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Life cycle assessment of high-technology buildings: Energy consumption and associated environmental impacts of wafer fabrication plants

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ABSTRACT

Effective environmental control and energy efficiency in high-technology buildings have become an important subject of investigations across continents since the last decades. This study aims to quantify energy use and associated environmental impact of four high-technology buildings for wafer fabrication in a subtropical region of Asia using life cycle assessment techniques. Wafer fabrication process and its energy and steam consumption were associated with "summer smog," "heavy metals," and "acidification potential" on the environment. All fabs used natural gas, diesel oil, and steam, which together accounted for about 5% of the total energy consumption. Two metrics – production efficiency index (PEI) and the electricity utilization index (EUI) were used to characterize and normalize environmental impact of each of the four high-technology buildings within which dynamic random access memory (DRAM) wafers were manufactured. The GHG emissions in PEI and EUI have declined from 601 g to 367 g (by 39%) and from 28.9 g to 13.7 g (by 53%), respectively, between 1999 and 2007. Energy intensity per unit area of wafer production has increased from 195 to 268 associated with a 37% increase in emission rate of CO_2-equivalent greenhouse gas (GHG) from 195 kg to 268 kg (by 73 kg) per unit area of wafers produced.

1. Introduction

Effective environmental control and energy efficiency in high-technology buildings have become an important subject of investigations across continents since the last decades [1]. Past studies addressed effectiveness of environmental control within high-technology buildings for various applications and cleanliness grades (list five refs on simulations/experiments [2]). Some studies characterized operational energy use and savings potentials at component, system, or plant level [3–5]. Energy use for the operation of high-technology buildings has been found to be highly intensive compared to commercial buildings, and is an expected cause for intensive emissions of greenhouse gas (GHG) because non-renewable energy source was typically used to generate power supplied to them.

In order to understand environmental impact of energy end use in buildings, life cycle assessment (LCA) focusing on source analysis is useful to quantify the impact on environment, health, or societal systems. For example, LCA can be used to compare environmental impacts of two or more operational scenarios that perform the same function.

Large amounts of energy, chemicals, and water are consumed throughout the life cycle of semiconductor devices; in particular, the production stage appears to be highly resource-intensive. In recent years, a number of LCA studies have been conducted on semiconductor fabrication issues [6–14].

Liu et al. [15] indicated that major environmental concerns of producing resource-intensive high-technology products were non-renewable energy consumption and GHG emissions (e.g., CO_2, PFC). They applied Eco-indicator 95 and IMPACT 2002+ (refs) to assess summer smog and respiratory inorganics, and suggested that PFC substitutions and electricity saving were effective ways to decrease environmental impacts of DRAM fabrication. Williams et al. [14,16] characterized environmental impacts associated with the production of semiconductor devices from two perspectives: a qualitative survey of key issues and quantitative analysis of energy and entropy associated with processes in the production chain. The total weight of secondary fossil fuels and chemical input required to produce and use a single 2 g 32 MB memory chip in high-technology buildings was estimated to be 1600 g and 72 g, respectively.

In emerging economies, high-technology buildings are increasingly built over the last decades, which are normally operated on the basis of 24 h by 7 days throughout the year. In subtropical

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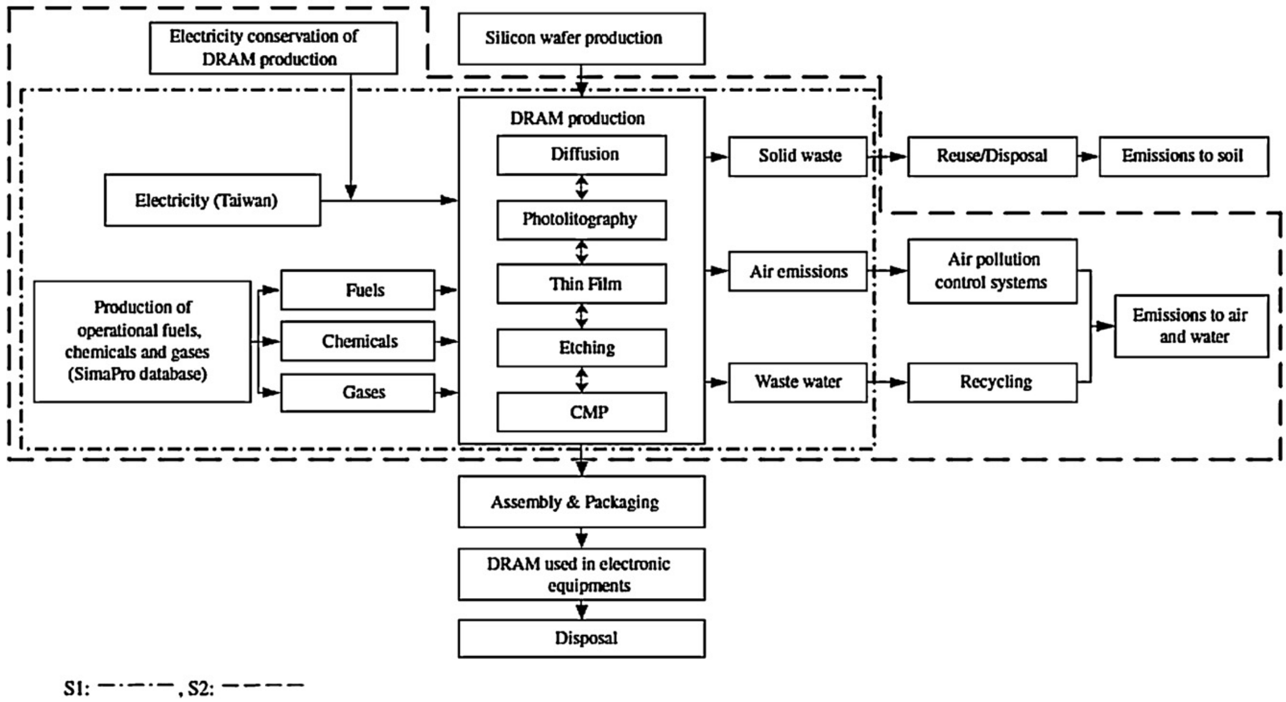

Fig. 1. Scope and boundary of analysis [16].

region of Taiwan, foundries and memory manufacturing dominates its integrated circuit (IC) business. For example, memory products accounted for over 40% of total IC manufacturing revenue in 2006, while dynamic random access memory (DRAM) wafers accounted for more than 90% of all memory products [15,16]. With increasing demand for larger memories in mobile and hand-held devices, energy demand and associated environmental impacts for DRAM fabrication has become an issue of growing interests.

The objective of this paper is to advance the understanding of environmental impacts associated with DRAM fabrication and energy use in high-technology buildings, through performing evaluations of environmental impacts of energy consumption for DRAM production in four high-technology buildings in a subtropical region by using LCA method.

2. Methodology

ISO 14042 and ISO 14044 [17,18] standards, carrying out a life cycle assessment typically includes three major components:

(1) Goal and scope definition: statement of the study objective and definition of system boundaries are provided with a clear direction for data gathering;
(2) Life cycle inventory (LCI) analysis: an inventory of flows from and to environment for a product system, e.g., data-based process for quantifying input of water, energy and raw material; and output – releases to air, land and water, including operations parameters throughout the process life cycle, production, or activity;
(3) Life cycle impact assessment (LCIA): a systematic assessment of environmental impact of processes or products based upon LCI flow results, involving data classification, model characterization, and may include normalization, grouping and weighting pending the defined goal and scope.

2.1. LCA goal and scope definition

Understanding of environmental impacts associated with the DRAM fabrication stage in high-technology buildings can be obtained for various fabs using the different system boundaries.

Typical production of DRAM consists of the following process modules (Fig. 1):

1. Raw wafer manufacturing: silicon production and purification.
2. Wafer processing: generation of electrical structures on DRAMs.
3. Wafer finishing: encapsulation of wafers in DRAM and production of assemblies.

This LCA study focuses on DRAM wafer processing in the fab, including wafer processing equipment (69%), testing equipment (16%), other front-end production equipment (8%), and assembly and packaging equipment (7%). Fig. 1 also shows the system boundary in this study. The functional unit of LCA analysis in this study is kilowatt hours (kWh), which will be estimated at the receiving end.

The following is outside of the system boundaries for this study: (1) silicon production and purification, (2) assembly and packaging, and (3) production of supplies and disposal.

2.2. Life-cycle inventory

Life-cycle inventory (LCI) is the quantification of raw material and fuel inputs as well as the solid, liquid, and gaseous emissions from a product system. For the proposed DRAM system, this includes the material, energy, and other resource consumption used in raw materials extraction/acquisition, materials processing, product manufacture, transportation, and final disposal. For the conventional lighting system, this includes the energy saved as a result of implementing the DRAM.