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A three dimensional system approach for environmentally sustainable manufacturing

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ABSTRACT

Sustainable manufacturing has received enormous attention in recent years as an effective solution to support the continuous growth and expansion of manufacturing industry. In this paper, we present a three dimensional system approach for sustainable manufacturing from environmental perspective. This method attempts to address the sustainability issues of manufacturing from a pollution prevention standpoint, considering the three key components of manufacturing: technology, energy, and material. Case study is performed on an emerging nano-manufacturing technology, atomic layer deposition. This system approach, when appropriately adopted, could be useful in real sustainable manufacturing practices for overall sustainability management and improvement.

1. Introduction

As manufacturing converts raw materials into products, environmental wastes and emissions are simultaneously generated from the consumption of materials and energy in manufacturing processes. Statistical data shows that the U.S. manufacturing industry annually consumes 21.1 quadrillion Btu energy (about 21% of total U.S. energy consumption) and generates more than 1.4 billion metric tons of CO_2 emissions (about 26% of total U.S. CO_2 emissions) [1]. In 2009, U.S. manufacturing and related industry released more than 3.37 billion pounds of toxic chemicals into the environment [2]. Such manufacturing wastes and emissions cause not only environmental problems but also economical issues due to the efforts associated with the environmental emission mitigation, control, and recovery within and outside the manufacturing system. As the environmental impacts of manufacturing industry are so significant in the amount of emissions and wastes, sustainable manufacturing has attracted enormous attention in recent years as a comprehensive strategy for reducing the environmental impact and improving the economic performance of manufacturing industry.

In current sustainable manufacturing research, significant efforts are put on the development of metrics and tools for environmental performance analysis of manufacturing processes. However, little work has been done in the system level of thinking for the development of an approach to improve the overall sustainability of manufacturing [3]. A comprehensive system approach for sustainable manufacturing needs to be conducted through a life cycle assessment (LCA) approach since the environmental impacts of manufacturing extend well beyond manufacturing, to such life cycle phases as raw material acquisition, material production, usage, end-of-life, etc. [4]. As manufacturing is a key stage in LCA which links materials to products, and consumes significant amounts of materials and energy in the manufacturing system, in this research, the focus is put on development of a system approach for sustainable manufacturing from environmental perspective.

A system approach for environmentally sustainable manufacturing needs to consider the components of manufacturing from a comprehensive manner [5]. As the most effective and economical strategy for environmental impact control is pollution prevention [6], the ideal system approach for environmentally sustainable manufacturing should focus on pollution prevention in manufacturing. In manufacturing, the environmental emissions and wastes are generated from the materials and energy consumed either directly or indirectly in various manufacturing processes. However, what dictates the materials/energy consumptions and the emission generations in manufacturing are those manufacturing technologies and process parameters being employed. Accordingly, the pollution prevention opportunities for environmentally sustainable manufacturing are recognized with these three components of manufacturing: technology, energy and material.

2. A three dimensional system approach

In this paper, a system approach is developed to support industrial efforts in improving the overall sustainability of manufacturing from pollution prevention perspective. The system approach is developed on the three components: technology, energy and material, of a manufacturing system, and provides a framework for implementation of pollution prevention strategies to reduce the environmental impact and improve the sustainability performance of a manufacturing system. The three components in an environmentally sustainable manufacturing system are cross-linked with each other. A schematic structure of the system approach is shown in Fig. 1 below.

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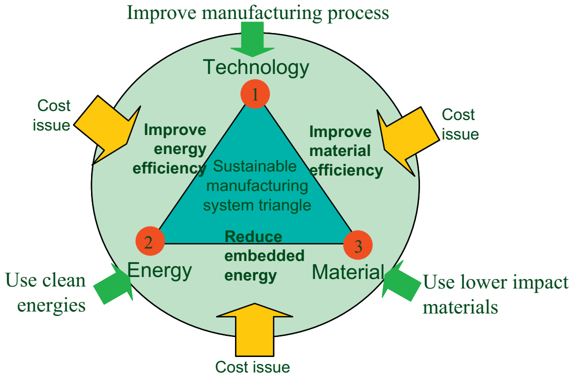

Fig. 1. Sustainable manufacturing system scheme.

The first dimension of the system approach is technology employed in manufacturing, which is critical in determining the sustainability performance of manufacturing since both materials and energy consumptions are determined by the requirements of manufacturing processes. Improving technological processes for reducing both material and energy consumptions can improve the sustainability performance of manufacturing. For sustainable manufacturing through technological improvement, process-based analytical models play an important role in quantifying the inputs (materials, energy, etc.) and outputs (products, emissions, wastes, etc.) of manufacturing. Among these analytical models, material flow analysis and energy flow analysis are two useful tools widely adopted to quantify and track the material/energy flows within manufacturing. As an illustration, schematic of a single material flow in a manufacturing system is shown in Fig. 2 below. M is the total amount of the material loaded into the manufacturing system, M_i ($i = 1,2,\ldots,n$) is the amount of material input in process i for product-making, W_i is the amount of material wasted in process i.

Material utilization efficiency, as defined below on a specific material assuming that the waste material is not re-entering the material flow, is a meaningful metric for measuring sustainability performance of a manufacturing system. The higher the efficiency η is, the better the sustainability performance is.

$$\eta = \frac{M - \sum_{i=1}^{n} W_i}{M} \tag{1}$$

Energy flows can be similarly modeled through the above procedure for energy flow analysis. Energy consumption in manufacturing can be modeled using an equipment centric approach. So the total energy consumed in a manufacturing process equals the sum of energy consumed by each manufacturing facility:

$$Q = \sum_{j=1}^{N} P_j \times \delta_j \times t_j \tag{2}$$

where Q is the total energy consumption; P_j is the power demand of facility j; δ_j is the operating efficiency of facility j; t_j is the operating time of facility j; N is the total number of facilities in the manufacturing process.

After understanding the internal flows of materials/energy in manufacturing, those key process parameters of manufacturing technologies can be identified and the manufacturing processes can be optimized to improve the sustainability performance through improving both material and energy efficiency. A mathematical objective function expressed in a general format below can facilitate the technological improvement in this aspect:

$$\text{Minimize} \quad F(M, Q) = f(x, y, z, \ldots, t) \tag{3}$$

where x, y, $z\ldots$ are manufacturing process parameters dictating material use and/or energy consumptions; t is the manufacturing process time.

The second dimension of the system approach is energy which aims to improve the sustainability of manufacturing from energy perspective. The total amount of energy consumed in a manufacturing process, as expressed by Eq. (2), can be minimized to reduce the energy consumption and mitigate the associated environmental impact. In addition, clean energy supply such as solar photovoltaic, wind, fuel cells, etc., can also be used to partially replace the energy consumption of manufacturing to improve its environmental performance. For clean energy supply, cost benefit is an important indicator for their actual applications. Eq. (4) below shows a cost benefit model of using clean energy supply for greenhouse gas (GHG) emission mitigation from conventional grid power supply [7]:

$$G = \frac{(E_{local} - E_k) \times A_k \times T_k}{(C_{Nk} + C_{Vk} \times T_k + C_{Fk})A_k} \tag{4}$$

where G is the amount of GHG reduction, ton/\$1000; E_{local} is the emission factor of GHGs from local grid power supply, kg/kW h; E_k is the life cycle GHG emissions of clean energy k, kg/kW h; A_k is the total installed capacity of clean energy, k; T_k is the operational life time of clean power system, k, in hours; C_{Nk} is the overnight cost of clean power system, k, \$/kW; C_{vk} is the variable O&M cost of clean power system, k, \$/kW h; C_{Fk} is the Fixed O&M cost of clean power system, k, \$/kW.

The third dimension of the system approach is material which covers all types of materials supplied into and generated out of a manufacturing system. Materials used in manufacturing are major sources of the environmental impact, not only from the materials themselves but also from the embedded energy and resources used to produce these materials. For example, the embedded energy used in producing 1 kg aluminum is about seven times that used in producing 1 kg steel [8]. The environmental impact of manufacturing through material management can be reduced through such preventive efforts as minimizing material use, using lower impact materials, etc. In particular, toxic chemicals used in manufacturing are one of the major impact sources. More frequently, toxic chemicals are characterized for their potential impact on human health within a life cycle impact framework. While there are multiple other impact methods such as aquatic toxicity, terrestrial toxicity, etc., a broad range of impacts of toxic chemicals need to be measured in comprehensive sustainability management. In principle, the human health impact of a toxic chemical can be simply characterized through [9]:

$$I_c = f(R_c, T_c) \tag{5}$$

where I_c is the human health impact of chemical c; R_c is the daily risk of health damage from exposure to chemical c; T_c is the persistence of chemical c in the environment.

3. Case study

Case study for application of the system approach is illustrated on an emerging nano-scale manufacturing, Atomic Layer Deposition (ALD). ALD is a bottom-up nano-scale manufacturing technology, derived from Chemical Vapor Deposition (CVD), for depositing highly uniform and conformal thin films by alternating exposures of a surface to vapors of two or more chemical reactants [10]. As a key enabling nanotechnology, ALD has already been adopted in industrial-scale semiconductor manufacturing and is under rapid development for a broad array of industrial applications including solar cells, fuel cells, medical devices, sensors, polymers, etc.

ALD nano-manufacturing is typically modeled on the deposition of Al_2O_3 high-k dielectric films [11]. This is a process developed for replacing conventional SiO_2 dielectric gate in the Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) as the semiconductor process is down-sizing from 90 nm to 45 nm. By using ALD technology, the accuracy of Al_2O_3 film thickness can be controlled at 0.1 ± 0.01 nm scale [12], with surface roughness

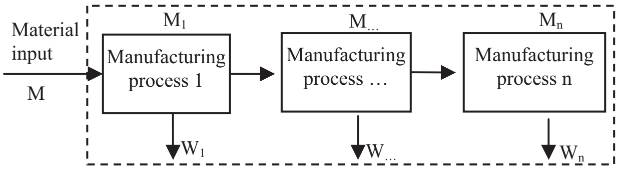

Fig. 2. Schematic of a single material/energy flow in a manufacturing system.

controlled less than 0.3 nm [13]. Typical ALD of Al_2O_3 uses Trimethylaluminum (TMA), $Al(CH_3)_3$, as the metal source, and deionized water, H_2O, as the oxidant. Deposition mechanism of Al_2O_3 by ALD is based on the CVD reaction: $2Al(CH_3)_3 + 3H_2O = Al_2O_3 + 6CH_4$. ALD splits the reaction into the following two steps and operates repeatedly in the deposition:

$$Al{-}OH + Al(CH_3)_3 \rightarrow Al{-}O{-}Al(CH_3)_2 + CH_4 \tag{6}$$

$$Al{-}CH_3 + H_2O \rightarrow Al{-}OH + CH_4 \tag{7}$$

With the binary reaction nature, the two ALD precursors are alternative pulsed into the reactor to allow surface reactions only. All the unreacted precursors are pumped out and end as wastes and emissions, which causes significant sustainability problem of the technology and limit its rapid development toward large-scale industrial applications [14]. For ALD of Al_2O_3, the precursor TMA is a flammable and toxic chemical. The principle byproduct of the ALD Al_2O_3 process is methane, which is a major greenhouse gas and has a global warming potential 25 times that of carbon dioxide [15]. This case study is to illustrate how to use the system approach to improve the sustainability of ALD Al_2O_3 through the three dimensions of the manufacturing system.

3.1. Technology improvement for ALD sustainable manufacturing

The sustainability performance of ALD nano-manufacturing is dictated by a number of process parameters including precursor pulsing pressure, cycle time, process temperature, etc. For technological improvement following Fig. 2, a material flow analysis for the ALD of Al_2O_3 using TMA and H_2O precursors on 4 inch silicon wafer at 600 mTorr is illustrated in Fig. 3 below. The material flow chart shows the amount of precursor materials loaded in, converted into products (Al_2O_3 thin film), and generated as emissions (TMA, CH_4) from the ALD nano-manufacturing. ALD precursor material utilization efficiencies, as expressed in Eq. (1), are analyzed for both TMA and H_2O at three typical operating conditions: 1000, 800 and 600 mTorr, as shown in Fig. 4. Here H_2O is analyzed for material waste, not for environmental impact. The results indicate that the material utilization efficiencies are all below 20%, but reducing the operating pressure in ALD system can improve the precursor material utilization efficiency and accordingly improve the sustainability performance of ALD nano-manufacturing.

3.2. Energy management of ALD for sustainable manufacturing

ALD is energy-intensive. ALD typically operates at the vapor phase of precursor materials, which demands energy to supply the activation energy and requires ultra-high vacuum conditions that also need high energy input for such process operations as heating, pumping, monitoring, controlling, etc. For semiconductor applications, the ALD of Al_2O_3 reaction has been identified with an extremely high reaction energy requirement [16]. The measured energy consumption in our study shows that a total of 1.2×10^6 J of energy input is required to deposit a 20 nm Al_2O_3 high-*k* dielectric gate on a 4-in. silicon wafer [14]. ALD energy consumption is dependent on ALD process temperature and cycle time. Fig. 5 below shows the amount of ALD unit energy consumption at various temperature and cycle times. The ALD energy consumption can be minimized through Eq. (3) as a function of cycle time and process temperature.

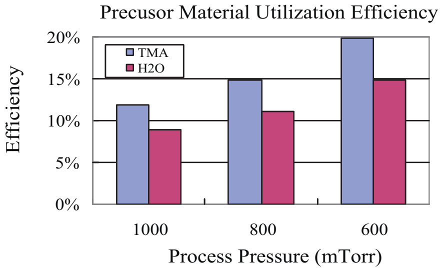

Fig. 4. Precursor utilization efficiencies in ALD of Al_2O_3 [14].

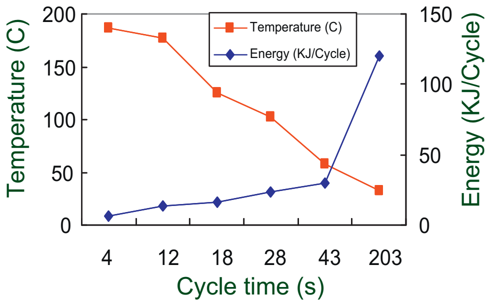

Fig. 5. ALD energy dependence on process parameters [14].

Current ALD energy consumption is supplied by grid power which is mainly generated by fossil fuels. For improving sustainability of ALD from energy perspective, clean power supply such as solar PV, wind, fuel cells, etc., can be employed. Fig. 6 below shows the cost benefit of using such three clean energy supplies for greenhouse gas mitigation, based on Eq. (4). The technical parameters of clean energy technologies are selected as the average of those most popular clean power systems on the commercial market [7]. As the ALD case study is for semiconductor manufacturing, the location of the study is selected as the silicon valley of U.S. (San Jose, CA, Latitude: 37°20′21.984″N; Longitude: 121°53′38.004″W). The results indicate that wind power has the best cost benefit among the three clean energy options. Wind power can reduce an average of 9.26 tons GHG per $1000 economic input, with a range between 6.26 and 12.66 tons/$1000 in San Jose, CA.

3.3. Material management for ALD sustainable manufacturing

Sustainability of ALD nano-manufacturing can also be improved through material management. In current ALD processes a large

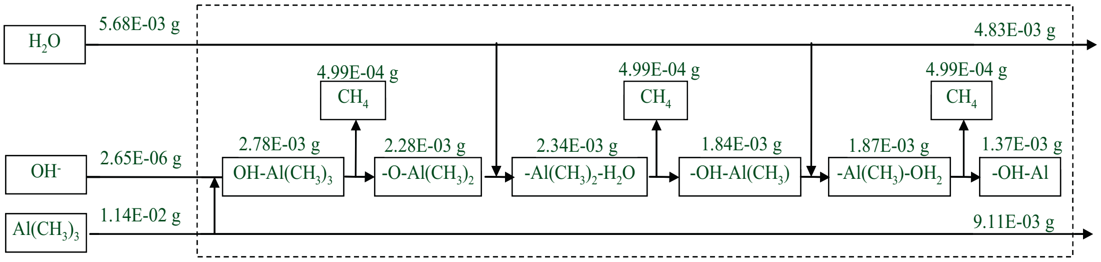

Fig. 3. ALD material flows of 200 cycle operations at 600 mTorr.

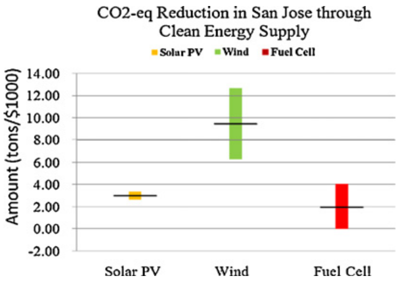

Fig. 6. Cost benefit of clean energy supply in San Jose, CA.

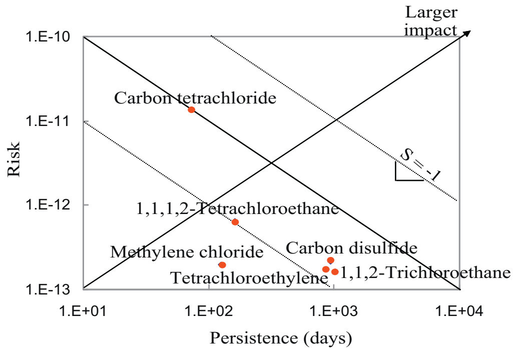

Fig. 7. Sustainable material selections of toxic chemicals [7].

proportion of precursor materials are wasted (more than 80%, as demonstrated in Fig. 4 above). The material wastes could be reduced through optimizing ALD process parameters and/or sustainable design of ALD manufacturing system. In ALD nanomanufacturing system, one major concern is the toxic chemicals. Besides the chemical precursor, some chemicals are also used for cleaning and preparing the wafer. Fig. 7 below shows an example on sustainable material selection of six chemicals widely used for cleaning in semiconductor manufacturing, using a schematic benchmarking method based on Eq. (5) above. The results demonstrate that among these six toxic chemicals methylene chloride has the least impact on human health and should be favorably selected among these six chemicals to improve the sustainability performance of ALD.

4. Concluding remarks

A three-dimensional system approach is presented in this paper as a decision-support framework for environmentally sustainable manufacturing. This system approach considers the three components of manufacturing: technology, energy and material, which can be employed to improve sustainability of manufacturing from an individual or combined perspective. This system approach presented here is generic and can be adapted to various manufacturing systems and technologies. A case study is conducted on atomic layer deposition for improving its sustainability performance in semiconductor manufacturing.

This system approach is mainly for improving the sustainability of manufacturing from a pollution prevention perspective. The methods and tools currently used in this system approach are mainly for quantifying and reducing the sources of environmental impact from manufacturing. Accordingly, both upstream and downstream environmental impact assessment of manufacturing emissions and wastes are not included in this system approach at this moment. But the supporting metrics and tools can be expanded in future to accommodate the needs toward a comprehensive system approach from life cycle perspective.

Acknowledgment

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References

[1] EIA (Energy Information Administration), 2010, Annual Energy Review 2009, http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf.
[2] EPA, 2010, 2009 Toxic Release Inventory National Analysis, http://www.epa.gov/tri/tridata/tri09/nationalanalysis/index.htm.
[3] Seidel M, Seidel R, Tedford D, Cross R, Wait L (2008) A System Modeling Approach to Support Environmentally Sustainable Business Development in Manufacturing SMEs. *Proceedings of World Academy of Science, Engineering and Technology, vol. 36*, 866–874.
[4] Westkamper E, Alting L, Arndt G (2000) Life Cycle Management and Assessment: Approaches and Visions towards Sustainable Manufacturing. *CIRP Annals – Manufacturing Technology* 49(2):501–526.
[5] Hon KKB (2005) Performance and Evaluation of Manufacturing Systems. *CIRP Annals – Manufacturing Technology* 54(2):139–154.
[6] Yuan, Y., 2009, A System Approach for Reducing the Environmental Impact of Manufacturing and Sustainability Improvement of Nano-scale Manufacturing, Ph.D. Dissertation, U.C., Berkeley.
[7] Zhai Q, Cao HJ, Zhao X, Yuan C (2011) Cost Benefit Analysis of Using Clean Energy Supply to Reduce Greenhouse Gas Emissions of Global Automotive Manufacturing. *Energies* 4(10):1478–1494.
[8] Gutowski TG (2004) *Design and Manufacturing for the Environment in Handbook of Mechanical Engineering*, Springer-Verlag, New York, U.S.A..
[9] Yuan C, Dornfeld D (2010) A Schematic Method for Sustainable Material Selection of Toxic Chemicals in Design and Manufacturing. *ASME Journal of Mechanical Design* 132(9):091014.1–091014.7.
[10] Lim B, Rahtu A, Gordon R (2003) Atomic Layer Deposition of Transition Metals. *Nature Materials* 2:749–754.
[11] George SM (2010) Atomic Layer Deposition: An Overview. *Chemical Reviews* 110(1):111–131.
[12] Gao KY, Seyller T, Ley L, Ciobanu F, Pensl G, Tadich A, Riley JD, Leckey RGC (2003) Al_2O_3 Prepared by Atomic Layer Deposition as Gate Dielectric on 6H-SiC(0001). *Applied Physics Letters* 83(9):1830–1832.
[13] Greer, J., 2003, Preliminary Rate Equations for Al_2O_3 Film Growth, IST-2000-29295, Deliverable D6.1, European Community Information Society Technologies Program.
[14] Yuan C, Dornfeld D (2010) Integrated Sustainability Analysis of Atomic Layer Deposition for Microelectronics Manufacturing. *Journal of Manufacturing Science and Engineering* 132(3):030918.1–030918.7.
[15] IPCC, 2007, Changes in Atmospheric Constituents and in Radiative Forcing, http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Print_Ch02.pdf.
[16] Widjaja Y, Musgrave CB (2002) Quantum Chemical Study of the Mechanism of Aluminum Oxide Atomic Layer Deposition. *Applied Physics Letters* 80(18): 3304–3306.