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Quantifying the Environmental Footprint of Semiconductor Equipment Using the Environmental Value Systems Analysis (EnV-S)

Nikhil Krishnan, Sebastién Raoux, and David Dornfeld

Abstract—**Many environmental and health impacts from semiconductor processing are tied to the design of the manufacturing equipment. Evaluating solutions to properly treat effluents from semiconductor tools has become an increasingly important part of supply chain management and equipment procurement decisions. Accordingly, understanding the environmental footprint associated with equipment sets is essential for both equipment manufacturers and semiconductor manufacturers seeking to improve their products' environmental and financial performance. Equipment environmental performance must be evaluated within the context of the factory infrastructure and auxiliary equipment sets, with appropriate allocations of impacts from additional steps, both upstream and downstream of the wafer processing tools (chemical precursor delivery as well as byproducts treatment). Several challenges to environmental assessments arise from the nature of semiconductor manufacturing itself, due to short process life cycles, complexity of processes, and the need to track diverse inter-related impacts. Environmental value systems analysis (EnV-S) is an analytical tool to evaluate the environmental performance of semiconductor processing. EnV-S develops environmental assessments through a "bottom-up" analysis approach, assembling equipment environmental models to describe a system. This paper presents the use of EnV-S as a tool to quantify the environmental impact of a product or process by creating an operational signature along multiple dimensions of cost and environmental and health factors. The use of EnV-S is illustrated through a case study comparing systems that abate emissions from dielectric chemical vapor deposition processes.**

Index Terms—**Cost of ownership, design for environment (DFE), environmental impact.**

I. Introduction

As THE semiconductor sector is growing rapidly, the need to reduce the environmental and health impacts of semiconductor processing is growing in importance. Since a large portion of the environmental impact of semiconductor chips may occur during chip manufacturing, it is essential to understand the manufacturing equipment's environmental performance [1].

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EnV-S is a "bottom-up" equipment-centric approach to support both the analysis of environmental, health, and safety (EHS) implications and the design of semiconductor manufacturing processes. A "bottom-up" approach offers the flexibility in analysis required by designers and buyers. This paper focuses on the use of EnV-S methodology to evaluate the environmental and health "footprint" of equipment sets, specifically guiding the choice of exhaust treatment systems.

The use of EnV-S as a qualification tool is illustrated through a case study in abating emissions from a dielectric chemical vapor deposition (DCVD) process. DCVD is selected for analysis in this paper because it currently represents the fab's largest gaseous emissions contributor. In particular, fluorinated compound emissions from this process require treatment, especially during DCVD chamber cleaning. The case study in this paper focuses on a DCVD undoped silicate glass (USG) process module used as an insulating dielectric material in a semiconductor device [2], [3].

EnV-S compares the overall environmental footprints of four different technologies to treat DCVD air emissions: combustion and water scrubbing, electric oxidation and water scrubbing, hot-bed, and cold-bed technologies. The comparisons presented in this paper are representative of generic technologies rather than specific products. In practice, EnV-S data can also represent specific equipment configurations, rather than the broader technology comparison presented here. The following sections discuss the scope and methodology of EnV-S, the environmental metrics used, and the kinds of analyses and decisions that are offered by the model.

II. Brief Review of Semiconductor Environmental Design Tools and Studies

There have been several previous approaches to developing environmental design and evaluation tools for the semiconductor industry. The computerized assessment of relative risk (CARRI) [4], [5] is a risk assessment tool, based on toxicity data, that aims to compare the relative risks of alternative manufacturing processes with respect to mass/flow and exposure information. The environmental and health metrics supported by CARRI require the use of SEMATECH S70 [6] (a mass balance tool). The principle challenges in CARRI and S70 appear to be the large toxicological data requirement and issues with proprietary information sharing among the member companies. The cost of ownership (CoO) metrics supported by CARRI require the use of the SEMATECH EHS CoO tool [7], [8] that focuses on environmental costs and allows for sensitivity analysis of cost to input parameters. Other standard

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CoO methods, such as the cost models developed by SEMI [9] and SEMATECH [10] do not explicitly focus on environmental costs.

A modular mass/flow evaluation tool E_4 has been developed by Galli *et al.*, [11] based on a top-down facility-scale evaluation. A facilities-level input–output approach, however, does not lend itself to understanding equipment details.

To provide the flexibility needed to develop predictive life cycle inventories within facilities, Murphy has developed a module-based parametric analysis of semiconductor environmental impacts [12]. This module-based analysis is not directly equipment-centric, but it could support equipment DFE efforts.

Environmental analysis of semiconductors has been progressing toward life cycle assessment (LCA). Although a few LCA and large system-scale studies have been conducted [1], [13]–[16], a generic LCA tool to support semiconductor manufacturing does not yet exist. Challenges still remain in developing LCA tools to keep pace with technology changes, handle uncertainty and inform detailed equipment decision making.

III. Scope and Methodology of EnV-S

The current scope of EnV-S includes "within-facility" impacts, including semiconductor manufacturing and downstream disposal operations that represent real environmental costs borne by semiconductor manufacturers. However, the analysis can be expanded to include additional impacts in conjunction with other life cycle tools. The analysis proceeds in three stages [17]–[19].

In the first stage—process modeling—a combination of process models and data are developed to track mass and energy flows around individual units, establishing a link between process parameters and equipment environmental characterization. Units refer to the equipment itself or subcomponents of the equipment, such as a water scrubber or a pump. Uncertainties in system parameters are defined and propagated through the analysis. In the second stage—sequencing—the user can specify the units that are to be included in the analysis (Fig. 1), including facility infrastructure units, such as acid scrubbers, piping requirements, and facility-scale treatment systems. The third and final stage of the analysis characterizes the overall system in terms of environmental cost of ownership and the environmental and performance metrics to generate a multidimensional operational signature.

Note that EnV-S is not expected to directly depict a complete facility-wide environmental analysis, although such an analysis will eventually emerge through the development of a large library of unit models. Rather, the primary focus is to support specific equipment and process design questions, within a broader systems perspective, allowing for the possibility to expand system boundaries.

IV. DCVD Process

The DCVD process can be used to deposit an insulating dielectric layer of undoped silicate glass (USG) for advanced intermetal dielectric (IMD) and premetal dielectric (PMD) processes [20], [21]. For this USG application, the process typically uses silane (SiH_4) and oxygen (O_2) as deposition precursors diluted with argon (Ar). Silane is converted to SiO_2 in the process

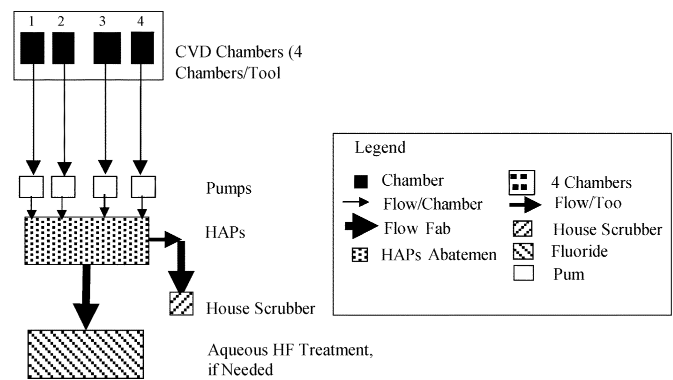

Fig. 1. Example of sequencing units in the system sequencing shell.

TABLE I
Gas Masses Used During the Deposition and the Clean/Seasoning Process on a per Wafer Basis

	Ar	O_2	SiH_4	NF_3
Deposition (g/wafer)	0.80	1.45	0.63	None
Clean and Seasoning (g/wafer)	2.89	0.22	0.07	7.96

chamber in the presence of a plasma and is deposited on the wafer and the chamber walls. After deposition, the residue in the chamber is cleaned, in this case, using NF_3 gas dissociated in a remote plasma source placed upstream of the DCVD chamber. Note that with this technique the NF_3 clean gas dissociation can attain 99%, virtually eliminating emissions of global-warming perfluorocompounds and the need to abate them. The byproducts of the NF_3 decomposition (N, N_2, F, and F_2 molecules and free radicals) are then injected in the CVD chamber where the etching species (fluorine radicals) react with the SiO_2 deposits to form gaseous byproducts (essentially SiF_4 and O_2) that are pumped away from the chamber [22]. A seasoning recipe is used immediately after the clean process, consisting of running a short deposition process in the chamber prior to the introduction of the next wafer. Seasoning coats the interior of the chamber and removes fluorine residues that may be adsorbed on the walls and reduces the fluorine at the interface between the wafer and the film to be deposited.

Gas flows into the DCVD process chamber are calculated based on a typical recipe for the deposition and clean and seasoning steps (Table I). The primary byproduct of concern in the deposition process is silane (SiH_4) which is a pyrophoric gas. The primary byproduct of concern in the clean and seasoning process is molecular fluorine (F_2) originating from the recombination of fluorine free radicals that did not react with the DCVD deposition residues. For the purposes of this analysis, a process tool with four chambers is considered with pump flow rates of 50 l/m nitrogen per chamber.

Emissions from the deposition and clean processes can be measured after the chamber pumps using Fourier transform infrared spectroscopy (FTIR) and quadrupole mass spectroscopy (QMS) methods to estimate species and flow rates [16], [23], [24]. Typical measurements made at the exhaust of the vacuum pump (at atmospheric pressure) during the deposition process indicate that nearly all SiH_4 is destroyed in the process chamber (Table II). Measurements made during the clean and seasoning process indicate that most of the NF_3 (with a high global warming potential (GWP) of 8000) is destroyed ($\sim$99%), but

TABLE II
EMISSIONS MEASURED POSTPUMP

	SiH_4	NF_3	SiF_4	F_2	HF
Deposition (g/wafer)	<5.71E-3	None	None	None	None
Clean and Seasoning (g/wafer)	None	0.06	0.46	5.89	0.05

TABLE III
OPTIONS FOR ABATEMENT

Abatement Technologies	SiF_4	F_2	SiH_4	HF	NF_3	Selected for Analysis?
Catalytic and Water Scrubbing	Yes	Yes	No	Yes	Yes[1]	No
Combustion and Water Scrubbing	Yes	Yes	Yes	Yes	Yes[1]	Yes
Combustion and Dry Scrubbing (Hot or Cold Bed)	Yes	Yes	Yes	Yes	Yes[1]	No[2]
Plasma Decomposition	No[3]	Yes	No[3]	No	Yes[1]	No
Cold Bed Adsorption	Yes	Yes[1]	Yes	Yes	No[4]	Yes
Hot Bed Adsorption	Yes	Yes[1]	Yes	Yes	Yes[1]	Yes
Electric Oxidation and Water Scrubbing	Yes	Yes	Yes	Yes	Yes[1]	Yes

Note:
[1]Limited flow capacity, depending on operating conditions
[2]Not considered because a dry scrubber could abate fluorine directly, without the need for a combustion unit
[3]Can abate all emissions, but solids are formed that may cause production-worthiness problems; may therefore require combination with other technologies to provide an effective solution
[4]Not normally capable of abating NF_3 low temperature; but NF_3 abatement is not typically required when using the Remote Clean™ technology which already provides >99% NF_3 removal efficiency (Section IV) [22]

it is largely converted into fluorine (F_2), which is hazardous because of its toxicity. House scrubbers are not recommended for fluorine abatement due to concerns associated with transport through the exhaust (corrosion) and the potential for cross reactions. Furthermore, house scrubbers can be overwhelmed by the excess fluorine from all deposition and etch processes in the facility. Point of use (POU) abatement systems are, therefore, recommended for DCVD applications. In general, POU systems may lead to reduced safety risks (ductwork fires, corrosion, exhaust restrictions, etc.) and reduced environmental risks (meeting emissions limits) [25].

V. DIELECTRIC CVD ABATEMENT

The emissions from the DCVD process include SiH_4, SiF_4, F_2, NF_3, and HF (Table II). In general, several feasible POU technologies are available to treat those gases individually. However, the above gases can be present at any time in the abatement system; for example, one chamber can run a deposition process while the other chambers run a clean process. Therefore, a proper abatement system must be capable to treat any and all of the DCVD byproducts. This requirement leads to the elimination of some technology options. It can be seen that of the seven technology options considered, only four can really be used to treat all DCVD emissions: combustion and water scrubbing, electric oxidation and water scrubbing, cold-bed adsorption and hot-bed adsorption technologies (Table III). Hot and cold chemical beds and oxidation and wet scrubbing technologies are also among those recommended by SEMATECH for POU abatement for oxide deposition applications [25]. These four technologies are, therefore, studied further.

POU combustion systems use fuel such as methane or hydrogen to combust toxic and other flammable and pyrophoric emissions [26]. The combustion of fluorine-rich emissions leads to the conversion of F_2 to HF gas, which is typically water scrubbed within the POU unit into an aqueous form. Hot-bed systems use heat to help the gases reach reaction temperatures and then react with bed substrates. Some hydrides such as silane (SiH_4) are thermally decomposed by heat. Bed substrates can be made of a mixture of metals and base oxides such as lime. The metals react with fluorine, SiF_4, HF, etc., to form metal halides which are then neutralized by a base, such as lime, to form salts [23]. Cold-bed systems use chemisorptive resins to adsorb and subsequently react with fluorine and can operate passively at ambient temperatures [27]. Fluorine and other fluorinated species are typically removed using bed materials made of silica or metal oxides. Electric oxidation and water-scrubbing systems use electric heat to break down the byproducts and may use hydrogen or water to convert F_2 to HF. The HF is scrubbed out within the POU unit into an aqueous form. In this paper, an electric oxidation and water-scrubbing system that uses hydrogen as a reagent is considered.

VI. EnV-S APPLIED TO EXHAUST MANAGEMENT EQUIPMENT

In this paper, numerous process models and data are used to estimate environmental cost of ownership (CoO) and environmental impacts (Table IV).

EnV-S includes all units downstream of the DCVD process tool that are involved in emissions treatment (Fig. 1). The analysis, therefore, includes the primary POU abatement device (combustion and water scrubbing, hot-bed adsorption, cold-bed adsorption, and electric oxidation and water scrubbing) and any subsequent downstream treatment required. One upstream factor is also considered: greenhouse gas emissions from electricity generation. This is included to allow a comparison between combustion systems that use fuel as an energy source and electric oxidation and hot-bed systems that use electricity as a source of energy. Since all four abatement technologies use the same chamber pumps, pump data and models are not directly included in the analysis. However, the pump flow rate is used to estimate the exhaust loading from the different abatement devices and to calculate an exhaust cost associated with the use of the facility house scrubbers.

Following the chamber pump, the emissions pass through one of four primary POU abatement technologies: combustion and water scrubbing, hot-bed adsorption, cold-bed adsorption or electric oxidation and water scrubbing. The liquid waste from combustion and water-scrubbing and electric oxidation and water-scrubbing systems is then piped into a downstream facility-scale wastewater treatment system. The downstream fluoride treatment uses sodium hydroxide and calcium hydroxide to neutralize the HF waste and produce fluoride sludge. Both the hot-bed and the cold-bed systems do not require downstream fluoride treatment, but they generate spent bed cartridges which need disposal.

VII. EnV-S EXHAUST VALIDATION RESULTS

A. Environmental CoO

For each equipment subcomponent in the EnV-S, environmental costs are aggregated along numerous subcategories. The environmental CoO metric takes into account facility infrastructure, system, equipment, and production categories and builds on current industry CoO models [9], [10] and EHS

TABLE IV
SUMMARY OF PROCESS MODELS AND DATA

Analysis Units	Combustion and Water Scrubbing	Hot Bed Adsorption	Cold Bed Adsorption	Electric Oxidation and Water Scrubbing	Fluoride Treatment
Fixed Costs	~ $90,000, 200 slm flow rate	~$59,000 for ~9000 l HF capacity	~$78,000 for ~39,000 l HF capacity	~$74,000, 200 slm flow rate	$2,000,000 for a 100 gpm system
Electricity	~1.2 kW	~3 kW	~0.07 kW	~5.6 kW	13 kW (100 gpm system)
Water	City water use calculated based on ~0.2% F- concentration in drain; cooling water at 6 gpm	Cooling water at 6gpm	No water use	City water use calculated based on ~0.2% F- concentration in drain; cooling water at 5 gpm	No water use
Consumables	Spares ~ $4,000/year; fuel use ~37 slm CH_4	Cartridge capacity is ~9,000 l HF, ~$1,800	Cartridge capacity is ~39,000 l HF, ~$4,000	Spares ~ $4,000/year, hydrogen use is 1 to 1.5 times stoichiometric requirements for avg. fluorine loading (1.3 slm)	Average incoming HF at 290 ppm; 50 % excess $CaCl_2$ and ~400 lb of NaOH/day
Disposal	Disposal costs relate to fluoride treatment models Exhaust costs calculated assuming complete combustion $XCH_4 + Y(O_2+3.76N_2) + ZN_2 = XCO_2 + 2XH_2O + (3.76Y+Z)N_2 + (Y-2X)O_2$ X and Z are known inputs	Spent cartridges are usually a mixture of lime and metal oxides, and are non-hazardous Disposal costs are based on ~30 min changeout time Disposal weight is based on ~40 kg/cartridge Exhaust flow volumes assumed similar to input volumes (largely N_2)	Spent cartridges are a mixture of silica and metal (usually iron) oxides, and are non-hazardous Disposal costs are based on ~30 min changeout time Disposal weight is based on ~118 kg/cartridge Exhaust flows volumes assumed similar to input volumes (largely N_2)	Disposal costs relate to fluoride treatment models Exhaust flow volumes assumed similar to input volumes (largely N_2)	16 ppm of HF in discharge; removed fluorine goes to CaF_2 sludge and pressed to 20% solids
Hazardous Air Emissions (including HAPs) and Criteria Air Pollutants	DRE for F_2, SiF_4 are ~99% (emissions of 0.059 and 0.0046 g/wafer). DRE for HF and SiH_4 are ~99.9% Observed CO emissions at 0.053 g/wafer (~0.02% of estimated CO_2 emissions) Observed NO and NO_2 are 0.42 and 0.02 g/wafer respectively	DRE for F_2, SiF_4, HF and SiH_4 assumed similar to combustion and water scrubbing systems Assume no criteria air pollutants	DRE for F_2, SiF_4, HF and SiH_4 assumed similar to combustion and water scrubbing systems Assume no criteria air pollutants	DRE for F_2, SiF_4, HF and SiH_4 assumed similar to combustion systems Assume NO and NO_2 emissions are same as combustion and water scrubbing systems Assume no CO emissions	None
Global Warming Gases	DRE for NF_3 ~96% at very low NF_3 input level of <10sccm (emissions of 0.0-024 g/wafer) CO_2 emissions are accounted for assuming combustion equation above Electricity use assuming 0.21 kgCE/kWhr for U.S. electricity mix	DRE for NF_3 assumed similar to combustion and water scrubbing systems Electricity use assuming 0.21 kgCE/kWhr for U.S. electricity mix	NF_3 is not removed (emissions of ~0.06 g/wafer) Electricity use assuming 0.21 kgCE/kWhr for U.S. electricity mix	DRE for NF_3 assumed similar to combustion and water scrubbing systems Electricity use assuming 0.21 kgCE/kWhr for U.S. electricity mix	Based on electricity use assuming 0.21 kgCE/kWhr for U.S. electricity mix

CoO models [8]. The focus of the environmental cost is on the purchase, installation, use, handling, training, monitoring, treatment, and disposal of process equipment inputs, outputs,

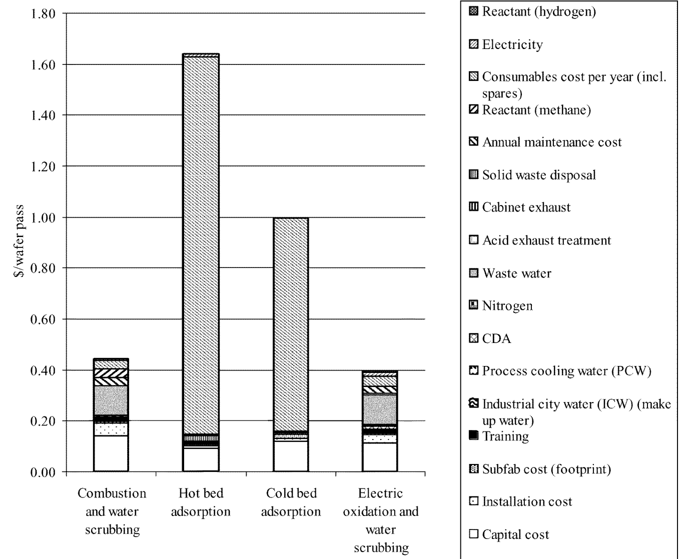

Fig. 2. Detailed costs of alternative abatement technologies.

and secondary flows (e.g., energy, exhaust, water, cleaning agents, dilution streams, etc). Total environmental costs of a system $\mathrm{CoO}_{\mathrm{System}}$ are estimated as

$$\mathrm{CoO}_{\mathrm{System}} = \frac{\sum_{i=1}^{n}(FC_i + OC_i)}{\mathrm{wpy}} \tag{1}$$

where n represents the number of unit cost models in a system, FC_i and OC_i are the fixed and operational costs ($/year) related to unit i, and wpy is the number of wafers processed per year.

Wafers processed are estimated based on wafer throughput, uptime, and utilization of the equipment. Uptime is initially estimated based on total production hours and scheduled maintenance and is then adjusted to include unscheduled downtimes. Major cost categories for the four systems appear in Fig. 2.

Capital and other fixed costs are depreciated over five years. Many operational cost categories are calculated by multiplying annual usage data by unit costs. For instance, the annual electricity costs for the combustion and water-scrubbing systems are based on average usage (~1.2 kW) and the cost of electricity (~6 cents/kWh for a typical U.S. fab) and are quite low (~$600/annum). Hot-bed systems and electric oxidation and water-scrubbing systems have higher electricity costs due to the need for electric heating (~3 and 5.6 kW, respectively). Most consumable costs for combustion and water-scrubbing systems are related to fuel use and spares. For hot-bed and cold-bed adsorption systems, the consumable costs of new cartridges are significant and represent the primary operational costs of these systems. Treatment and disposal costs are high for combustion and water scrubbing and electric oxidation and water-scrubbing systems because of the cost of treating fluoride-rich wastewater.

It can be seen that under nominal operating conditions, combustion and electric oxidation and water-scrubbing systems have lower costs than cold- and hot-bed adsorption systems. The principle reason for the higher costs of cold- and hot-bed systems are related to the cost of consumables. With an annual HF flow of ~964 500 liters, the consumables cost of the hot-bed adsorption system is $1.49/wafer (~$192 900/year; $1800/cartridge with a capacity of 9000 l of HF; Table IV). The

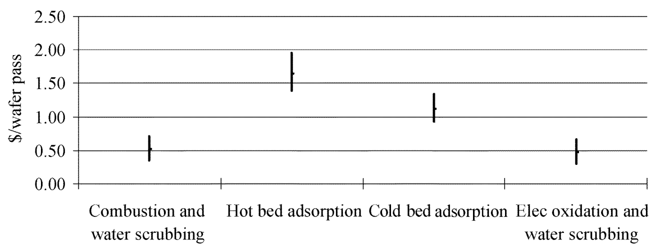

Fig. 3. Output cost uncertainties of technologies.

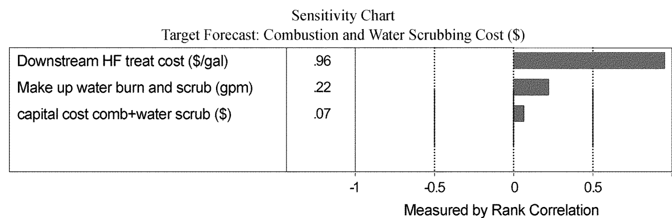

Fig. 4. Sensitivity analysis for combustion and water scrubbing.

column consumables cost of a cold-bed adsorption system is \$0.83/wafer (~\$107 000/year; \$4328/column with a capacity of 39 000 l of HF; Table IV).

EnV-S also defines uncertainties for most inputs (including cost, recipe, and facility parameters) and uses a Monte Carlo simulation to evaluate forecasts. For instance, the flow rate of methane can vary anywhere between 27–47 l/m with a nominal value of 37 l/m, and it can be represented by a triangular distribution. A Monte Carlo simulation with 30 000 trials was conducted for the four technologies. In looking at cost forecasts following an uncertainty analysis, it can be seen that the combustion and electric oxidation and water-scrubbing technologies represent a robust choice as the least expensive alternatives (Fig. 3). The upper and lower uncertainty bounds in Fig. 3 correspond to 2.5th and 97.5th percentile values, and the median value is indicated by a short horizontal line.

Following a Monte Carlo simulation, sensitivity analysis of output parameters is conducted using rank order correlation. The main effect on the cost of combustion and electric oxidation and water-scrubbing systems is from the cost of downstream aqueous HF treatment and the flow of makeup water, with rank order values of 0.96 and 0.22, respectively, for combustion and water-scrubbing systems (Fig. 4). There is a large uncertainty in the cost of treating aqueous HF, from 1 to 30 cents/gal, based on data from facility-scale HF treatment systems. SEMATECH numbers represent the high end of this scale (~\$0.28/gal) [28]. In the absence of a facility-scale treatment system, the use of independent contractors to haul-off HF waste could amount to \$3/gal. Since a manufacturing facility is unlikely to operate with such high costs, this case for hauling HF waste is not considered. Cold-bed and hot-bed adsorption system costs are sensitive to uncertainties in cartridge capacities, costs, and process factors (fluorine loading). For instance, there is significant uncertainty related to capacity data for cold-bed cartridges (29 250–39 000 l of HF).

B. Environmental Metrics

The four technologies were compared relative to a set of metrics that track resources used, air emissions, and solid waste

TABLE V
ENVIRONMENTAL IMPACTS OF DCVD ABATEMENT TECHNOLOGIES ON A PER WAFER PASS

Resources Used	Combustion and Water Scrubbing	Hot Bed	Cold Bed	Electric Oxidation and Water Scrubbing
Total Electricity (kWhr/wafer)	0.09	0.20	0.00	0.38
Industrial City Water (ICW) (gal/wafer)	1.20	0.00	0.00	1.20
Chemicals and Consumables (kg/wafer)	0.12	0.03	0.02	0.01
Emissions				
AIR EMISSIONS				
HAPs Emissions (HF Equivalent kg/wafer)[1]	6.55E-05	6.55E-05	6.55E-05	6.55E-03
Global Warming Emissions (kgCE/wafer)	0.11	0.05	0.18	0.08
Criteria Air Pollutants (kg/wafer)	4.90E-04	N/A	N/A	4.37E-04
LIQUID				
Liquid Waste (gal/wafer)	1.20	0.00	0.00	1.20
SOLID				
Hazardous Solid Waste (kg/wafer)	N/A	N/A	N/A	N/A
Non-hazardous Waste (kg/wafer)	0.02	0.03	0.02	0.02

[1]Assuming similar Destruction and Removal Efficiencies (DRE) for the four technologies

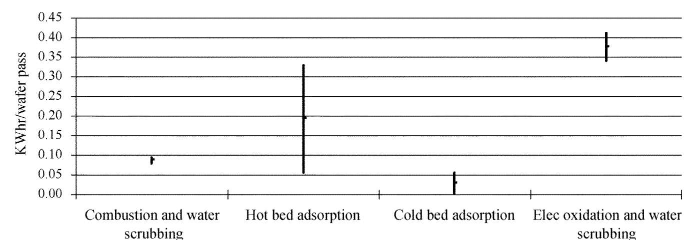

Fig. 5. Electricity used.

generated. Combustion and water-scrubbing, electric oxidation and water-scrubbing solutions and hot-bed adsorption systems seem to use more resources and generate more waste than cold-bed adsorption solutions, except for global warming emissions (GWE) (see Table V).

In terms of resources used, combustion and water scrubbing and electric oxidation and water-scrubbing systems use more water than the cold-bed and hot-bed systems. Electric oxidation and water-scrubbing systems use the most electricity, but hot-bed systems have the greatest variation in electricity use due to the uncertainty in electrical heating requirements in the available data (Fig. 5).

Combustion and water-scrubbing systems use the largest amount of chemicals and consumables (Table V) due to fuel use. Cartridge use is the main component of chemical and consumable use for the hot-bed and cold-bed systems. Approximately 107 hot-bed cartridges are consumed per year, each weighing 40 kg, leading to an overall consumption of 0.03 kg/wafer (4.3 tons/yr; Table IV). Approximately 25 cold-bed columns are consumed per year, each weighing 118 kg, leading to an overall consumption of 0.02 kg/wafer (3.0 tons/year; Table IV).

This analysis assumes similar F_2, HF, and SiF_4 abatement efficiencies for all the technologies (Table IV); therefore, HF equivalent emissions from the four systems are similar (Table V). However, combustion and water-scrubbing systems may also generate CO and NO_x, which are criteria air pollutants. These emissions may range from 0.4 to 0.5 g/wafer pass. GWEs are calculated based on electricity use, regional power data (or national power mix, depending on the analysis), and emissions data for the equipment. For instance, GWEs from combustion and water-scrubbing systems are calculated based on combustion of methane into CO_2, taking into account the

amount of NF_3 and unreacted CH_4 in the exhaust and electricity use as follows:

$$\mathrm{GWE}_{\mathrm{comb,waterscrub}} = Q_{\mathrm{CO_2}}\frac{12}{44}\mathrm{GWP}_{\mathrm{CO_2}} + Q_{\mathrm{CH_4}}\frac{12}{44} \times \mathrm{GWP}_{\mathrm{CH_4}} + Q_{\mathrm{NF_3}}\frac{12}{44}\mathrm{GWP}_{\mathrm{NF_3}} + \mathrm{GWE}_{\mathrm{Electricity}} \quad (2)$$

where Q_i is the mass of greenhouse gas i emitted (in kg/wafer pass), GWP_i is the global warming potential of gas i (1 for CO_2, 23 for CH_4, and 10 800 for NF_3) and GWEs from electricity generation are calculated using the following:

$$\mathrm{GWE}_{\mathrm{Electricity}} = \mathrm{Electrical\,Consumption} \times 0.21 \quad (3)$$

where electrical consumption is expressed in kilowatt hours per wafer pass. The factor of 0.21 kgCE/kWh reflects a typical U.S. electricity mix (this number may vary greatly depending on the generation mode of electrical power) [29].

Cold-bed adsorption systems have the largest global warming impacts, primarily because they cannot destroy NF_3. Postpump NF_3 emissions of 0.06 g/wafer pass are discharged from the system. Since NF_3 has a GWP of 10 800, this emission causes a global warming impact of ~0.18 kgCE/wafer pass following a similar calculation as described in (2). For hot-bed adsorption and electric oxidation and water-scrubbing systems, GWEs include emissions from electricity generation.

Both combustion and electric oxidation and water-scrubbing technologies generate liquid waste at approximately 1.20 gal/wafer, with a variation from 0.89 to 1.51 gal/wafer. None of the systems generate hazardous solid waste. Hot-bed adsorption systems generate the most solid waste from discarded cartridges, which are sent to a nonhazardous landfill.

C. Health Metrics

Health impacts are evaluated based on a streamlined version of the multicriteria hazard (MCH) evaluation technique [30], [31]. The MCH evaluation considers health and safety aspects of process outputs under six categories: acute toxicity, systemic toxicity, reproductive/developmental toxicity, carcinogenicity, physical hazards, and standards and regulations. However, there are significant complications in understanding chemical health effects in facilities, due to changing chemistries and interacting agents [32], lack of data for numerous chemicals [33]–[36], and lack of health data for the six MCH categories. Therefore, EnV-S utilizes three of the MCH categories: acute toxicity, physical hazards, and standards and regulations. Multiple endpoints are considered under each category. Data for these categories are frequently attainable in publicly available health databases and material safety data sheets (MSDS). The essentials of this hazard assessment technique are summarized below. Further details are available in Thurwachter *et al.* [30], [31].

A chemical i is assigned a score $X_{i,j,k}$, for each category j, for every endpoint k for which data are available. These scores are assigned on a logarithmic scale from 1–10, based on the scaling factors. The overall category score for chemical i in category j, $C_{i,j}$ is then obtained by

$$C_{i,j} = \sum_{k=1}^{m_{i,j}} \frac{X_{i,j,k}}{m_{i,j}} \quad (4)$$

TABLE VI
HAZARD ASSESSMENT CATEGORY DATA CONVERTED TO LOGARITHMIC SCALE

	Chemicals							
Categories and Endpoints	SiH_4	NF_3	SiF_4	F_2	HF	CO	NO	NO_2
Category 1: Acute Toxicity								
Lethal Dose, 50% of population (LD50)		6					5	
Lethal Dose (LD)					6		6	
LC50 (Lethal Concentration, 50% of population)	4	5	6	6	6	5		7
LC (Lethal Concentration)	4				7	8		6
Threshold Dose Level (TDL)					4			
Threshold Concentration Level (TCL)					6	5		7
Category 1 Totals	4	5.5	6	6	5.8	6.0	5.5	6.7
CATEGORY 2: Physical Hazards								
Lower Explosive Limit (LEL)	9					5		
Explosive Limit Range (EL Range)	10					10		
Hazard Management Information System Health (HMIS HH)						3	8	
Hazard Management Information System Flammability (HMIS FH)						10		
National Fire Protection Agency Flammability (NFPA FR)	10					10		
National Fire Protection Agency Reactivity (NFPA RR)	8	1	6	10	3	1		
National Fire Protection Agency Hazard (NFPA HR)	5	3	8	10	10	8	8	8
Category 2 Totals	8.7	4.7	8.0	10	7.7	8.0	6.8	9.0
CATEGORY 3: Standards and Regulations								
OSHA/ACGIH Short Term Emission Limit (STEL)				5				5
OSHA Permissible Exposure Limit (OSHA PEL)		3	4	5	4	3	3	
NIOSH Time Weighted Average (NIOSH TWA)	4	3	4	5	4	3	3	
ACGIH Threshold Limit Value (TLV)	2	1	2	2	2	1	1	2
Reportable Quantity (RQ)				7	4			
Category 3 Totals	3	2.3	3.3	4.8	3.5	2.3	2.3	3.5

where $m_{i,j}$ is the number of endpoints with available data for chemical i and category j.

The overall category score for a process stream with a mixture of l chemicals in category j, PC_j, is calculated by mass weighting the logarithmic category scores of individual chemicals as follows:

$$\mathrm{PC}_j = \log M_P + \log \sum_{i=1}^{l} (m_i \cdot \log^{-1} C_{i,j}) \quad (5)$$

where m_i is the mass fraction of chemical i in the process stream, and M_p is the total mass of the process stream.

The hazards of a process are compared to a "worst case" reference mixture made up of chemicals that have the highest known (or most toxic) scores for each category j, $C_{\mathrm{Ref,j}}$. The overall process category scores for the reference mixture are also calculated based on (5) by mass weighting the category scores for the reference mixture $C_{\mathrm{Ref,j}}$ with a reference mass stream M_{Ref} as follows:

$$\mathrm{PC}_{\mathrm{Ref},j} = \log M_{\mathrm{Ref}} + C_{\mathrm{Ref},j} \quad (6)$$

where M_{Ref} is set equal to the largest mass of the process streams being compared.

Note that the MCH assessment is a hazard assessment, not a risk assessment. It can be used to estimate the potential hazards posed by chemicals along multiple categories, but it does not take into account risk of failure, fate and transport, exposure, etc. The category scores and endpoints for the individual chemicals considered are summarized in Table VI. These category scores are then mass weighted by the process mass streams according to (5) to determine overall process category scores (Fig. 6). The MCH assessment is applied to: 1) the inputs to the chamber (Table I); 2) postpump emissions (Table II); and 3) outputs from each of the four abatement technologies (Table IV). It is observed that DCVD process outputs have similar or slightly greater health hazards compared to process input chemicals, due to conversion of SiH_4 and NF_3 to F_2, HF, and SiF_4 (Fig. 6). Abatement systems reduce these hazards significantly, but there

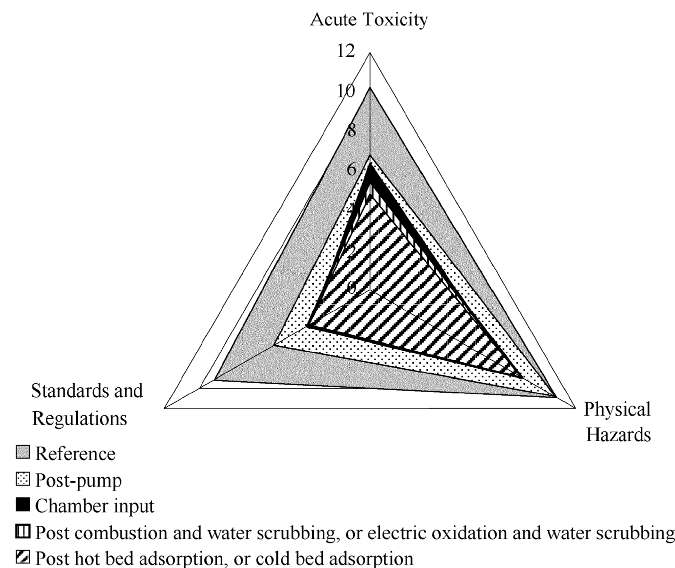

Fig. 6. Hazard profile of the DCVD USG process.

TABLE VII
SUMMARY OF FACILITY PARAMETERS AND ENVIRONMENTAL IMPACTS

GENERAL FACILITY PARAMETERS	
Size of Wafer (inches)	12
Number of Wafer Starts per Week	5000
Number of USG Layers Considered	1
Number of Active Deposition Tools	2

RESOURCES USED	Combustion and Water Scrubbing	Hot Bed Adsorption	Cold Bed Adsorption	Electric Oxidation and Water Scrubbing
Total Electricity (Including Fluoride Treatment, if Applicable) (kWhr/year)	22,591	52,571	859	97,997
Industrial City Water (ICW) (kgal/year)	313	0	0	313
Other Chemicals and Consumables (tons/year)	31	9	6	4
EMISSIONS				
AIR EMISSIONS				
HAPs Loading, No Abatement (HF Equivalent Tons/Year)	2	2	2	2
Global Warming Emissions (Including Fluoride Treatment) (tonsCE/year)	27	13	46	22
Criteria Air Pollutants (tons/year)	1.27E-01	0	0	1.14E-01
LIQUID				
HF Discharged as Liquid (From POU Device) (tons/year)	0.02	0	0	0.02
Final Liquid Waste (After Fluoride Treatment, if applicable) (kgal/year)	312	0	0	312
SOLID				
Hazardous Solid Waste (tons/year)	N/A	N/A	N/A	N/A
Non-hazardous Waste (tons/year)	6[1]	9	6	6[1]

[1]Mainly CaF_2 After Fluoride Treatment

are still some postabatement hazards due to the incomplete destruction of NF_3, F_2, and SiF_4 for all technologies. Combustion and electric oxidation and water-scrubbing systems have slightly greater hazards than the other two technologies, due to the generation of NO_x, and also a small amount of carbon monoxide, for combustion and water-scrubbing systems. Note that in this paper, the streamlined MCH analysis is applied only to gaseous emissions from the four technologies. The fluoride solid waste or other solid wastes generated from the four technologies are not included because they are considered nonhazardous (CaF_2 and other salts).

VIII. Total Loading at the Facility Level

A facility model is constructed to understand fluorine loading from the DCVD process (Table VII). Fluorine emissions are of concern from a regulatory perspective because they could lead to the generation of HF, which is regulated as a hazardous air pollutant (HAP). U.S. facilities could be classified as major sources of HAPs if they exceed regulatory limits of 10 tons/year for a single HAP or 25 tons/year for a combination of HAPs. It can be seen that, unabated, the DCVD process itself could potentially account for 2 tons/year in HF equivalent emissions, for a single layer of deposition. Since the manufacturing of a state-of-the-art logic device could involve nine or more interconnect layers, abatement of DCVD gaseous emissions abatement is extremely important.

Overall, cold-bed technologies seem to have the lowest environmental impacts except for greenhouse gas emissions. Water use and liquid waste generated are the main impacts for combustion and water scrubbing and electric oxidation and water-scrubbing technologies. Chemical and material use is higher for the combustion and water scrubbing technology. Hot-bed adsorption and electric oxidation and water-scrubbing technologies have higher electricity use. Note, however, that the boundaries of this analysis are primarily restricted to "within facility" impacts (Section III). While this study does not consider the upstream life cycle, environmental impacts of manufacturing chemicals, materials, equipment, etc., it should be kept in mind that including these elements could alter the environmental ranking between these four technologies. For instance, the embedded energy in the metals used in hot- and cold-bed adsorption cartridges could be significant. Challenges remain, however, in developing successful LCA tools for semiconductor manufacturing (Section II) and we leave this topic as a direction for future work.

IX. Summary

The manufacturing of semiconductor devices is a complex process involving hundreds of different complex chemistries and process steps with short process lifetimes (18 months). The EnV-S is helpful in developing an environmental footprint of process equipment using a combination of data and process models. Each equipment-based model can be instanced using a wide variety of recipe data, emissions data, and facility infrastructure options (pumps, abatement devices, facility scale treatment, etc.). Such a bottom-up approach is useful in semiconductor manufacturing where there are rapid changes in processes and in equipment sets (every few years) because it is possible to vary the analysis depending on altered manufacturing conditions and, therefore, minimize data collection requirements.

The validation of equipment, specifically exhaust management equipment, is one of the key areas in which the EnV-S may be used. An extended environmental CoO metric is developed that is related to process models and data and includes items such as cost of downstream treatment of effluents in facility systems, infrastructure requirements, exhaust requirements, etc. Resource use, emissions (air, liquid, and solid), and health hazard metrics are also supported. The evaluation is meant to be transparent and to maintain separation of metrics so that a user, in a rapidly changing environment, can make effective value choices based on numerous characterization metrics.

A case study is presented in which the EnV-S is used to evaluate environmental impacts of four products and technologies to reduce toxic and potentially hazardous emissions from

the DCVD process. An uncertainty analysis is developed for the alternative technologies, and environmental projections are also made for impacts at the facility scale. It is seen that, in general, electric oxidation and water scrubbing and combustion and water-scrubbing systems are most cost effective at treating DCVD emissions, but have higher water and chemical use and generate more liquid waste. These systems may also have slightly higher health hazards due to the generation of CO (for combustion systems) and NO_x. A system selection decision can, therefore, be based on understanding these environmental and cost impacts. Note that the analysis presented here is generic for technology types. In practice, greater resolution and accuracy can be obtained if data used are specific to the equipment configurations that will be deployed in particular facility locations.

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