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Environmental impacts of microchip manufacture

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Abstract

Environmental impacts associated with the manufacture of semiconductor devices are characterized from two perspectives: a qualitative survey of key issues and quantitative analysis of energy and entropy associated with the processes in the production chain. The main issues of environmental concern are emissions from fabs, health effects on line workers and high energy and material use. Results of analysis of material use in the production chain suggest that total weight of secondary fossil fuel and chemical inputs to produce and use a single 2-g 32MB DRAM chip are 1600 and 72 g, respectively. Secondary inputs of fossil fuels to manufacture a chip total 600 times its weight, high compared to a factor of 1–2 for an automobile or refrigerator. Due to its extremely low-entropy, organized structure, the materials intensity of a microchip is orders of magnitude higher than that of ‘‘traditional’’ goods.

Keywords: Semiconductor device; Microchip; Life cycle assessment; Energy; Chemical use

1. Introduction

Since the creation of the first semiconductor transistor in 1947 and the first integrated circuit in 1959, semiconductor devices have come to play a fundamental role in modern economies and societies. A substantial industry has developed to meet the demand for these now ubiquitous devices. World production of semiconductors was valued at US$150 billion in 1999, with average yearly growth 13% per year over the last two decades [1]. In addition to high growth, the industry has been defined by rapid and sustained technological improvement.

Given the scale and continued rapid growth of the semiconductor industry, it is natural that concern should arise over possible environmental impacts associated with manufacture. 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 as well as posing an occupational risk for line workers. Certain substances used by the industry are potent gases contributing to global warming and ozone depletion. There are also secondary environmental impacts associated with supplying the main raw materials for the industry: chemicals, energy, water and silicon.

2. Survey of environmental impacts of semiconductor manufacture

The different categories of potential environmental impacts associated with semiconductor manufacture are summarized in Table 1 and discussed in greater detail below.

2.1. Chemical emissions

There are a number of cases from the 1980s where emissions from the semiconductor industry contaminated water supplies. The main source of these emissions was from accidental leakage of chemicals from storage tanks. The earliest and most famous case occurred in Silicon Valley, in which 15,000 l of 1,1,1-trichloroethane (an organic solvent) leaked from the storage drums of Fairchild Semiconductor from 1977 to 1981, entering local water supplies [2]. An epidemiological study carried out by local authorities indicated a noticeable rise in miscarriages and birth defects in the affected areas [3]. A separate study showed a correlation between exposure to 1,1,1-trichloroethane and cardiac abnormalities in rats [4]. Citizens filed a class-action lawsuit, and in 1986, Fairchild, IBM, and the local water company paid an undisclosed multimillion-

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Table 1
Overview of potential environmental impacts in integrated circuit manufacture

Impact category	Description	Example
Chemical emissions [3–5]	Routine or accidental leakage of toxic substance	Leakage of 1,1,1 trichloroethane in silicon valley 1977–1981.
Worker health [6–11]	Long-term health effect due to chemical exposure	Lawsuits filed by workers against IBM and National Semiconductor claiming birth defects and increased cancers.
High materials intensity [12–14]	Energy, chemicals and water used in fabrication or producing supplies	Study showing that 56 MJ (1.7 kg) of fossil fuels are used to produce and use one 32MB DRAM chip [14].

dollar settlement to 530 residents. Contamination cases (without the lawsuits) have also cropped up in Japan. Groundwater near the electronics plants of Toshiba in Kimutsu and Mitsubishi in Kumamoto were found to contain concentrations of tetrachloroethylene and trichloroethylene far exceeding regulated standards [5]. There is as yet no evidence, however, that these leakages resulted in damage to human health.

The industry has made significant efforts to reduce environmental impacts through chemical substitution, reduction of use, and improved treatment and storage technologies. At least in the United States, obvious contamination cases like those in the 1980s did not re-appear in the news of the 1990s—a sign that the situation has probably improved. As the amount of publicly available data is scarce, however, it is difficult to accurately judge the current situation. It is also worth considering that although production of semiconductors was until recent years dominated by the industrialized world, production in East Asia, especially in Taiwan and China, has dramatically increased. Production is, to a large degree, under the control of multinationals that, hopefully, implement waste treatment systems on a comparable level as practiced in the industrialized world. There is almost no information available, however, regarding the environmental practices of subsidiaries of multinationals or local firms in the industrializing world.

2.2. Health of semiconductor workers

The occupational health and safety of workers on fabrication lines is of particular concern. Because semiconductor production is a light manufacturing industry, the worker illness and injuries that occur day-to-day are not as severe as in heavy industries. The main health concern for the industry is whether long-term chemical exposure increases rates of birth defects and cancer. The extent of risk to workers is still unclear; connections between long-term exposure and illness are notoriously difficult to prove (or disprove), and this is especially true for the semiconductor industry, due to the complexity of its chemical mixes and frequent changes in processes. Epidemiological evidence points to potential negative effects on reproductive health: three studies indicated that female fabrication workers displayed an elevated incidence of miscarriages [6–8]. This increased miscarriage rate was correlated, though not conclusively, with exposure to ethylene glycol compounds

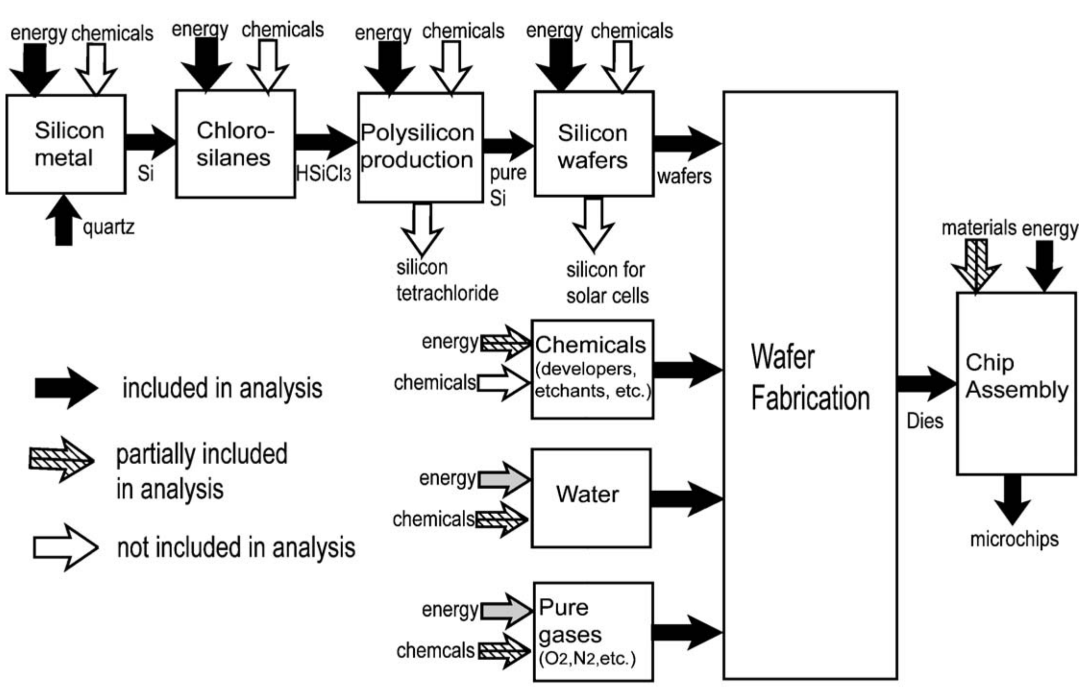

Fig. 1. Network of manufacturing processes in chip manufacturing.

(used as a photoresist solvent). Many firms reportedly stopped using these chemicals as a result of these studies.

Elevated miscarriage rates are considered a warning signal of possible elevated rates of birth defects and cancers. IBM and National Semiconductor have been facing a barrage of lawsuits from former workers claiming that chemical exposure led to birth defects or cancer. Most cases are still pending, but those completed were settled out of court for undisclosed compensation and no admission of guilt [9]. There is no scientific evidence either supporting or denying workers' claims. Only one publicly available epidemiological study investigating birth defects and cancers in the semiconductor industry currently exists. This study, carried out by health authorities in the United Kingdom, found that cancer rates for workers at a Scottish plant were comparable to the average population, though there were noticeable distinctions in the patterns of cancer that developed. Plant workers showed higher incidences of lung, stomach, breast, and brain cancer. This work has been criticized, however, due to its small sample size (71 deaths) and lack of distinction made between different work duties at the plant [10]. There has been a long-standing need for a serious study of cancer and birth defects in the semiconductor industry, but so far firms and governments have shown little initiative to carry out such work [11].

2.3. Energy and material use

The semiconductor industry is materials-intensive, an issue that is explored on a per-chip basis on in later sections. It is also important to consider the use of perfluorocarbons (PFCs) when considering the contribution of the sector to global warming. PFCs (such as CF_4 and C_2F_6) are used in etching processes and are potent greenhouse gases. According to 1993 estimates by SEMATECH, an international research consortium of the semiconductor industry, the global warming impact (in carbon dioxide equivalent) of PFC emissions in manufacturing is of a similar order of magnitude to the global warming impact of electricity use by the industry [12]. The industry has been making efforts to phase out PFC use and, while thus far unquantified, it is plausible that emissions are declining.

The consumption of water in semiconductor fabrication is also significant (32,000 l per 32MB DRAM chip). The extent to which this places burdens on water supplies depends on local conditions. A recent drought in Taiwan pitted high-tech firms and farmers against one another in a competition for limited water resources [13].

Table 2
Inputs to semiconductor fabrication [14]

Material	Description	Amount per memory chip (1.6 cm^2 input silicon wafer)
Silicon wafer		0.25 g
Chemicals	Dopants	0.016 g
	Photolithography	22 g
	Etchants	0.37 g
	Acids/bases	50 g
	Total chemicals	72 g
Elemental gases	N_2, O_2, H_2, He, Ar	700 g
Energy	Electricity	2.9 kW h
	Direct fossil fuels	1.6 MJ
	Embodied fossil fuel	970 g
Water		32 l

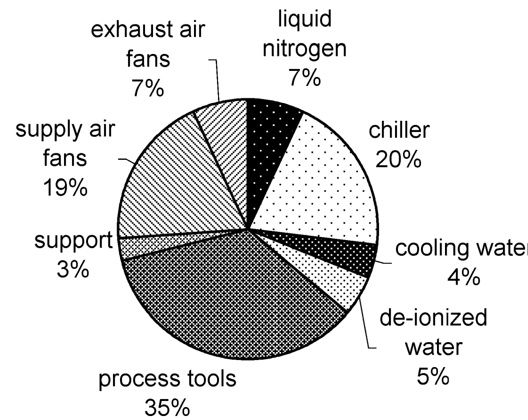

Fig. 2. Breakdown of electricity use in semiconductor fabrication facilities [15].

3. Energy and materials used in microchip fabrication

Fig. 1 shows a simplified diagram of the network of processes involved in manufacturing microchips. Chip fabrication lies at the heart of this network, it is a process that uses considerable amounts of chemicals, water, and energy. Quantitative data for inputs of silicon, aggregate chemicals, fossil fuels, and water are shown in Table 2 [14]. Some tens to hundreds of chemicals are used; detailed breakdowns showing use of individual chemicals can be found in previous work of the author and collaborators [12,14]. "Embodied fossil fuel" reflects both direct consumption in processes and indirect use to produce the electricity purchased for chip production. The fossil fuels required

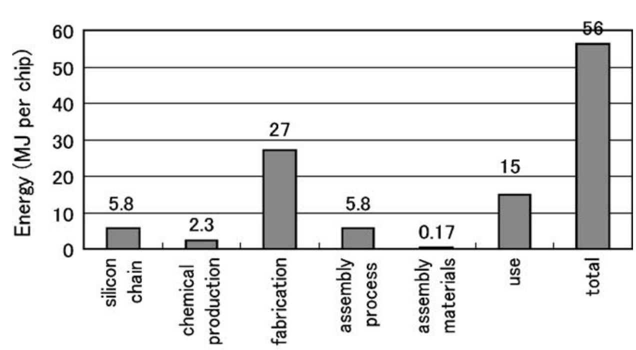

Fig. 3. Energy use in different phases of life cycle of 32MB DRAM chip [14].

per kilowatt-hour (kW h) is taken at 320 g of fossil fuel per kW h, a figure that reflects the global mix of energy technologies. The average energy density of directly consumed fossil fuels is assumed to be 40 megajoules per kilogram (MJ/kg). Fig. 2 shows a breakdown of electricity use in an average of 12 fabrication facilities [15].

4. Energy, fossil fuel and chemical use in microchip production chain

The total energy needed to produce a single microchip can be estimated by adding together the contributions of the different processes in Fig. 1. The results of such an analysis for a single 32MB DRAM chip are shown in Fig. 3 [14], the total energy to produce one chip is 56 MJ. While detailed data were used to estimate energy to produce silicon wafers, none was available for purification of semiconductor-grade chemicals. Thus, the 2.3 MJ for chemicals represents the energy needed to produce conventional industrial grade chemicals, a lower bound on the true figure. This is expected to significantly increase if chemical purification processes are accounted for. The use phase energy is obtained by multiplying the wattage consumption by the total time the device is used over its lifetime. A 32MB DRAM chip consumes about 0.3 W of electricity, which yields 0.88 kW h energy consumption over a 4-year lifetime. Kilowatt-hours of electricity are converted to mega joules of fossil fuels consumed using a factor of 10.7 kW h/MJ.

Wafer fabrication (48%) and the use phase (27%) are the two dominant factors in the life cycle. Energy use to produce the main structural materials in the chip, aluminum and epoxy, represent a tiny share of the total (.3%). The energy investment in a chip is thus mainly in its complex *form* rather than its 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 estimated mass of fossil fuel and chemical inputs needed to produce and use one 2-g microchip are 1670 and 72 g, respectively. Fossil fuels used in production total 600 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, as is indicated in Table 3.

Table 3
Comparison of energy used to manufacture and mass of different products

Product	Total fossil fuels (coal, oil, gas) used in manufacture (kg)	Mass of product (kg)	Fossil fuels used for manufacture/ mass of product
32MB DRAM chip	1.2	0.002	600
Passenger automobile	1000	1200	0.83
Refrigerator	53	35	1.5

5. Entropy analysis

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.

Purifying water and nitrogen accounts for 5% and 7% of fabrication facility electricity use, respectively [15]. Production of silicon wafers is some 160 times more energy intensive per kilogram than the usual industrial grade [14]. These data indicate that the need to purify input materials is an important issue to clarify for explaining energy use. One possibility is that energy use is driven by the entropy difference between crude and high-grade forms. To explore this idea, the entropy change associated with purifying tap water to semiconductor grade is estimated. Using the formula for entropy of mixing of a binary substance

$$\Delta S = -R[(1-x)\ln(1-x) + x\ln x],$$

the entropy shift associated with water of 100 ppm purity versus 1 ppb is estimated at 17 J/kg at room temperature. This is a factor 20 less than the 420 J/kg required according to process data, the difference between entropy change and energy use is far larger considering nitrogen and silicon wafers. The magnitude of entropy change alone does not explain the high energy use. An alternative possibility is that the *efficiency* of entropy reduction *decreases* with increasing purity, asymptotically approaching zero the nearer one gets to perfect purity. For temperature, this type of behavior is displayed in the third law of thermodynamics, which states that zero temperature cannot be attained in a finite number of steps. Thermodynamic-style arguments can be used to suggest that a similar phenomenon holds for purity as well. First, postulate that it is impossible to maintain a given macroscopic system to contain only one species of particle. This is supported by the observation that at fundamental level all substances react to a certain degree, thus maintaining perfect purity requires an absolutely perfect vacuum, presumably impossible. From this it follows that one cannot design a process that will remove all impurities from a macroscopic quantity of substrate. Since the fraction of impurities removed in one step must be less than one, it is clear that attaining higher purities requires applying a given process in increasing number of times. Different separation techniques (such as distillation or reverse osmosis) will presumably have distinct curves for energy use to achieve a given level of purity, but all should display asymptotically increasing energy as zero purity is approached.

Cleanroom use (ventilation, heating, cooling) accounts for 46% of electricity consumption in fabrication facilities [15]. This suggests that in addition to purification of input materials, the need to create low-entropy environments when combining materials is also important in understanding energy consumption. It is conceivable that the reduction in entropy associated with the mesoscopic order in a microchip could account for this energy use. One can test this hypothesis by using the fundamental definition of entropy

$$S = k \ln W, \quad W = \text{number of states}$$

and a simple checkerboard model. There are roughly 3 million configurations for a microchip die 1×2 cm, manufactured with 1.1 μm feature-size technology. This results in an entropy of 6.2×10^{-20} J at room temperature associated with the mesoscopic order of a fabricated die, many orders of magnitude lower than energies used in fabrication. The magnitude of entropy change in the final product thus does not explain energy use in manufacturing. A theoretical explanation connecting energy use and need for low-entropy environments is beyond the scope of this article, it is however worth observing that present cleanrooms, which are designed to accommodate workers, have a physical volume many orders of magnitude larger than the materials involved. Automation of fabrication facilities may thus be one promising avenue to pursue with regards energy efficiency. Further work is needed to understand how entropy considerations relate in practice to energy and material use in manufacturing.

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