

The 1.7 Kilogram Microchip: Energy and Material Use in the Production of Semiconductor Devices

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The scale of environmental impacts associated with the manufacture of microchips is characterized through analysis of material and energy inputs into processes in the production chain. The total weight of secondary fossil fuel and chemical inputs to produce and use a single 2-gram 32MB DRAM chip are estimated at 1600 g and 72 g, respectively. Use of water and elemental gases (mainly N₂) in the fabrication stage are 32 000 and 700 g per chip, respectively. The production chain yielding silicon wafers from quartz uses 160 times the energy required for typical silicon, indicating that purification to semiconductor grade materials is energy intensive. Due to its extremely low-entropy, organized structure, the materials intensity of a microchip is orders of magnitude higher than that of "traditional" goods. Future analysis of semiconductor and other low entropy high-tech goods needs to include the use of secondary materials, especially for purification.

1. Introduction

We live in the semiconductor age. Microchips have become part of everyday life, playing essential roles in ubiquitous devices such as computers, cell phones and even automobiles. A global semiconductor industry has arisen to meet the demand for microchips, a business that has grown in leaps and bounds the past few decades. Estimates place the overall economic scale of the semiconductor at \$140 billion in 2000 with an average 16% growth per year over the past few decades (1).

The environmental implications of this new industry are a matter of potential concern, especially given its substantial economic scale and high rate of growth. Microchips themselves are small, valuable and have a wide variety of applications, which naively suggests that they deliver large benefits to society with negligible environmental impact. On the other hand, the semiconductor industry uses hundreds, even thousands of chemicals, many in significant quantities and many of them toxic. Emissions of these chemicals have potential impacts on air, water and soil systems and potentially pose an occupational risk for line workers. Historical incidents of environmental impacts on soil and

water systems are discussed by Mazurek (2), and LaDou and Rohm review occupational hazards in the industry (3). Also, the industry is well-known to be intensive in its use of energy, water and materials.

It is safe to assert that there is little consensus regarding impacts of the industry. While individual firms presumably understand their own practices fairly well, publicly available environmental data and analyses of the sector are scarce. Given rapid process change and evident effort the industry is making toward environmental protection (e.g. ref 4), it is plausible to believe claims that emissions issues have been largely addressed. However, little real evidence exists to support or refute this. Also, semiconductor firms are unlikely to have a complete picture of impacts associated with the supply chain for raw materials, which could be significant. It is thus appropriate that civil society, in particular academia and NGOs, put forth a community to work toward a wider understanding of and response to the industry's environmental issues.

Materials flow analysis of the semiconductor production chain could make a valuable contribution to identifying the scale of environmental impacts and directions for further work. Materials flow analysis utilizes process material input-output data to characterize the use and emissions of materials within and between processes (5, 6). Materials flow analysis designed to characterize material use and/or environmental impacts associated a particular product or service is called life cycle assessment (7, 8). Starting with an earlier study (9), in this article we undertake materials flow analysis of the semiconductor production chain as well as a life cycle assessment of a computer memory chip.

There is a limited body of publicly available literature relevant to materials analysis of the semiconductor industry. In its life cycle assessment of a workstation, the Microelectronics and Computer Technology Corporation (MCC) published results for electricity use, water consumption and aggregate chemical wastes for production of a complete set of microchips in a computer (10). The Electronics Industry Association of Japan (EIAJ) has carried out extensive work to characterize emissions trends in the Japanese semiconductor industry and also has reviewed inputs and waste management issues (11, 12). Their yearly waste surveys cover 98% of domestic capacity and report tonnage of emissions in the aggregate categories of sludge, oil, acids, alkali, plastic, metal, ceramics and glass (12). As part of the Toxics Release Inventory (TRI) program, the U.S. Environmental Protection Agency (EPA) surveys U.S. firms annually for emission quantities of around 650 different substances, reported when the facility's annual throughput of that chemical exceeds a threshold level of 11.3 metric tons (13). This information is published along with an environmental review of process technology and pollution prevention issues for the industry (14). The United Nations Environment Program (UNEP) and the United Nations Industrial Development Organizations (UNIDO) jointly published a report on the semiconductor industry surveying waste management issues, which included detailed data on materials inputs for "generic" integrated circuit fabrication process on a 4-in. diameter wafer (15). One would hope that data from environmental reports of semiconductor manufacturers could be useful in this context. However, publicly reported data on materials and energy use is only at the level of the entire firm (or regional division), which cannot be converted to the process level without additional information.

There are many gaps in the literature; we highlight three outstanding ones. One is a lack of process data describing

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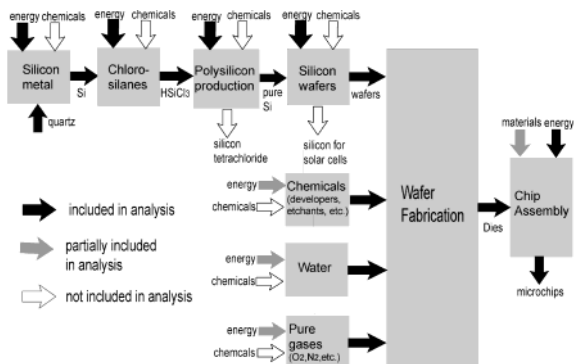


FIGURE 1. Production chain for semiconductor devices.

inputs and outputs. The UNEP/UNIDO work is the only report to quantify individual substances consumed, but specific quantities for many inputs are clearly missing. A second gap is the lack of comparison of different sources of process data. While comparison of results with those of other groups is de rigueur in the scientific community, this practice has yet to be generally adopted in reporting and analysis of process inputs/emissions. Last, there is as yet no publicly available materials/energy flow analysis or life cycle assessment addressing the production chain for microchips. We endeavor to address these three gaps. Recent process data from an anonymous industry source are presented and reviewed critically in the context of existing information. We analyze material input and outputs into industrial processes in the production chain in order to estimate total energy, fossil fuel use and aggregate consumption of chemicals in the manufacture and use of microchips.

2. Technology: Processes and Materials/Energy Use

This section overviews materials use by processes in the production chain for semiconductors. We consider the subset of processes shown in Figure 1, which includes wafer fabrication, production of silicon wafers starting from quartz, the synthesis of a subset of chemical inputs to fabrication, and the assembly/packaging stage. The precise meaning of "included" materials and energy is relevant to the life cycle assessment and is elaborated in Section 3. Excepting for the UNEP/UNIDO report, all input data described below refer to net input of material to a facility, reflecting the amount required *after* recycling some portion back into inputs.

2.1. Semiconductor Fabrication. Semiconductor fabrication, or wafer fabrication, is construction of a rectangular "die", a highly intricate set of patterned layers of doped silicon, insulators and metals that forms the functional heart of a microchip. The manufacturing processes are quite complex and we only describe materials use. Inputs to semiconductor fabrication are discussed below in terms of aggregate categories of chemicals, energy, water, elemental gases, and silicon wafers (process yields), summary results of which appear in Figure 2.

Chemicals. Fabrication processes use a wide variety of chemicals, many of them toxic, whence potential impacts of emissions on air, water, and ground systems are major environmental concerns. One important element of tackling the issue is identification of how much of what substances are used and emitted. We used five main sources of data on semiconductor chemical use and emissions. Sources of data at the process level are the UNEP/UNIDO report (15), the MCC study (10) and anonymous firm data (16). The anonymous firm data will be considered the baseline from which to perform analysis. Two sources of information at the national level are the Electronics Industry Association of Japan (EIAJ) work (11, 12) and the Toxics Release Inventory (TRI)

Inputs:		Outputs:	
Chemicals:	grams		
Dopants	.01	Fabricated wafer:	16-94 cm ²
Photolith.	14	Wastewater:	17 kg
Etchants	23	Solid Waste:	7.8 kg
Acids/bases	31	Air emissions:	-
Total	45		
Elemental gases:	grams		
(N ₂ , He, Ar, H ₂ , O ₂)	556		
Silicon wafer:	1 cm ² =		
	.16 grams		
Electricity:	1.5 kWh		
Direct fossil fuels:	1 MJ		
Water:	20 liters		

FIGURE 2. Summary input/output table for wafer fabrication (16, 21-25, 27).

in the U.S. (13). Given that nearly all chemicals used in semiconductor processing do not end up in the final product, mass balance dictates that use and emissions of chemicals should be nearly identical.

The detailed input table of the anonymous source appears in Table 1, the primary data from all other sources is in the Supporting Information section. Summary information including energy, elemental gas and water inputs appears in Figure 1, all figures are normalized to square centimeter of input silicon wafer.

We turn now to the task of comparing the different data sources, which is quite challenging given that they describe different mixes of processes from different years. Chemical use should be closely connected with the number of layers in a device, and thus could vary by orders of magnitude depending on whether one is fabricating a simple diode or a modern microprocessor. Rapid process change also suggests that material and energy use is a moving target. The Semiconductor Industry Association, Electronics Industry Association of Japan and many individual firms report large reductions in chemical emissions, and thus use, in the past decade. For example, the economic growth in the industry supplying wet chemicals is typically 8% per year as compared to the 16% growth of the semiconductor industry itself (17). These considerations must be kept in mind in the evaluation process.

The types of data presented vary considerably, comparison thus requires identifying some quantity calculable for all sources. We use aggregate chemical use and emissions per cm² of *input* wafer for this purpose. [Note that 1 cm² of input silicon corresponds to 0.16 g of silicon wafer and a functional output around 20 MB of DRAM (varies according to wafer size and yield).] For studies reporting national use or emissions, silicon input was normalized by dividing total input/emission by the national consumption of wafers for the appropriate year (18).

The relative aggregate chemical use per unit of input silicon for all data sources appears in Table 2. The results range from 9 to 610 g per cm² for aggregate chemical input and 1.2-160 g per cm² for aggregate emissions. UNEP/UNIDO and TRI sources represent the extreme ends of this spectrum, differing by a factor of 500.

We first discuss the TRI figure as it stands out as particularly low compared to others. We believe that TRI significantly undercounts emissions. One point of concern is that the TRI figure is less than 1/10 of the EIAJ value for Japanese emissions. U.S. and Japanese semiconductor industries are of comparable size and structure thus the figures should be roughly similar. Also, scaling up the consumption figures from the anonymous facility (Table 1) to the level of U.S. national consumption (using national

TABLE 1. Firm Data on Chemical Inputs to Semiconductor Fabrication per Square Centimeter of Input Wafer (16)

category	substance	input per wafer area (g/cm ²)	category	substance	input per wafer area (g/cm ²)
elemental gas	He	1.7E-01	acids/bases	HF 1 vol + NH ₄ 30 vol mixture	2.84E+00
	N ₂	4.4E+02		phosphoric acid H ₃ PO ₄ 86%	2.41E+00
	O ₂	3.0E+00		hydrofluoric acid 0.5%	3.42E+00
	Ar	1.7E+00		hydrofluoric acid 5%	4.55E-01
	H ₂	4.6E-02		hydrofluoric acid 50%	2.52E-01
deposition/dopant gases	subtotal gas:	4.5E+02	nitric acid 70%	1.19E+00	
	silane (SiH ₄)	7.8E-03	sulfuric acid 96%	7.85E+00	
	phosphine (PH ₃)	1.7E-05	hydrochloric acid 30%	2.52E+00	
	arsine (AsH ₃)	4.3E-06	ammonia 28%	7.76E-01	
	diborane (B ₂ H ₆)	4.3E-06	slurry	2.86E-01	
	dichlorosilane (SiH ₂ Cl ₂)	1.4E-03	HCl 30%	5.06E-01	
etchants	subtotal deposition/dopants:	9.3E-03	NaOH 50%	6.51E-01	
	ammonia (NH ₃)	1.2E-02	subtotal acids/bases:	2.32E+01	
	N ₂ O	7.2E-02	hydrogen peroxide 30%	4.43E+00	
	Cl ₂	4.8E-03	isopropyl alcohol	2.02E+00	
	BCl ₃	8.7E-03	tetramethylammonium hydroxide	4.31E+00	
	BF ₃	3.5E-05	methyl-3-methoxypropionate	1.48E+00	
	HBr	2.2E-03	acetone	5.54E-01	
	HCl	5.0E-03	hexamethyldisilazane	2.20E-02	
	HF	9.5E-04	hydroxyl monoethanolamine	1.42E+00	
	NF ₃	2.3E-03	subtotal photolithographic chemicals	1.42E+01	
	WF ₆	4.3E-04			
	SF ₆	6.5E-03	NaOH for neutralizing wastewater		
	C ₂ F ₆	5.0E-02		7.60E+00	
	CHF ₃	3.1E-02			
	CF ₄	3.0E-02			
	subtotal etchants	2.3E-01	total chemical input:	45.2 g/cm ²	

TABLE 2. Aggregate Chemical Use/Emissions for Wafer Fabrication (10–16)

data source	year	type	amount (g/cm ² of input silicon)	relative to firm
firm	1998	process input for memory chips	45	1
UNEP/UNIDO	1994	process input for generic 4" wafer	610	14
UNEP/UNIDO (excluding wet etchants)	1994	process input for generic 4" wafer	106	2.4
EIAJ	1996	national input for Japan	9.6	0.21
MCC	1993	process emissions for chips in 1 computer	160	4.9
EIAJ	1997	national emissions for Japan	18	0.4
TRI	1997	national emissions for U.S.	1.2	0.03

consumption of wafers), we estimate total use of sulfuric acid, hydrochloric acid, phosphoric acid, nitric acid, and ammonia to exceed TRI emissions by factors ranging from 10 to 96. Although the processes of the anonymous facility could consume more than the national average, the U.S. industry focuses on integrated circuits (as opposed to discrete,) thus one would expect them to be somewhat similar. The origins of the undercounting by TRI are not yet clear, the 11.3 ton cutoff may be so high that many toxic chemicals used in the semiconductor sector are missed by TRI.

Further analysis of the data sources provided in the Supporting Information suggests that while it is not possible to assert figures for chemical use and emissions with a high degree of confidence, most of the spread in data sources, except the TRI, can be attributed to differences in process mix and time. For the life cycle assessment we assume that the anonymous firm data indicating consumption of 45 g per cm² as the baseline. Expressed in different units, this corresponds to 280 kg of chemicals per kilogram of input silicon. It is clear from these figures that despite improvements due to technological progress, semiconductor manufacturing remains extraordinarily chemicals-intensive.

Energy. A substantial amount of electricity is consumed in semiconductor manufacturing. Examining first the structure of energy use in the fabrication stage, International Semiconductor reports that cleanroom heating, ventilation, and air conditioning are apparently major energy consuming

operations, accounting for around 50% of the total, while wafer processing tools account for 30–40% (19). A Lawrence Berkeley Laboratory website reports the following structure of energy use: 35% for process tools, 26% for ventilation, 20% for chilling, 7% for production of liquid nitrogen, and 5% for purification of water (20).

Various data sources provide information for electricity use, which represents the bulk of energy consumption. According to the 1997 National Technology Road map for Semiconductors, average electricity consumption was 1.4 kWh per square centimeter of silicon wafer processed (21). The 1993 MCC life cycle study reports that fabrication of semiconductor circuits on one 150-mm wafer requires 285 kWh of electricity, which corresponds to 1.6 kWh per square centimeter. The U.S. Census Annual Survey of Manufacturers reports yearly electricity consumption of sectors at the national level (22). Dividing the seven-year 1993–1999 electricity consumption by the total consumption of wafers yields an energy intensity of 1.52 kWh/cm². A report from Japan Electronics Industry Development Association (JEIDA) reports the 1997 electricity consumption of the Japanese industry at 1.44 kWh/cm² (23).

Considering now direct use of fossil fuels, JEIDA reports that 83% of total energy consumption in semiconductor is electricity, the remainder a mix of heavy oil, gas, LPG and kerosene (23). The U.S. Census Annual Survey of Manufacturers suggests a similar ratio of electrical to fossil fuel use (22).

In contrast to the chemicals data sources, there is reasonably close agreement among the different sources on energy consumption. We take the figure of 1.5 kWh/cm² for electricity consumption and 1 MJ/cm² for fossil fuels as a base for further calculation.

Water. The semiconductor manufacturing process also requires large amounts of high purity water. Water is generally purified on site in order to remove contaminants such as dissolved minerals, particulates, bacteria, organics, dissolved gases, and silica. A typical purification system will generally take municipal water with impurity levels in the parts per hundred or parts per thousand to the few parts per billion level (24).

A typical 6-in. wafer fabrication plant processing 40 000 wafers per month reportedly consumes 2-3 millions of gallons per day, which corresponds to 18-27 L per square centimeter of silicon (25). Two additional sources of data on water consumption were identified. The 1993 MCC study indicates that 10 600 L of water are used in fabrication of integrated circuits on one 150 mm wafer (10). This corresponds to a requirement of 58 L per cm² (3.6 million liters per kg of silicon) of wafer processed, clearly indicating a huge consumption per chip. Results of a 1996 SEMATECH survey indicated that water usage at U.S. chip manufacturing facilities varied from 5 to 29 L per square centimeter, with a typical figure being 17 L per square centimeter (24). It is not clear why the MCC study reports a significantly higher figure. As with chemicals, technological improvements between data sampling times and differences in process composition could lead to significant variations.

Elemental Gases. The use and emissions of elemental gases such as oxygen, nitrogen, or argon do not pose an environmental concern in and of themselves other than safety in handling. However, the energy associated with their separation and purification is perhaps significant. Lawrence Berkeley Laboratory reports a 7% share of facility electrical consumption accorded to on-site production of liquid nitrogen (20). According to the anonymous firm data from 2000 listed in Table 1, aggregate use of elemental gases is reported at 445 g/cm² of silicon input. The only other source for gas usage identified was the 1994 UNEP/UNIDO report, which reports a figure of 924 g per cm² (15). The factor of 2 difference is perhaps explainable by technological progress that occurred during the 6 year gap in data collection between the two sources. While it would be desirable to be able to estimate the energy cost associated these elemental gases, process data for production of highly purified gases is not available.

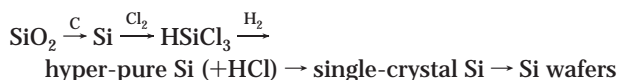
Process Yields. Achieving high yields over 100-200 complex process steps is a key challenge for the semiconductor industry. It is also important with respect to environmental performance, as the number of defective dies also significantly affects the environmental impact per output of functional product. Overall yield varies between 16 and 94% depending on the complexity and maturity of the technology (26).

For the purpose of the life cycle assessment, we take the example of a mature product: a 32MB DRAM chip fabricated on 200-mm wafers. A report from the trade magazine Semiconductor International shows an overall process efficiency of 82% (27). Considering also the wasted area around the perimeter of a wafer, 75% of input silicon wafer ends up as functional DRAM. Each 32MB DRAM chip requires an input of 1.6 cm² of wafer. Using this yield one can calculate the materials/energy requirement in production of a memory chip. For example, using a typical water and elemental gas use of 20 kg/cm² and 0.45 kg/cm² (to two significant figures), consumption to fabricate one 32MB DRAM chip is 32 000 g and 700 g respectively.

TABLE 3. Energy Use in Stages of Production of Silicon Wafers

stage	electrical energy input/kg silicon out	silicon yield (%)	data sources
quartz + carbon → silicon	13 kWh	90	(29-31)
silicon → trichlorosilane	50 kWh	90	(32, 33)
trichlorosilane → polysilicon	250 kWh	42	(32-34)
polysilicon → single crystal ingot	250 kWh	50	(32)
single-crystal ingot → silicon wafer	240 kWh	56	(32, 35)
process chain to produce wafer	2130 kWh	9.5	

2.2. Silicon Wafers. With impurities in the parts per billion, a silicon wafer is the purest product manufactured on a commercial scale. The chain of processes yielding wafers starting from raw quartz is technologically advanced and energy intensive. A simplified flow of the transformations involved is



The starting point is the reduction of quartz (mineral SiO₂) with some carbon source such as coal or charcoal in an electric furnace. The resulting "raw" silicon is typically 98.5-99.0% pure and must be purified in order to meet the demands of semiconductor fabrication. [Typical applications of "raw" silicon include use in iron alloys and in production of silicone compounds.] Powdered raw silicon is reacted with chlorine to yield trichlorosilane (HSiCl₃) (and silicon tetrachloride (SiCl₄)) that can be conveniently purified via distillation (28). The resulting trichlorosilane is at least 99.9% pure with metallic impurities in the several parts per billion (ppb) (29). In the most commonly used Siemens process, trichlorosilane is reacted with hydrogen to yield pure elemental silicon via chemical vapor deposition, the result of which is 99.9999% pure (metals <0.4 ppb) (29). This hyper-pure silicon is referred to as polysilicon in the industry. Molten polysilicon is drawn into single-crystal ingots via Czochralski or Floating Zone methods, which are sliced into wafers (26). Wafers are polished and cleaned via Chemical Mechanical Polishing.

We restrict the discussion of process input/outputs to consumption of electricity and silicon-containing intermediates. Table 3 displays the results of the data search and analysis, from which it is clear that purification and wafer preparation stages are very energy intensive. Also, significant silicon losses along the chain suggest that 9.4 kg of raw silicon are needed per kg of final wafer, increasing the total energy demand to yield wafers (29-35). The main result is that 2130 kWh per kilogram is used in the production chain for silicon wafers, some 160 times the amount used to produce "raw" silicon. Energy consumption in purification is thus much more important than in preparation of the starting crude material. Electricity consumption to produce one square cm of wafer is 0.34 kWh, nearly one-fourth that of the 1.5 kWh needed for fabrication, implying that wafer production is a significant factor in the life cycle assessment of a semiconductor device.

For detailed discussion of silicon processing technologies and input/output data, the reader is referred to refs 8 and 36.

2.3. Chemicals. As mentioned in section 2.1, some tens to hundred of chemicals are used in fabrication. It is not within the scope of this article to describe the many processes that yield these materials. However, the general issue of purification must be discussed. To prevent contamination, all ingredients to the fabrication process must be extremely

pure. For example, semiconductor grade ammonia is 99.999–99.9995% pure. Similarly, other chemicals, water, elemental gases, and quartz containers used in the industry allow impurities in the low parts per million, compared to industrial grades which run in the 90–99% range. All chemical inputs to semiconductor processes must thus go through rigorous purification processes, generally based on vacuum distillation. Distillation is well-known to be an energy intensive process, accounting for around 7% of energy consumption of the U.S. chemical industry as a whole (37). Achieving 95–99% pure grades of chemicals typically requires several megajoules per kilogram (37). On the other hand, the two-step trichlorosilane-Siemens process for silicon purification indicates that semiconductor grades may require energy in the tens or even hundreds of megajoules per kilogram.

Data on production of semiconductor grade chemicals was unavailable. While it is possible to estimate such using simulations of distillation processes, this is a task left for future work. For the time being, we indicate a lower bound for energy used in producing input chemicals by using data for standard industrial grades. The Boustead database contains energy data applying to standard grades for a subset of chemical inputs accounting to 71% of the total input mass into semiconductor production (38). These chemicals and their energy data appear in the Supporting Information. Using the inputs given in Table 1 and adjusting energy requirements according to concentration, the energy investment in producing 71% (by weight) of input chemicals is calculated at 1 MJ per cm² of input silicon. Assuming this average applies to the remaining 29%, the total energy input to produce input chemicals is 1.45 MJ per cm².

2.4. Assembly. Assembly is the encasing of rectangular segments of fabricated wafer, called dies, into a protective package with external leads (“the black box with silver legs”) (26). Plastic and ceramic packages are used; we describe only the former which in any case is by far the most common. A lead frame, made of iron–nickel or copper alloy, forms the physical skeleton of the package and also provides the external leads in the final chip.

Quantitative information on input/outputs to the assembly process is scarce. The MCC report states that energy use in the packaging stage is 0.34 kWh per cm² of silicon (10). JEIDA publishes that 30 g of packaging material per cm² of input silicon was consumed by the Japanese national industry (23). The relative aggregate consumption for lead frames and molding materials in 1995 was 61.4% and 34.1% respectively, the remainder in miscellaneous materials.

A calculation of the energy investment in the structural materials of a DRAM chip is needed for the purposes of the life cycle assessment in section 3. We make a rough estimation based on a plausible construction of a memory chip. We assume a copper lead frame and epoxy package and that these two substances make up nearly all the weight of the package. The chip itself is 2 g, thus the respective contents of copper and epoxy are 1.2 and 0.7 g respectively. According to the Boustead database, energy to produce copper and epoxy resin are 64 and 140 MJ/kg respectively (38), thus the total energy investment in producing these materials is roughly 0.17 MJ per chip. It must be emphasized though that this is a lower bound, purification of these materials for semiconductor use likely increases the energy investment significantly.

3. Energy and Materials Use in Production and Use of a Memory Chip

In this section we calculate life cycle energy and chemical use in production and use of a single 32MB microchip. A sample chip comes in a 1.0 cm × 2.7 cm rectangular epoxy resin package, containing a fabricated die with area 1.2 cm²

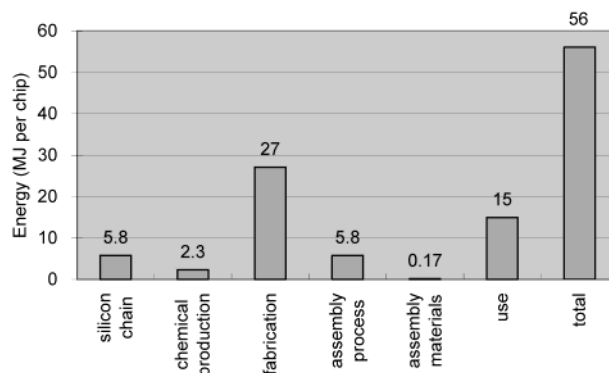


FIGURE 3. Energy consumption in production and use of a 32MB DRAM chip.

and a copper lead frame. The total packaged chip weighs 2.0 g. We use the representative process data and DRAM yields from Section 2 (e.g. 1.6 cm² of input wafer per chip). Three quantities are estimated: total energy, weight of fossil fuels used and aggregate chemical consumption. Quantities of fossil fuel use correlate accurately with carbon dioxide emissions. Aggregate chemical use is suggestive of potential impacts of pollution on local air, water, and soil systems but is not an accurate indicator of such. Actual impacts depend on the types of chemicals used, waste management practices, and local conditions, analysis beyond the scope of this article. We should mention that the definition of chemical use encompasses deposition/dopant materials, etchants, acids/bases, and photolithographic chemicals but does not include elemental gases used (due to negligible environmental impact of emissions).

The system boundary of the analysis is indicated in Figure 1. Energy use in production of chemical is marked as partially included according to the discussion of Section 2.4. Energy for water and pure gases is marked similarly because a reasonable fraction is onsite at fabrication facilities. Included materials for chip assembly are constitutive copper and epoxy only. Use of chemicals in stages other than wafer fabrication is not included.

We begin with life cycle energy use. Combining process energy consumption data per cm² of input wafer with wafer yields for 32MB DRAM chips gives the total energy use in the production stage. The use phase energy is obtained by multiplying the wattage consumption by the total time the device is used over its lifetime. Chip manufacturer product specifications report that a 32MB DRAM chip consumes about 0.32 W of electricity while in use. For total usage time, we use a scenario of typical home use: 4-year lifetime with 3-hour use per day 365 days per year. This yields 1.4 kWh energy consumption over the chip’s lifetime. We convert all Kilowatt-hours of electricity to megajoules of fossil fuels using a factor of 10.7 MJ per kWh, which assumes average global mix of electricity generating technologies (39, 40).

Figure 3 shows the final results for fossil energy consumption in different stages of chips production and use. Wafer fabrication (48%) and the use phase (27%) are the two dominant factors. Energy use to produce the main structural materials in the chip, copper and epoxy, represent a tiny share of the total (0.3%). The energy investment in a chip is thus mainly in its complex *form* rather than bulk *substance*. The third point is that the preparation of silicon wafers has a substantial share (10%). Purification of materials thus substantially affects the result. The figure for chemical production reflects the energy investment for the industrial grade of only a subset of the chemical inputs. 2.3 MJ (4%) is thus a lower bound on the contribution of chemicals and is expected to significantly increase if purification processes are accounted for.

Next the mass of fossil fuels and chemicals use is estimated. To convert electricity use into mass of fossil fuels, the global mix of electricity generation technologies and European process input/outputs to calculate a conversion factor of 320 g of fossil fuels per kWh (39, 40). For nonelectrical fuel inputs (a relatively small share), we assume an average energy content of fuels of 40MJ per kilogram. The result of the calculation is a mass input of 1200 g of fossil fuels to produce a 2-gram DRAM chip, and 440 g during the use phase. For chemicals, we multiply the aggregate input of 45 g per cm² by the yield of memory chips per input silicon, 1.6 cm² per chip. This yields a 72-gram chemical input per chip.

Postponing further interpretation until the next section, we comment on uncertainties in the above results. The contribution of wafer fabrication to energy use is probably accurate to at least one digit, as there was reasonable agreement among several sources for base data. There was only one data point for energy use in some steps in the silicon processing chain (Table 3), thus that factor is somewhat suspect. However, the largest uncertainty by far is in the energy use in producing input chemicals and packaging materials is the most uncertain, as no data was available for semiconductor grades of these materials. Thus the above results should be interpreted as a *lower bound* on the energy and secondary material use to produce a memory chip. We suggest a plausible estimate of the order of magnitude of this factor by assuming that distillation of semiconductor grade chemicals requires the same energy as for trichlorosilane, namely 50 kWh per kg (see Table 3). Presuming this is the case, energy to produce 72 g of input chemicals jumps from 1.5 MJ to 39 MJ and the secondary input of fossil fuels to manufacture a 32MB chip increases from 1200 g to 2300 g, nearly doubling the result.

4. Discussion

The lower bound of fossil fuel and chemical inputs to produce and use one 2-gram microchip are estimated at 1600 g and 72 g, respectively. Secondary materials used in production total 630 times the mass of the final product, indicating that the environmental weight of semiconductors far exceeds their small size. This intensity of use is orders of magnitude larger than that for "traditional" goods. Taking an automobile as an example, estimates of life cycle production energy for one passenger car range from 63 to 119 GJ (42). This corresponds to 1500–3000 kg of fossil fuel used, thus the ratio of embodied fossil fuels in production to the weight of the final product is around two.

Why should the secondary use of materials be so comparatively high for semiconductor devices? The fundamental explanation lies in the realm of thermodynamics. Microchips and many other high-tech goods are extremely low-entropy, highly organized forms of matter. Given that they are fabricated using relatively high entropy starting materials, it is natural to expect that a substantial investment of energy and process materials is needed for the transformation into an organized form.

At the general level, we hope these results stimulate a greater awareness of the importance of secondary materials and energy use in production of microchips and other high-tech products. For energy, the production phase becomes more relevant than the use phase, a reversal of the situation for products such as automobiles and many household appliances. The analysis also has specific implications for: the future practice of life cycle assessment and materials flow analysis, the debate on dematerialization, and environmental policy.

With respect to the practice of life cycle assessment and materials flow analysis, the result that silicon wafer production requires 160 times the energy of "raw" silicon suggests

that the issue of the *quality* of materials used requires greater attention. Purification processes are routinely overlooked in most life cycle assessments; current process databases (such as Boustead) do not even refer to the purity of materials.

Dematerialization is the idea that technological progress leads to radical reductions in the amount of materials (and/or energy) required to yield goods and services in the economy (42). The microchip is often assumed to be a prime example of dematerialization since value and utility is high while the weight of the product is negligible. As the relative use of secondary materials is much higher for the microchip than for traditional goods, our analysis suggests that this may not be the case. From a broader perspective, the results indicate the existence of a possible counterforce to dematerialization, a trend we term *secondary materialization*. Secondary materialization is the proposition that increasingly complex products require additional secondary materials and energy to realize their lower entropy form. While thermodynamic considerations dictate that this trend exists to a certain degree, it is as yet unclear if the additional secondary materials required are significant compared to savings gained through process improvement. In this work we can only assert a specific case of inter-sector secondary materialization: the semiconductor sector displays much higher economic growth and degree of secondary use of energy and materials compared to many "traditional" sectors. Further consideration of this issue is a task for future work.

The most direct application of the work to environmental policy relates to the Toxic Release Inventory (TRI). The results of section 2 showed that national emission figures from TRI are far below what one would expect based on process data. Other studies have also suggested that TRI vastly underestimates emissions (43). Though currently flawed, we believe TRI is a valuable initiative that can become a much more reliable tool given appropriate actions to fix it. We suggest three such actions. First, the TRI survey should also include the economic value of the output of the facility, with some appropriate aggregation of results so as to protect anonymity. This economic value can be used as a weighting to estimate what fraction of economic output, and thus of total production, is reflected in the survey. The second point is another addition to the survey: inclusion of purchases of TRI chemicals as inputs to the facility. Including both inputs and outputs forces a mass balance check at the facility level. Third, the academic community should analyze TRI data for various industries using process data and sector statistics in order to check reliability and provide feedback on how the system can be improved.

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Supporting Information Available

Section A, discussion comparing data sources on chemical use and emissions in semiconductor fabrication; section B, input/output data on wafer fabrication processes; section C, details of estimation of energy required for production of chemical inputs to fabrication of integrated circuits, and section D, reference tables. This material is available free of charge via the Internet at <http://pubs.acs.org>.

Note Added after ASAP Posting

This paper was released ASAP on 10/25/02 with a mismatch between data in the text and data in the table. The third paragraph of Section 3 was updated, and the last sentence of the Acknowledgments was added. The correct version was posted 11/14/02.

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