Life cycle impact assessment of the DRAM chip industry in Taiwan

C. H. Liu[1], S. J. Lin[1] & C. Lewis[2]
[1]Department of Environmental Engineering, National Cheng Kung University, Taiwan, Republic of China
[2]Department of Resources Engineering, National Cheng Kung University, Taiwan, Republic of China

Abstract

Semiconductor manufacturing has played an important role in the macro-economy of high technology industries in Taiwan. It also has an advantageous position in the global semiconductor industry's value chain. Despite this industry's prominence, environmental concerns include emissions from factories, health effects on workers and high energy and material consumption. The purpose of this study is to analyze the environmental impacts of the semiconductor industry by using life cycle assessment (LCA). The LCA software SimaPro 5.1, including Eco-indicator 99 and EPS2000, was utilized to evaluate the environmental impacts caused by a DRAM manufacturing industry. In addition, results from these two methods were compared. From results of this study we find that the environmental impact was mainly from the photolithography process, followed by the etching, thin film, diffusion and CMP processes. As a whole, the most significant impacts are summer smog, depletion of energy and resources, heavy metals pollution and acidification. Furthermore, the damages from such processes are mainly caused by high energy and resource consumption of the semiconductor industry. Though the results from Eco-indicator 99 and EPS2000 have slightly different impact values in the characterization result, the overall results of these two methods are very consistent in the distribution trends and level of impact endpoints.
Keywords: life cycle assessment, semiconductor industry, DRAM, environmental impact, Eco-indicator 99, EPS2000.

1 Introduction

The memory chip manufacturing industry has been developing in Taiwan for the last 20 years and has become the country's most significant export industry. It not only promotes advancement of high-tech human resources and employment opportunities, but it also produces considerable overall GDP growth and significant industrial linkages in Taiwan's economic development. In recent years, the memory chip manufacturers in Taiwan have established several 12-inch (300mm) wafer fabrication facilities. However, during the product production, it uses many kinds of acid solutions, organic solvents and toxic gases. Furthermore, it discharges organic/inorganic waste water, gas, solvents and sludge that cause a huge amount of pollution. To be socially responsible, the memory chip manufacturing process must successfully implement environmental management from traditional end-pipe treatment to raw materials substitution, through process optimization and so on. At present, the memory chip manufacturers have not established a bad environmental, safety and health (ESH) performance record in Taiwan, but it is important for the industry to continue their endeavors in these areas. As Life Cycle Assessment (LCA) increase in popularity, some private sectors are providing more of their annual budgets to conduct LCA related studies. There are numerous applications of LCA like identification of product improvement, decision-making, evaluation of product's environmental performance, and market claims. In addition, application of LCA not only contributes to identifying the environmental issues associated with the product system studied, but also with environmental issues in general (Baumann and Rydberg [1]). The semiconductor industry in Taiwan is seeing a move towards LCA, which is the idea that the environmental impacts of a manufacturing process should be evaluated across all stages of its life-cycle. Moreover, given the complexity of processes and the rapid rate of change, it is essential to develop LCA tools and studies that can be adapted rapidly with changes in technology, and that can account for absent or inconsistent data (Krishnan et al [2]). However, a sustainable mechanism of data sharing and maintenance in Taiwan has not been established, and life cycle impact assessment methodology development is still in its infant stage. A number of LCA studies have been conducted recently with a focus on semiconductor fabrication issues (Taiariol et al. [3], Schischke et al [4], Murphy et al. [5], Plepys [6], Williams [7]). Many results indicate that large amounts of energy, chemicals and water are consumed throughout the life cycle of semiconductor devices, and the production stage appears to be particularly resource intensive. According to some estimates, up to three times more energy is consumed in semiconductor fabrication than in the use stage. The focus of this paper is to evaluate the environmental impacts of the Dynamic Random Access Memory (DRAM) fabrication in Taiwan. We analyzed energy and chemical use in the production chain for semiconductor devices. The LCA software SimaPro 5.1, including Eco-indicator 99 and EPS2000, was utilized to evaluate the potential environmental impacts and damage. Results from these two methods were then compared. We hope the findings can provide a reference for the product design and the pollution improvement of the integrated circuit industry and relevant organizations in Taiwan.

2 Analytical systems

2.1 Scope

The scope (Fig. 1) of the current study is limited to the unit processes associated with DRAM fabrication, and processes such as assembly and packaging are not within the system boundaries. The production of supplies and off-site disposal are also not the subjects of this study. While different facilities may have slightly different groupings, the processes to be considered in the analysis are diffusion, etching, photolithography, thin film and chemical-mechanical polishing (CMP). In this system, the raw materials and energy used to produce the DRAM chip, as well as emissions to air, water and land are the major components.

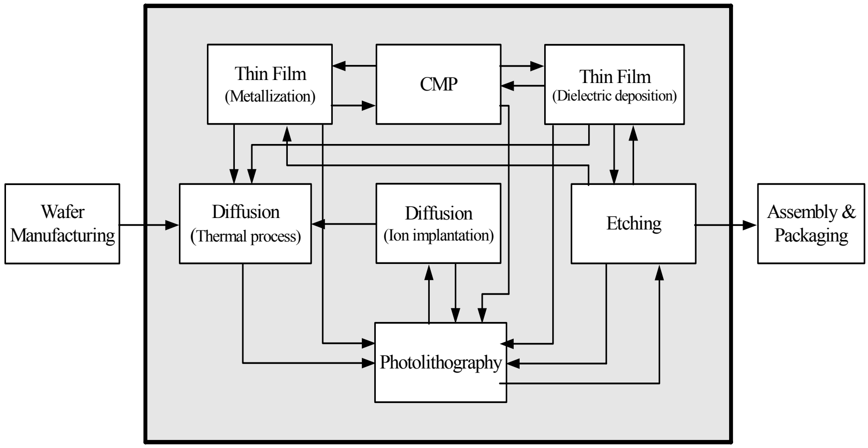

Figure 1: System boundary for DRAM fabrication.

2.2 Functional unit

The functional unit defined as one producing 100,000 wafers in the DRAM fabrication process is used as the benchmark. All energy and materials which are transported into the system, as well as discharge of environment pollutants, are calculated under the load of this functional unit.

2.3 Inventory

The inventory data are generated from questionnaires of a well-known semiconductor industry that passed the ISO 14000 standard in Taiwan. The energy and material flows of input and output within the system are carefully inventoried. The top-down approach, where information is gathered at the factory level and then disaggregated to the unit process level, is used in this study. However, some factory-level data may be hard to disaggregate and assign to individual unit processes, and are limited due to confidentiality. This study makes the following assumptions:

1. After data collection of some factory-level pollutants, it is assumed that the amount of each unit process's water consumption is used as reference base to distribute pollutants into each process.
2. Because of the limitation of data, we use the sum of electricity and the total amounts of oil consumption. We distribute the energy consumption into each process according to the number of each unit process's equipment after consulting experienced engineers.
3. Regarding the electrical level chemicals like photo-resistive liquids, slurries, developers etc., the Material Safety Data Sheets (MSDS) refer to main components and weight percent, and we calculated the weight proportion by mass balance from chemical equations.

In order to ensure the quality of the data, the information gathered was verified by the Center for Environmental Safety and Health Technology Development (CESH) of the Industrial Technology Research Institute (ITRI) in Taiwan. For some of the LCI values, data was compared from more than one source to reduce the uncertainty from data inventory.

3 Comparison procedures

A fundamental difference between these two LCIA methods is that Eco-indicator 99 is a damage-oriented approach to impact assessment, as opposed to EPS 2000 is a monetary- oriented approach. Since two methods focus on different aspects and give few results which can be compared, the difference in approach to impact assessment makes it difficult to perform a meaningful comparison based on the final scores. The main focus of this paper is thus the quantitative comparison and the qualitative inferences of the Eco-indicator 99 and EPS 2000 methods performed on the characterized indicator scores and on the damage assessment scores.

4 Results and discussion

This study evaluates the environmental impacts of DRAM fabrication in Taiwan by two LCIA methods (Eco-indicator 99 and EPS 2000). Firstly, in the "characterization" step, the results are expressed in Fig. 2 and Fig. 3. The main outcomes and differences from the synthesis comparison are as follows:

- No matter which method is chosen, the environmental impacts of the CMP process is the lower.
- For the Eco-indicator 99 "respiration organics" and EPS 2000 "life expectancy" categories, the photolithography process has a large contribution because of discharging massive VOC gases.

- For the Eco-indicator 99 “ozone layer” category, the results indicate that the etching process is the main source to produce environmental impacts, and the proportion is more than 50%.
- According to the result of Eco-indicator 99, the arsenic ion air pollutant discharged by the diffusion process is the most important source of cancer risk from the DRAM fabrication.
- From an environmental ecology viewpoint, the result from EPS 2000 reveals that the diffusion, etching and thin film processes have specific impacts on the natural ecosystem; it is therefore essential to make pollution prevention as complete as possible.

The “damage assessment” step exists in both the Eco-indicator 99 and EPS 2000 methods. The former is divided into three damage categories – “human health”, “ecosystem quality” and “resources”, and the latter is divided into “human health”, “ecosystem production capacity”, “abiotic stock resource” and “biodiversity”. The results are described as follows.

- According to the results of damage categories like Eco-indicator 99 “resources” and EPS 2000 “abiotic stock resource”, the photolithography and etching processes consume more resources and energy during the DRAM fabrication.
- For Eco-indicator 99’s three damage categories, the environmental impact of “resources” is larger than “human health” and “ecosystem quality”. This fully demonstrates that the IC manufacturing industry is a high energy depletion and high water consumption industry.
- In the “human health” topic, the diffusion and etching processes were evaluated by Eco-indicator 99 as the main impact sources, and the total impact value amounts to 68.2%. In the EPS 2000, because of the environmental impact from VOC was classified into “life expectancy” in this study, the photolithography process has the largest environmental impact, and it reached 47.5%.
- The environmental categories like Eco-indicator 99 “ecosystem quality”, EPS 2000 “ecosystem production capacity” and “biodiversity” all belong to the ecological environment correlation category. Results show that if the company has to reduce the ecology damage level from the DRAM production, it should consider the improvement of the diffusion, etching and thin film processes as a first priority, because the total percentage of three processes is more than 80%.

Only the Eco-indicator 99 method has a “normalization” step. The main environmental impact is resource consumption (Table 1). The photolithography process is the major contributor to main environmental impact scores, following by the etching, thin film, diffusion and CMP processes.

The “weighting” and “single score” steps also exist in both methods. When normalization values are multiplied by the weighting factors, the results show that the “resources use” obtains a greater proportion than other kinds of

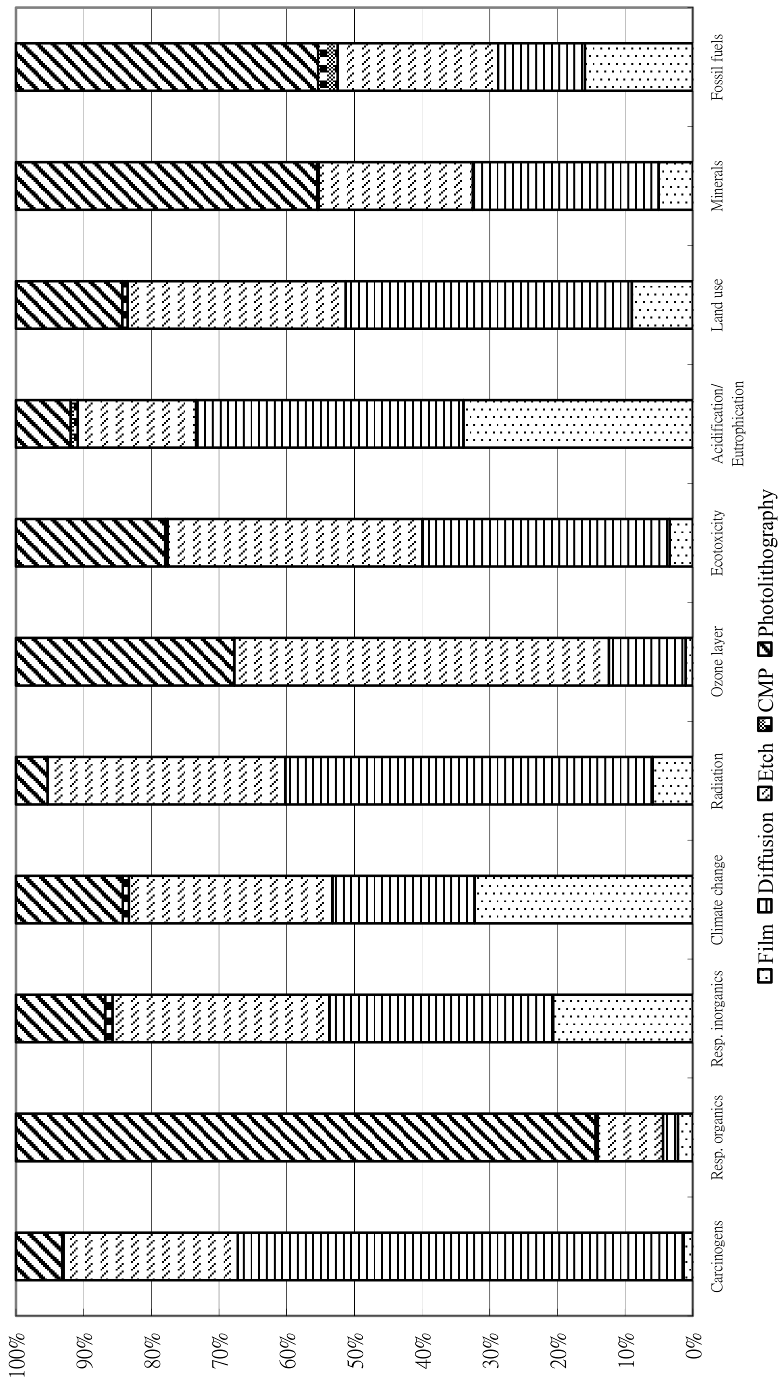

Figure 2: Characterization results of DRAM by Eco-Indicator 99 method.

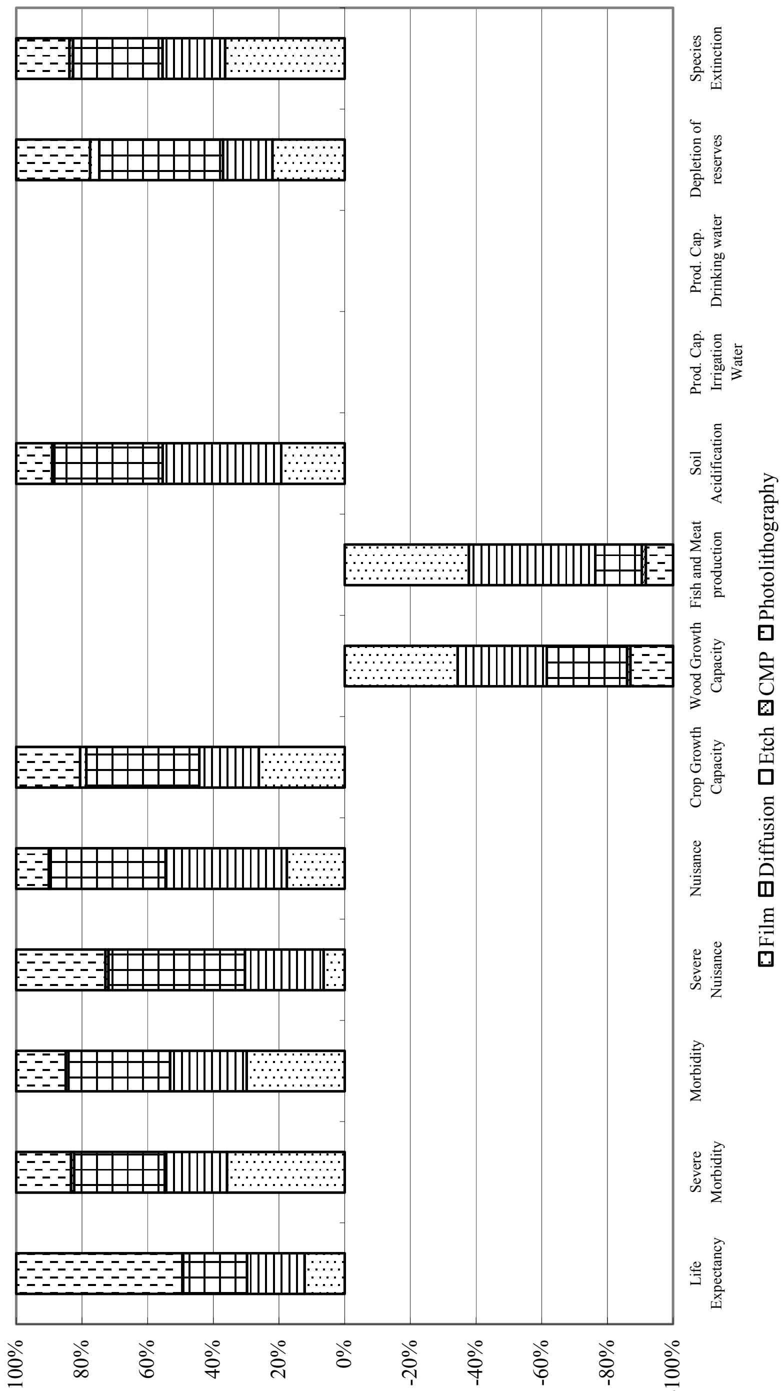

Figure 3: Characterization results of DRAM by EPS 2000 method.

Table 1: Normalization results of DRAM chip by Eco-Indicator 99 method.

	Human Health	Ecosystem Quality	Resource consumption
Unit	Pt	Pt	Pt
All Processes	86.7	14.3	815
Thin Film	14.8	3.14	130
Diffusion	34.7	5.77	105
Etching	25.2	3.6	193
CMP	0.7	0.12	23.8
Photolithography	11.3	1.86	364

environmental impacts. If we can improve the waste water recycling percentage, enforce the energy conservation measures and reduce the resource consumption, it might moderately reduce the environmental impacts of DRAM fabrication. Results (Table 2) show that no matter which method is used, the "photolithography" process has the most significant environmental impacts in all production processes. Furthermore, the "chemical mechanism polishing" process has the lowest environmental impacts of all production processes.

Table 2: Single scores of various processes in two LCIA methods.

	Eco-indicator 99	EPS 2000
Unit	Pt	Pt
All Processes	276,210	1,120,000
Thin Film	44,700 (16.20%)	208,000 (18.57%)
Diffusion	44,100 (15.97%)	183,000 (16.34%)
Etching	67,000 (24.26%)	340,000 (30.36%)
CMP	7,410 (2.68%)	19,600 (1.75%)
Photolithography	113,000 (40.91%)	371,000 (33.13%)

5 Conclusion

This study compares two LCIA methods and evaluates the environmental impacts of the DRAM production in Taiwan. The application of the LCA approach shows promising results in terms of providing an overview of the environmental impacts of the DRAM chip manufacturing processes.

Although Eco-indicator 99 and EPS 2000 methods include different impact categories and involve different view points, the comparison reveals that these two methods yield similar results for DRAM chip production processes. The photolithography process produced the most serious environmental impact scores, following by the etching, film, diffusion and CMP processes. Among the three damage categories of the Eco-indicator 99 method, the normalized results show that the major potential environmental damage from DRAM chip production is resource consumption, rather than human health and ecosystem quality. It deserves to be mentioned that the extensive use of special chemicals in the DRAM chip industry presents a major challenge to analysis, because their identities are confidential. Most industries refuse to disclose the composition and amounts of certain chemicals, in order to maintain a competitive advantage. Hence, further improvements of this paper are necessary to deal with these chemicals and energy consumption which can't be investigated clearly at present. Additionally, techniques to deal with uncertainty issues relating to the available data will also need more discussion.

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