D Help From Other Nations," page 89.

100. Kokusai Electric builds epi reactors in Japan. The total market was estimated at between $163 million and $175 million. Market share figures vary. Electronic Business (VLSI Research) characterized the 1984 as Applied Materials 38%, Gemini 16%, and Kokusai 16%. Nomura Research gave Applied Materials and Kokusai 35% each, with JPC Electronics third at 10%. Gemini is participating in the emerging CMOS epi equipment market through its subsidiary, Tetron. ASM America has also developed a limited R&D partnership with Epsilon Technology, in Tempe, Arizona, to develop a next-generation CMOS epi reactor. Other competitors include Japan's Toshiba Machine and Anicon, Inc., based in San Jose, CA.

101. Electronic Business, October 1, 1985, "Will latch-up lock up a whole new CMOS market?" pages 104-5.

102. personal communication with Japanese firms.

103. Although the ultimate size of the market for these machines remains in dispute, E-beam technology is increasingly important for new product development. Due to their slow speed and immense cost (product development costs upwards of $40 million and each machine costs more than $3 million up front), E-beam direct-write systems are now used primarily to fabricate or repair masks for optical lithography or for forming prototype circuits in R&D labs. These machines offer finer resolutions and greater flexibility than competing approaches can currently provide;

they allow manufacturers to bypass expensive photomasks and can be quickly modified to handle multiple runs of low-volume custom circuits.

104. IBM reportedly spent approximately $50 million developing a system solely for internal use. E-beam equipment is also manufactured by the Dutch giant Philips, and by Britain's venerable Cambridge Instruments.

105. Electronic Business, October 15, 1985, op. cit., page 78.

106. Electronic Engineering Times, April 13, 1987, "Perkin-Elmer: A Healthy 50," pages 22-24. The fledgling European Silicon Structures (ES2) consortium has also ordered two of the machines.

107. Electronics, March 10, 1986, "Is E-Beam Lithography Finally Ready?" pages 15-16.

108. Electronic Business, March 1, 1985, "E-beam lithography: The direct-write stuff?" pages 44-6.

109. This account of competition in the mask making sector derives from Charles H. Ferguson, American Microelectronics in Decline: Evidence, Analysis, and Alternatives, Department of Political Science and Program in Science, Technology, and Society, Massachusetts Institute of Technology, December 1985. Draft for private circulation.

110. Aside from fine-line lithography, focused ion beams are also used for maskless ion implantation, repairing masks, selective etching, and sputtering. Focused ion beam implantation involves the direct writing of an implanted pattern, which eliminates photomasking and lithography; this technology is presently very slow, because of the very low beam currents now in use and the serial nature of the process. Slow speed is not a major limitation, however, in the fabrication of optoelectronic devices (devices which integrate both optical and electrical components on a single chip), a major Japanese development goal.

111. Although commercial 4 Mb chips will probably be built with optical lithography, the introduction of 16 Mb DRAMs and other devices with 0.3 micron geometries will signal the commercial emergence of X-ray lithography, probably in the early 1990s.

112. A synchrotron produces high-energy X-rays by use of magnetic fields that accelerate electrons around a storage ring.

113. The Fraunhofer Institute for Microstructure Technology in West Berlin has possessed a superconducting storage ring (an X-ray source) since the late 1970s; such early access to a research synchrotron suitable for X-ray lithography accounts for West Germany's apparent lead in this field. Working together under a government-sponsored project, equipment producers and two leading German chipmakers--Siemens and Telefunken--have not only developed new X-ray techniques and equipment; they have actually used them to fabricate the first sub-micron devices made using X-ray lithography. See Electronics, February 5, 1987, "West

Germany Grabs the Lead in X-Ray Lithography," pages 78-80.
114. The 13 are Toshiba, Fujitsu, NEC, Mitsubishi, Matsushita, Oki, Hitachi, Canon, Nikon, Sharp, Sanyo, Sony, and Sumitomo Electric. Sumitomo Heavy Industries is reportedly also conducting research in this area, but its efforts are targeted at applications to steel manufacturing. Electronic News, "Japan Forms X-Ray Litho Venture," June 9, 1986, page 66.
115. Electronic News, March 30, 1987, "Bell Labs Cuts Back X-Ray Litho Program," page 42.
116. Electronics, June 23, 1986, "Wisconsin Ring Shines for X-Ray Work," pages 19-20.
117. To the extent that the Defense Department acts as a primary source of funds for the consortium, Sematech represents an industry attempt to re-create the conditions of the late 1950's and early 1960's, when military procurement played a critical role in creating commercial viability for integrated circuits. For a variety of reasons, including the increasingly divergent needs of civilian and military consumers of semiconductor devices, such an attempt is not likely to succeed. See Michael Borrus and Jay Stowsky, "The Pentagon's scenario to bolster chip makers: Following defense priorities will not," San Jose Mercury News, March 8, 1987, page 7C. See also Jay Stowsky, "Competing With the Pentagon: The Future of High Tech R&D," World Policy Journal, Vol. III, No. 4, Fall 1986, pages 697-721; or Jay Stowsky, "Beating Our Plowshares Into Double-Edged Swords: The Impact of Pentagon Policies on the Commercialization of Advanced Technologies," BRIE Working Paper #17, Berkeley Roundtable on the International Economy, University of California, Berkeley, April 1986.
118. This is the finding of the Japanese Technology Evaluation (JTECH) Report on Megatronics, as reported in MCC Technical Report, Number ILO-007-86, "Japanese Government and Industry Efforts to Improve Semiconductor Manufacturing Capabilities," Microelectronics and Computer Technology Corporation, 1986.
119. According to G. Dan Hutcheson of VLSI Research Inc., Newsweek, June 29, 1987, page 50.
120. Electronic News, "Equipment Makers Try to Position for Role in Sematech Consortium," May 25, 1987, pages 1 and 33.
121. Electronic News, "SEMI Chapter to Participate in Sematech," June 1, 1987, page 34.
122. Cohen and Zysman (1987), op. cit., page 149.
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