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Deconstructing Energy Use in Microelectronics Manufacturing: An Experimental Case Study of a MEMS Fabrication Facility

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Semiconductors are quite energy intensive to manufacture on the basis of energy required per mass of material processed. This analysis draws on original data from a case study of the Analog Devices Micromachined Products Division MEMS fabrication facility to examine the consequence of process rate on the energy intensity of semiconductor manufacturing. We trace the impact of process rate on energy intensity at different length scales, first presenting top-down data, then results of a bottom-up study, and concluding with individual process analyses. Interestingly, while production increased by almost a factor of 2 over the course of the study, energy demand remained virtually constant. At its most efficient, 270 kWh of electricity were required per six inch wafer in the manufacture of the MEMS devices produced at the fabrication facility. In part, the large amount of energy required per unit output is a function of the preponderance of energy used by support equipment; our data show that the facility support equipment is responsible for 58% of total energy requirements.

Introduction

Semiconductor devices are a pillar of the modern economy. Their value extends far beyond the roughly $250 billion generated annually by the worldwide semiconductor manufacturing industry (*1*). By enabling automation, interconnectivity and communication, and massive data processing and storage, semiconductors have powered a phenomenal surge in productivity over the last half century and a corresponding rise in the standard of living in the developed world and increasingly in developing nations. The proliferation of semiconductor-driven devices has been paralleled by a similar rise in environmental consciousness, which has led to a debate over the net total environmental impact of semiconductors. It is often posited that semiconductor manufacturing is energy intensive in comparison with other manufacturing sectors; the sector is responsible for about 1.5% of the industrial electricity consumption (*2*) in the United States even though the industry's center of gravity has shifted to Asia. Why is semiconductor manufacturing so energy intensive?

Although data on energy and materials use in semiconductor manufacturing is relatively scarce and closely guarded by industry participants, there have been several well-researched studies on the subject published over the past decade. Three of them apply a top-down approach to determine energy and material requirements in the manufacture of a defined product (*3*−*5*). The 1993 Microelectronics and Computer Technology Corporation (MCC) study was the first of its kind. In it, the authors evaluated the energy and material inputs required to manufacture a model computer workstation. They found that an average six inch wafer required 285 kWh of electricity or 1.6 kWh/cm^2 (the unit of energy intensity—energy per square centimeter of product wafer—is a standard that allows comparison between facilities of different size producing wafers of various diameters) (*3*). The 2002 Williams et al. paper presents a life cycle assessment (LCA) of a memory chip using data gathered from a variety of sources (*4*). In a subsequent paper, Williams applied a hybrid LCA model to evaluate the manufacture of an entire computer workstation, analogous to the MCC study (*5*). Other studies have taken a more process-oriented approach (*6*−*10*). In 2003, Murphy et al. presented a model that quantified the energy used in certain processes on the basis of select variables (*6*). The model was built from a collection of process data that is discussed in more detail in an associated report (*7*). Several articles published in trade magazines contribute to the discourse by providing valuable process data (*8, 9*). The most recent contributions are the 2008 comprehensive hybrid life cycle inventory (LCI) of a CMOS microprocessor by Krishnan et al., which contains extensive process data in addition to the thorough analysis of a semiconductor life cycle (*10*), and the analysis of the energy demand and global warming potential of computational logic by Boyd et al. (*11*).

In this article, we present a synthesis of primary data supplemented by thermodynamic analyses of several of the constituent processes within semiconductor manufacturing. The approach taken is to examine energy consumption within a MEMS fabrication facility (fab) at multiple length scales, beginning with the overall fab, then applying bottom-up data, and concluding with specific processes to illustrate the relative importance of material and energy contributions to overall process efficiency. We trace the impact of rate on the energy intensity of the processes through these length scales and conclude that the energy intensity of semiconductor manufacturing is an intrinsic function of the rate at which material is processed.

The second objective of this article is to present a cohesive picture of how energy is used in a semiconductor manufacturing plant using original data. The supporting data are gathered from a MEMS fabrication facility processing material in real time. Although lacking information on emissions (at the process and plant levels), this article complements the work of Krishnan et al. (*10*) by quantifying the energy used by auxiliary equipment in addition to that of the processing equipment. The goal is to make this information transparent and accessible.

Data Acquisition

Data collection took place between August 2007 and March 2008 at the Analog Devices, Inc., Micromachined Products Division (MPD) wafer fabrication facility in Cambridge, MA. This facility produces accelerometers, gyroscopes, and a variety of other chipsets on six inch silicon wafer substrates that fall under the wider definition of MEMS. MEMS have come to include a broad class of devices that vary substantially in structure and function and therefore in manufacturing procedure. Nonetheless, the vast majority of MEMS manufacturing processes are similar to those used in traditional

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integrated circuit manufacturing, even if MEMS manufacturers employ some of them in a unique fashion. The most notable process differences are (1) the etching of high-aspect ratio features in the definition of the mechanical portion of the device, which can include the use of non-photoactive mask materials such as the polymer PMMA and (2) the use of laser trimming to precisely tune analog circuits, an energy intensive serial manufacturing step. Additionally, the MEMS products being manufactured at the MPD fab require some 500 processing steps, roughly 2−4 times as many as are required for logic or memory chips.

This plant is responsible only for the front-end manufacturing processes associated with chip production; wiring and encapsulation are completed at a separate facility. Data on waste emissions and disposal were unattainable. Data on input materials for the entire fab were also gathered and are in the Supporting Information. The data sets collected from the MPD facility include the following:

1. Top-Down Electrical Data. Total fab electrical inputs for 2007 were taken directly from electric company billings. Although the two switchgears supplying the fab power some nonfab loads (e.g., lobby lighting), the size of those loads compared to the size of the fab-related loads is negligible (<1%).

2. Product Wafers. Managers at the MPD facility provided data on the number of 6 inch wafers produced per quarter. The data do not specify the type of product produced, number of chips produced per wafer or yield; that information is confidential. The different product lines require roughly the same number of process steps (∼500); it is therefore reasonable to aggregate the various product lines into a single output unit.

3. Bottom-Up Electrical Data. The purpose of the bottom-up energy use assessment was to track how and where electrical power is used in the fab with high resolution. To this end, a measurement program was implemented in which the facility's electrical loads were measured in a series of tests over a six month period. Each test recorded the power consumed by a target electrical load for a period of 6 h to 3 days. The standard test length was 24 h. Electrical measurements were taken with an AEMC PowerPad three-phase power meter, model 3945-B, which logs more than 20 different power metrics.

Facility support equipment [chillers, deionized (DI) water production equipment, compressors, etc.] was measured on a case-by-case basis. For process tools, the power consumption of individual pieces of equipment was measured as much as possible. Given the large number of electrical loads in the fab, however, most measurements were taken of electrical panels that power multiple pieces of equipment "upstream" of the level of individual equipment. In the latter case, data gathered in brief follow-up spot measurements were used to allocate to specific process areas the average power recorded during the long-duration test.

The methodology applied to the bottom-up analysis required the critical assumption that the manufacturing system can be approximated as steady state. For justification, see section 1 of the Supporting Information.

4. Process Analyses. In addition to the effort to quantify the inputs and outputs to the entire manufacturing system, we also evaluate specific processes. For each of seven processes—plasma-enhanced chemical vapor deposition (PECVD) of silicon dioxide (SiO_2) and silicon nitride (Si_3N_4), sputter deposition of AlCu, and wet and dry etching of SiO_2 and Si_3N_4—the energy and material inputs and the useful outputs were measured. The electrical data were gathered using the same power meter as for the bottom-up measurements. Material consumption data were gathered manually but in real time from the digital readouts of the various tools and corroborated with process recipe data. The useful output from each process (e.g., thickness of material deposited or etched) was taken from the process recipe.

Top-Down Electrical Power Consumption

We begin with a broad perspective of the manufacturing facility to provide a reference for the more focused analyses in the succeeding sections. As indicated in Figure 1, the MPD fab metabolizes electrical power at an average rate of 1.4 MW with a seasonal variation that rises from a daily low of around 1.3 MW in winter to a high of 1.5 MW in the summer months. Excluding seasonal variability, power consumption appears little changed from 2006 to 2007.

The seemingly dull fact that power use did not increase from 2006 to 2007 becomes interesting when contrasted with the marked increase in wafer production over the same period. Between the first quarter of 2006 and the closing quarter of 2007, wafer production roughly doubled, while energy consumption remained virtually constant. These results support the claim that the functional independence between power consumption and throughput that was reported earlier for individual micro- and nanoscale processes (*12*) also applies to the factory as a whole. The following sections will discuss this relationship in more detail, but it deserves mention here that not only is a fab composed of a collection of individual processes that tend to run continuously regardless of throughput, but MEMS and other small-feature-scale production processes require environmental conditioning and air handling systems that have large fixed power requirements. As shown in the bottom-up electrical power consumption section, these facility support systems typically run continuously and can require an energy input exceeding that of the process tools.

Rate and Energy Intensity in Manufacturing

The relationship between power consumption and throughput in manufacturing has been analyzed in previous work (*12, 13*). In all manufacturing processes, the energy requirement for the process can be divided into two components: (1) the base (auxiliary) power required to run all supporting process operations and (2) the variable power needed to effect the physical transformation associated with the process. In metal casting, for example, the base power would correspond to that required to heat the crucible and operate mechanical components of the system. The variable power would correspond to the incremental additional power required to heat and melt a unit of metal. As a first approximation, the total power consumption rate ($\dot{W}$, in kW) may be modeled as a linear function of the auxiliary power ($\dot{W}_0$, in kW) and the product of the physically determined constant of material conversion (k, in kJ/unit processed) and throughput ($\dot{v}$, in unit processed/time)

$$\dot{W} = \dot{W}_0 + k\dot{v} \tag{1}$$

Dividing both sides of this equation by the throughput $\dot{v}$ yields an expression for the specific energy consumption (SEC) of a process (w, in energy/unit processed)

$$w = \frac{\dot{W}}{\dot{v}} = \frac{\dot{W}_0}{\dot{v}} + k \tag{2}$$

The latter equation has two interesting features. At high throughputs (typically defined on a mass or volumetric basis), the term ($\dot{W}_0/\dot{v}$) becomes very small and the SEC approaches a constant value given by the material conversion constant (k). Bulk forming processes (like metal casting and injection molding) are examples of processes that operate in this throughput range, where the SEC is largely determined by the energy required to heat and melt the input material. At

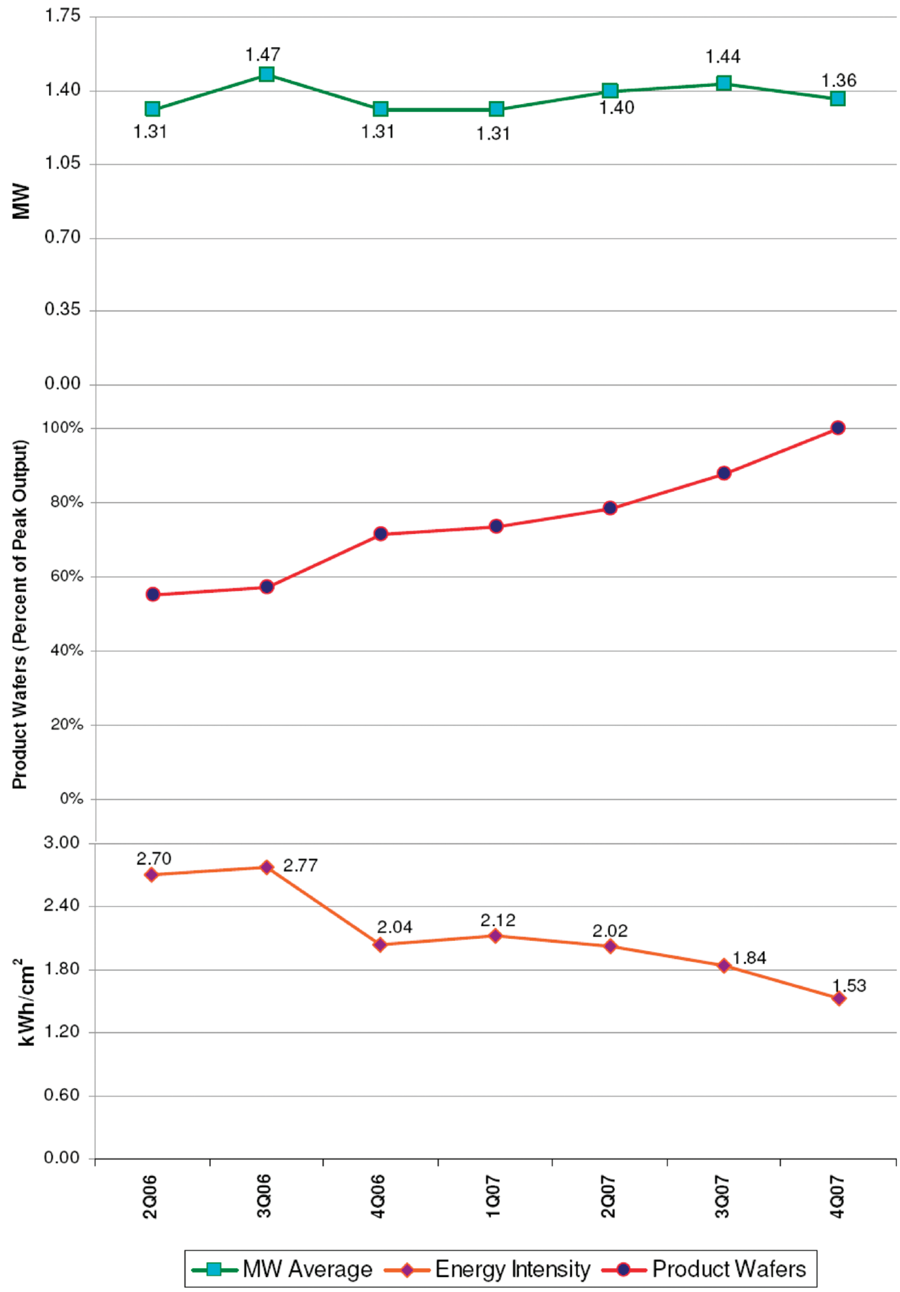

FIGURE 1. From top: Quarterly average power consumption rate, six inch wafer output, and specific electricity consumption for the MPD fab.

lower throughputs, the material conversion constant (k) is dwarfed by the term ($\dot{W}_0/\dot{v}$) and SEC becomes inversely proportional to throughput. Because semiconductor manufacturing processes operate in this regime, it is expected then that the SEC of semiconductors should decline with increasing throughput.

As noted in the preceding section, it appears that eqs 1 and 2 can be applied to the factory as a whole in addition to individual processes. Using the top-down data on power consumption, the energy intensity of the Analog Devices manufacturing facility is presented in the lower graph of Figure 1. As anticipated, the energy intensity of the manufacturing system has declined as throughput has risen, precisely the pattern expected for a low-throughput and high-auxiliary power system.

The origin of the decline in energy intensity is not so much a story of improving efficiency but rather of increasing production. In the eighteen months ending December 2007, production at the facility grew at a 49% percent annual rate. This gain in production has come almost entirely through improved manufacturing flow and increased tool utilization and not through capacity expansion. In fact, over the same time period, absolute energy consumption in the fab has grown only about 4% annually. Of course, there are competing effects at play. For example, some upgrades to more efficient pumps and motors have been made. More importantly, yearly variation in climate conditions can veil changes in tool energy consumption because such a large percentage of fab power goes toward climate control. Nonetheless, the relationship between throughput and energy intensity is clear.

Since the conclusion of this study, the MPD fab has maintained an energy intensity around the 1.53 kWh/cm^2 value found in the fourth quarter of 2007. This value for MEMS manufacturing is comparable to other values found in the literature for semiconductor manufacturing. For example, it falls within 5% of the value reported in the MCC study and the value used in the Williams et al. LCA (*3, 4*). This agreement is likely not coincidental; as in those earlier studies, most

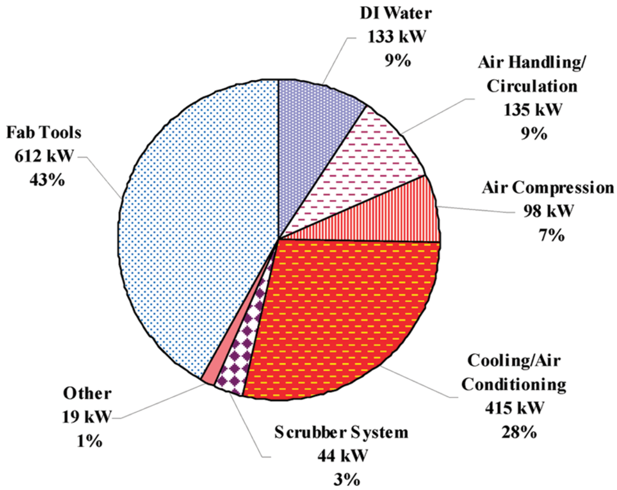

FIGURE 2. Bottom-up assessment of power consumption at the Analog Devices MPD fab (1457 kW total).

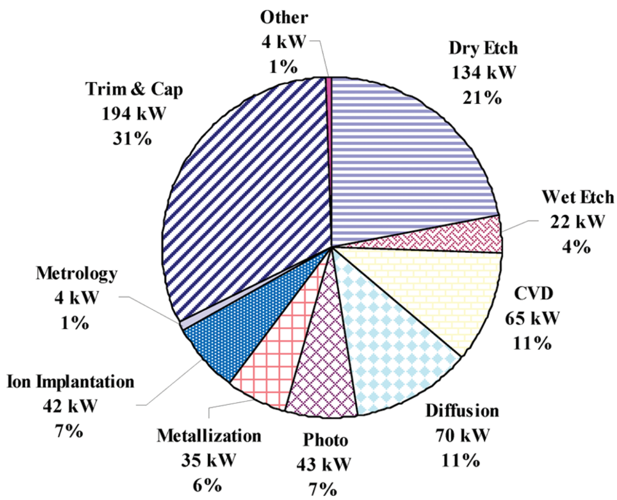

FIGURE 3. Tool power consumption breakdown by process area (612 kW total).

MEMS manufacturers use 6 inch wafers and similar manufacturing equipment. Interestingly, the Krishnan study puts the energy requirements for the manufacture of microprocessors produced on 12 inch wafers at about 0.97 kWh/cm^2 (*10*), which suggests it is more efficient to process these now standard larger wafers than the smaller six inch ones still largely used in the MEMS industry. This conclusion is consistent with the process rate argument.

Bottom-Up Electrical Power Consumption

Greater understanding of how energy is used in the MPD fab can be gained by peering inside the black box manufacturing system evaluated in the preceding section. To this end, every load in the facility was monitored individually over a six month period according to the protocol described in the data acquisition section. The results from that study are condensed in Figures 2 and 3. Expanded data can be found in the Supporting Information.

There are two principle insights to be gleaned from the results of this bottom-up study: (1) the preponderance of electricity required for the facility support equipment and (2) the impact of tool use patterns on energy consumption.

Facility support equipment—the chillers, fans, pumps, and compressors that provide services to the process equipment—consume almost 60% of the electrical power entering the MPD building, confirming findings from other studies (*9, 10, 14*). The reality that the support equipment is responsible for the majority of the fab's electrical consumption is a critical part of the explanation for why throughput has such a strong relationship with energy intensity in semiconductor manufacturing. Along with the energy required to power process tools in idle mode, the energy needed for the facility support equipment composes the base power of the fab ($\dot{W}_0$ from eq 1). It follows that the throughput versus energy intensity relationship in the top-down data in the previous section is in part a function of the predominance of support equipment.

Earlier studies have suggested that semiconductor manufacturing tools are idled at a major fraction of the power required when actually processing wafers (*6, 9*). The data gathered in this study confirm those findings. In spite of the reality that semiconductor manufacturing relies on batch processes, the electrical monitoring data from the MPD fab show a relatively steady power consumption from the process tools during and between runs (see samples in the Supporting Information, Figures S1−S4). In virtually every measurement taken during the study, the same phenomenon of high energy use during idling was present.

On a side note concerning the process tool data, it is curious that dry etching accounts for a greater portion of energy use at the MPD fab than CVD or diffusion given that the high energy intensity of CVD has been documented in the literature (*10, 15*). In justification of this result, we again turn to a process rate argument. Whereas Analog Devices' CVD tubes can run more than a hundred wafers at a time, virtually all of the dry etch steps are serial processes in which only one wafer is etched at a time. Thus, although it is true that CVD furnaces operate at very high temperatures, require vacuum pressures (in the case of LPCVD and PECVD), and use plasmas (in the case of PECVD), the much larger number of dry etch tools compared to CVD furnaces results in higher energy use by the dry etch process area.

Process Level Results and Exergy Analysis

The unifying argument of the preceding sections is that the rate of production is a key variable controlling the energy intensity of semiconductor manufacturing. Yet this argument has been made using only high-level data. We now turn to results from process analyses for insight into what is occurring at the process level that drives energy consumption at the fab level.

The task of assessing the efficiency of a process that involves the transformation of materials and energy has been a consistent challenge in sustainability science. In the ensuing section, we apply a thermodynamic approach to relate the material and energy inputs and outputs of various processes; this is done by quantifying the available potential energy (chemical, electrical, thermal, and mechanical) of the material and energy inputs and outputs (also known as exergy or availability analysis). For a more thorough description of the technique, please see refs *12, 16, and 18*. The great benefit of this analytical framework is the ability to incorporate the impact of energy *and* material flows on the efficiency of a process. Additionally, because the reference state used to define the chemical exergy of materials is that of the earth's crust and atmosphere, the degree of perfection may be thought of as a measure of the efficiency with which a process conserves the utility of natural resources.

For the purposes of this analysis, an understanding of the key summary statistic, the degree of perfection (η_P) should suffice. The degree of perfection provides a measure of the efficacy of a process in converting the input exergy, or work potential, into a useful output form. Mathematically, it is given as

$$\eta_P = \frac{B_{\text{Useful products}}}{B_{\text{Inputs}}} \tag{3}$$

where B represents aggregate physical and chemical exergy. The input exergy (B_{Inputs}) is that associated with the input materials to be processed, the exergy equivalent of the energy needed to drive the process and power auxiliary components, and the exergy of auxiliary materials which are consumed in the process but not incorporated into the final product. The useful product is the target output from a given process. For example, in one approach to PECVD deposition of silicon dioxide on a silicon wafer, silane (SiH_4) diluted with nitrogen reacts with nitrous oxide (N_2O) in the presence of a plasma. The input exergy in this illustration includes that of the reactants silane and nitrous oxide, the auxiliary gas nitrogen, and all electrical inputs. The exergy content of the silicon wafer is not included as a component of the input exergy; because it passes through the process effectively unmodified, we refer to the exergy of the wafer as transiting exergy and exclude it from the analysis. The useful output is the exergy of the silicon dioxide film that is deposited on the wafer surface.

The analysis of removal processes poses a problem because of the conflict over how to evaluate the efficiency of a process that necessarily reduces the exergy content of the input material. In processes where the objective is to effectively destroy a portion of the exergy content of an input material, we apply a metric related to the degree of perfection termed the exergetic efficiency of removal (η_R). Similar to the degree of perfection, the input exergy is defined as the exergy content of the material that is to be removed from the work piece and any additional materials or energy required to effect the removal. In the removal case, however, we identify the exergy of the material *that is to be removed* as the useful product. For example, given a silicon wafer with a silicon nitride layer on its surface, we can remove the nitride layer using sulfur hexafluoride without disturbing the silicon. The exergy of the etched silicon nitride, the sulfur hexafluoride, and any electrical inputs constitute the input exergy to the removal process. The silicon wafer (and any nitride that is not removed) passes through the process unmodified and is excluded from the analysis. The exergy removed (B_{Removed}) is defined as the input exergy content of the nitride that is to be removed. The exergetic efficiency of removal is given as the ratio between the exergy content of the material removed from the workpiece, B_{Removed}, and the exergy of the inputs, B_{Inputs}

$$\eta_R = \frac{B_{\text{Removed}}}{B_{\text{Inputs}}} \tag{4}$$

The presence of the exergy of the removed material in the numerator and denominator reflects that the removed material is both an input to the process as well as a measure of the desired process outcome (*18*).

The boundary used these analyses is given in Figure 4, where "tool-specific support equipment" refers to dedicated process pumps, RF generators, etc. and excludes facility-level support equipment such as the DI water system and the chillers. It is drawn such that electricity inputs are purely work interactions and heat is exchanged with the environment at ambient temperature and pressure. Aggregated material flows are shown with three components: (1) input materials, (2) useful output materials, and (3) waste outputs. For resource accounting purposes, these material flows are assumed to be at ambient temperature and pressure at the input and the output. Input materials to the tool-specific support equipment include nitrogen ballast used in vacuum pumps, cooling water lost in various systems, lubricants, oils, etc.; these materials contribute negligibly to the total

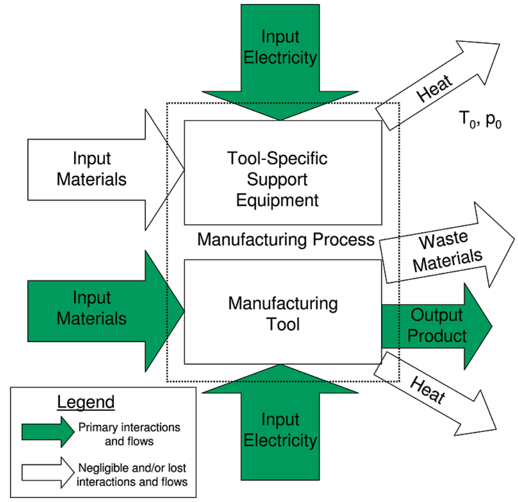

FIGURE 4. Boundary for process analyses, modeled as an open thermodynamic system with work interactions (electricity) and material flows. "Tool-specific support equipment" refers to the auxiliary equipment dedicated to individual tools and excludes facility-level support equipment.

process input exergy and are excluded. The aggregate results for dry etching and wet etching of silicon nitride and sputtering of AlCu are presented in Table 1, with the remainder given in Table S5 of the Supporting Information. In each case, the combined material and electricity input to the process is shown as well as the amount of material deposited (for sputtering) or removed (for the etch processes). The degree of perfection of other semiconductor processes are of similar magnitude to the results shown here (*10, 19*).

Perhaps the most dramatic result from the process analyses of Table 1 and the Supporting Information is how inefficient the processes are from a thermodynamic perspective; whereas the η_R and η_P of these semiconductor manufacturing processes range from 10^{-3} to 10^{-4} (and down to 10^{-6} when depositing or etching SiO_2), macroscale manufacturing processes such as conventional machining, grinding, waterjet cutting, and metal casting typically range from 0.01 to 0.75. In part, the low degree of perfection is a function of how little material is either etched or deposited during a given process. In contrast, the energy and material input is quite large. In other words, there is a disconnect between the scale of the energy and material inputs and the scale of the output; "macro" amounts of energy are being used to effect micro- and nanoscale processes.

The exergy analyses presented in Table 1 capture the energy intensity of individual processes with an additional nuance: in some cases, the exergy of auxiliary material inputs can be significant, even rivaling that of the electrical energy input (as in the case of wet etching). To be sure, many input materials for semiconductor processes have large exergy contents. Yet because those materials are often used in rather small quantities, the aggregate exergy of the inputs to most semiconductor processes is dominated by the electrical energy. More specifically, the electrical power input to a process is relatively constant during and between process runs. For example, in the PECVD deposition of silicon dioxide observed in the MPD fab, the vacuum pumps, chamber heaters, and electronics run continuously regardless of whether the PECVD tool is processing wafers. The only significant variation in power consumption occurs when the RF generator used to fire the plasma switches on, but the electrical power to run the RF generator is an incremental addition to what is already a significant base load. Because tools draw power at a fairly constant and high level, the degree of perfection and exergetic efficiency of removal become a strong function of the rate at which material is processed.

TABLE 1. Sample Process Analysis Results[a]

	inputs					outputs				
process	input	mass (g)	specific chemical exergy (kJ/g)	exergy (kJ)	total exergy in (kJ)	output	mass (g)	specific chemical exergy (kJ/g)	exergy of the output product	degree of perfection (η_P
sputtering of an AlCu film	Ar	3.43×10^{0}	2.93×10^{-1}	1.00×10^{0}						
	AlCu	2.44×10^{0}	3.24×10^{1}	7.90×10^{1}	3.00×10^{4}	AlCu film	4.98×10^{-1}	3.24×10^{1}	1.61×10^{1}	5.38×10^{-4}
	electricity			2.99×10^{4}						
									exergy of material removed (kJ)	**exergetic efficiency of removal (η_R)**
dry etching of a silicon nitride film	He	2.46×10^{-2}	7.59×10^{0}	1.86×10^{-1}						
	SF_6	2.69×10^{0}	1.93×10^{0}	5.19×10^{0}						
	Si_3N_4	3.29×10^{-2}	1.37×10^{1}	4.49×10^{-1}	1.18×10^{3}	etched Si_3N_4	3.29×10^{-2}	1.37×10^{1}	4.49×10^{-1}	3.79×10^{-4}
	electricity			1.18×10^{3}						
wet etching of a silicon nitride film	H_3PO_4	2.53×10^{2}	1.06×10^{0}	2.68×10^{2}						
	H_2O	7.24×10^{1}	5.00×10^{-2}	3.62×10^{0}						
	Si_3N_4	3.01×10^{-1}	1.37×10^{1}	4.12×10^{0}	8.02×10^{2}	etched Si_3N_4	3.01×10^{-1}	1.37×10^{1}	4.12×10^{0}	5.14×10^{-3}
	electricity			5.26×10^{2}						
waterjet machining of aluminum	H_2O	1.35×10^{2}	5.00×10^{-2}	6.75×10^{0}						
	$Fe_3Al_2(SiO_4)_3$	1.62×10^{1}	2.35×10^{-1}	3.82×10^{0}						
	Al	2.32×10^{-1}	3.30×10^{1}	7.65×10^{0}	5.31×10^{1}	removed Al	2.32×10^{-1}	3.30×10^{1}	7.65×10^{0}	1.44×10^{-1}
	electricity			3.49×10^{1}						

[a] From top: Sputtering of a 10000 Å aluminum copper film on 10 six inch wafers (serial process), dry etching of a 2000 Å silicon nitride film on 3 six inch wafers (serial process), wet etching of an 1100 Å silicon nitride film on 50 six inch wafers (batch process), and waterjet cutting of 1/4″ aluminum at 0.35in/sec and a kerf width of 0.021 in. ($Fe_3Al_2(SiO_4)_3$ is the mineral almandine garnet). Waterjet machining provided as a reference for larger-scale processes. Thermodynamic data from refs *16, 17*.

We see then at the process level that very small amounts of material are processed with large energy inputs. By extrapolating these results across the range of processes operating at the fab, the origin of the high energy intensity seen at the fab level becomes clear. This result is rather different than more conventional manufacturing processes (see waterjet machining example in Table 1). For these processes, the exergy of the input materials is more comparable to that of the input energy and the degree of perfection is generally higher.

Looking at the results of the process analyses and the preceding sections qualitatively, we see that only a fraction of the electrical inputs into these processes are used to provide the physically required minimum energy. However, a significant portion of the input energy goes to pulling a high vacuum, powering mechanical components, running electronics, and driving other indirect inputs to a given process. Even of the electrical energy that goes directly into effecting a deposition or removal process (such as that energy which is required to heat the precursor gases in chemical vapor deposition), the vast majority is not recaptured. The inefficiency in the conversion of electrical energy to a useful output and the myriad ways in which electricity is used in a process indirectly contributing to the final output are indicative of the scale mismatch between process tools and the processes themselves.

The analyses displayed in this section only attribute the standard chemical exergy content of the input materials and the exergy equivalent of the electricity input to processes in calculating the degree of perfection and exergetic efficiency of removal. If instead the analysis were expanded to include the processing steps required to produce those inputs, the calculated efficiencies would appear smaller still. For example, if the exergy value of the inputs needed to produce electricity were used instead of accounting for the electricity input as pure work, the input exergy of electricity would increase by roughly a factor of 3, using data from the United States. Using the exergy required in the production of the input materials would likely increase the input material exergy by an even greater factor (*20*). Thorough bottom-up analyses of high-purity chemical production processes are rare in the literature, and we see that as an important research need in the continued understanding of energy intensity in manufacturing processes and product lifecycles.

Acknowledgments

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Supporting Information Available

Section 1: Sample Power Measurements and Steady State Assumption Justification. Section 2: Bottom-Up Measurement Results. Section 3: Top-Down Materials Consumption. Section 4: Process Analyses. This information is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Semiconductor Industry Association (SIA). http://www.sia-online.org/cs/papers_publications/press_release_detail?pressrelease.id=1534 (accessed February 2, 2009).

(2) Department of Energy, Energy Information Administration (DOE-EIA). 2002 Energy Consumption by Manufacturers. Data Tables. Table 1.1. http://www.eia.doe.gov/emeu/mecs/mecs2002/data02/pdf/table1.1_02.pdf.

(3) *Environmental Consciousness: A Strategic Competitiveness Issue for the Electronics and Computer Industry*; Microelectronics and Computer Technology Corporation (MCC): Austin, TX, March 1993.

(4) Williams, E. D.; Ayres, R. U.; Heller, M. The 1.7 kilogram microchip: Energy and material use in the production of semiconductor devices. *Environ. Sci. Technol.* **2002**, *36*, 5504–5510.

(5) Williams, E. D. Energy intensity of computer manufacturing: Hybrid assessment combining process and economic input-output methods. *Environ. Sci. Technol.* **2004**, *38*, 6166–6174.

(6) Murphy, C. F.; Kenig, G. A.; Allen, D. T.; Laurent, J.-P.; Dyer, D. E. Development of parametric material, energy, and emission inventories for wafer fabrication in the semiconductor industry. *Environ. Sci. Technol.* **2003**, *37*, 5373–5382.

(7) Murphy, C. F. Allen D. T. *Development of Life Cycle Inventory Modules for Semiconductor Processing*. EPA Report. July 2004.

(8) Naughton, P. Measurement of conservation of energy by semiconductor manufacturing equipment and setting of targets for improvements. *Semicond. Fabtech* Q1, **2006**.

(9) Osborne, M. Making the most of energy conservation. *Semicond. Fabtech* 26th ed.; Q2, **2005**, http://www.fabtech.org/component/option,com_remository/Itemid,93/func,select/id,201/.

(10) Krishnan, N.; Boyd, S.; Somani, A.; Raoux, S.; Clark, D.; Dornfeld, D. A hybrid life cycle inventory of nano-scale semiconductor manufacturing. *Environ. Sci. Technol.* **2008**, *42*, 3069–3075.

(11) Boyd, S. B.; Horvath, A.; Dornfeld, D. Life-cycle energy demand and global warming potential of computational logic. *Environ. Sci. Technol.* **2009**, *43*, 7303–7309.

(12) Gutowski, T. G.; Branham, M. S.; Dahmus, J. B.; Jones, A. J.; Thiriez, A.; Sekulic, D. P. Thermodynamic analysis of resources used in manufacturing processes. *Environ. Sci. Technol.* **2009**, *43*, 1584–1590.

(13) Gutowski, T. G.; Dahmus, J.; Thiriez, A.; Branham, M.; Jones, A. A thermodynamic characterization of manufacturing processes. *Proc. IEEE Int. Symp. Electron. Environ.* **2007**, 137–142.

(14) Energy Efficient Cleanroom Information Site, March 24, 2000. Lawrence Berkeley National Laboratory. http://ateam.lbl.gov/cleanroom/technical.html (accessed February 23, 2007).

(15) Isaacs, J. A.; Tanwani, A.; Healy, M. L. Environmental assessment of SWNT production. *Proc. IEEE Int. Symp. Electron. Environ.* **2006**, 38–41.

(16) Szargut, J.; Morris, D. R.; Steward, F. R. *Exergy Analysis of Thermal, Chemical, and Metallurgical Processes*; Hemisphere Publishing Corporation and Springer-Verlag: New York, 1988.

(17) Pehlke, D. R. High Temperature Thermodynamics of the Silicon, Nitrogen, Silicon-Nitride System. Masters of Science in Materials Science Thesis, Massachusetts Institute of Technology, Cambridge, MA. May 1958.

(18) Gutowski, T. G. Sekulic, D. P. Thermodynamic Analysis of Manufacturing Processes. In *Thermodynamics and the Destruction of Resources*; Bakshi, B. R. Gutowski, T. G. Sekulic. D. P., Eds.; Cambridge University Press: 2010.

(19) Boyd, S.; Dornfeld, D.; Krishnan, N. Life cycle inventory of a CMOS chip. *Proc. IEEE Int. Symp. Electron. Environ.* **2006**, 253–257.

(20) Krishnan, N.; Williams, E. D.; Boyd, S. B. Case studies in energy use to realize ultra-high purities in semiconductor Manufacturing. *Proc. IEEE Int. Symp. Electron. Environ.* **2008**, 1–6.

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