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Publication Date

2006-05-08

Peer reviewed

Life Cycle Inventory of a CMOS Chip

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Abstract— A life cycle inventory for comparative assessment of assorted semiconductor device types is assembled using a library of process step-related information. In this paper, we present the structure of this library of energy use, material inputs and emissions data at the process equipment-level and facilities-scale, normalized per wafer. Selected results from a case study of a 130nm node CMOS device are presented and compared with a previous study of a comparable chip. Comparative production impacts of 6-layer and 8-layer CMOS devices are shown.

Keywords– Life Cycle Assessment (LCA); Life Cycle Inventory (LCI); Design for Environment (DFE); environmental management;

I. INTRODUCTION

Considerable attention is paid to environmental management in the integrated circuit industry, and Life Cycle Assessment (LCA) is emerging as a management tool in research and process development activities. In order to effectively support semiconductor manufacturing and design decision-making, LCA must keep pace with continuous change of production technologies. Over the past several years, various forms of LCA/LCI studies have in semiconductor manufacturing have been conducted including the development of inventory models at the level of process steps and chip stack [1], inventory models at the facility scale [2,5] and overall life cycle energy and fossil fuel use [3,4]. Each of these analyses provides insight into the resource impacts of a particular functional unit or device type.

In order to perform a comparative LCA of different device types and process flows to inform R&D and manufacturing planning, a comprehensive library of process step-related equipment and facility inputs and outputs is required.[1] In this work, material inputs and emissions data for such a process library are compiled based on equipment-level measurements as well as facilities-level data, normalized per wafer. We present the structure of this library of process steps and illustrate the use of the library in a case study of a CMOS chip.

II. METHODS

A. Overview

The library is a gate-to-gate inventory of all material and energy flows for each step, normalized per wafer, including: chemical inputs and outputs from production equipment, emissions from point-of-use abatement (POUA), facility-level energy requirements for the process tool and abatement

equipment (electricity, clean-room air and lighting, process cooling water, ultra pure water and volatile organics oxidation) as well as material inputs to facility abatement systems (acid waste neutralization, fluorine wastewater treatment and volatile organics combustion). Because process steps have wide variation in demands on facility-provided gases and liquids, and because the energy associated with facilities distribution, heating, cooling and treatment form a significant proportion of resources used, it is critical that facility loads are also included in the analysis, normalized and linked to each corresponding process step on a per-wafer basis.

Exhaust of deposition and etch processes which contain perfluorinated gases or other air pollutants should be treated using point-of-use abatement (POUA) equipment. The operation of POUA results in a post-POUA profile of emissions, as well as a set of facility requirements.

B. Example: CVD USG

The data for a single process step is shown using the example of plasma chemical vapor deposition (CVD) of undoped silicate glass (USG) in Table 1.

TABLE I. USG CVD PROCESS MATERIAL INVENTORY

Chemicals (g/wafer)	In	Out	Post-POU Abatement
CH ₄	69.41	-	0.04
NF ₃	31.06	2.37	0.09
F ₂	-	17.34	0.06
HF	-	0.03	-
SiF ₄	-	8.82	0.01
CO	-	-	0.16
NO	-	-	1.25
NO ₂	-	-	0.06
SiH ₄	0.95	0.23	0.23
O ₂	0.49	0.49	0.49
Ar	0.34	0.34	0.34
utility N ₂	196.90	196.90	196.90

– Below detection limits

Combined process and POUA equipment facility requirements for the given process step are given in Table II.

TABLE II. PROCESS AND POUA EQUIPMENT FACILITY INPUTS

Electricity (KWhr/wafer)	5.83
Ultra-pure water (liter/wafer)	0
Industrial city water (liter/wafer)	2.06
Process cooling water (liter/wafer)	410

C. Data Sources

Chemical measurement and identification at the production chamber outlet and abatement equipment exhaust have been performed using Fourier Transform Infrared Spectroscopy (FT-IR) and Quadrupole Mass Spectrometry (QMS) throughout the past decade at Applied Materials [7]. These emissions measurements form nearly all of the material inputs, chamber emissions and post-POUA emissions data in the library. In cases where emissions reports do not exist, standard recipes from literature [12] are used with the chamber breakdown efficiencies for each chemical from similar recipes. In cases where post-POUA emissions data is not available for a given process step requiring POUA, destruction removal efficiencies for each chemical from similar recipes are used. Process cooling water demands are taken from equipment specifications for standard operation.

Data for a typical abatement system are taken from manufacturer's data for typical operation. Post-POUA emissions data are taken from abatement tests performed at Applied Materials. For cases in which post-POUA emissions testing data is not available, Destruction and Removal Efficiencies (DREs) are approximated using typical DRE values for specific chemicals by the appropriate POUA system.

Process energy demand for plasma and ion generation and electrical heating in the process chamber is particular to the recipe. Idle power, drawn by the mainframe and ancillary equipment including process pumps and idle mode requirements of the RF generator and chamber, is dependent on the mainframe and chamber configuration. Process equipment power measurements for process and idle modes have been taken using standard power measurement protocols [7] for a majority of the steps included in the model from measurements performed within Applied Materials and in academic cooperation with the company [9]. Power for lithography equipment and power and oxygen use for conventional furnace operations are taken from Murphy [1].

TABLE III. FACILITY INPUTS

PCW electricity for cooling and supply (kWh/gal) ¹	3.45×10^{-3}
UPW purification (kWh/gal) ¹	8.33×10^{-2}
Clean-room lighting (kWh/wafer) ²	2.91×10^{-2}
Clean-room air filtration (kWh/wafer) ³	2.02×10^{-1}
VOC exhaust fan (kWh/wafer)	1.08×10^{-1}

¹[9][10]

²130kW ballroom lighting, 7,500 wafer starts/week, 24/7 operation

³9kW system, 7,500 wafer starts/week, 1hr residence time, 24/7 operation

Resources consumed in process cooling, lighting and air and water purification at the facility level based on facility

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capacities and wafer throughput and are applied to each process step per wafer or wafer-second processing time. The facility electrical requirements are calculated from industry literature [10] as well as standard equipment (compressors, pumps, lighting) used at Applied Materials Inc. and are given in Table III.

III. CASE STUDY: LCI OF A CMOS CHIP

A. Overview

The functional unit of study is a 130nm 6-layer copper CMOS microprocessor produced using 300mm wafers. The die is 11 by 11mm, with a margin of 2mm and a spacer of 0.1mm [11]; total yield is set to 80%, such that, averaged over many wafers, one processed wafer yields 393 die.

The list of all processes modeled is given in Table IV. The process flow for a 130nm CMOS device is taken from a textbook [7]. Each process step listed is modeled based on emission and power measurements, as illustrated in Table I and II, and using the facility per-wafer requirements summarized in Table III.

TABLE IV. CASE STUDY PROCESS FLOW

SOI:	Sacrificial oxide, High Current O Implant, Oxide Anneal, Wafer Clean, Epitaxial Si Dep, Wafer Clean, Screen Oxide, Litho Alignment Mark, Etch Oxide, Etch Si, Strip PR, Strip Screen Oxide
STI:	Wafer Clean, Oxidation Pad Oxide, LPCVD Nitride, Litho STI, Etch nitride and Pad oxide, Strip PR, Etch Si, Wafer Clean, Oxid Barrier Oxide, HDP-CVD USG, CMP USG, Strip Nitride, Strip Pad Oxide
Gate:	Wafer Clean, Sacrificial oxide, Litho N-well, N Well implant, NMOS Anti-punch-through implant, NMOS Threshold/VT adjust implant, PR Strip, Piranha Clean, RTA, Litho P-well, P Well implant, PMOS Anti-punch-through implant, PMOS VT adjust/Threshold, PR Strip, Piranha Clean, RTA, Strip sacrificial oxide, RCA Wafer Clean, Gate oxide, LPCVD Poly-Si, Litho Gate, Etch poly-Si, PR Strip, Wafer Clean, Polysilicon anneal and oxidation, Litho, Implant P LDD, PMOS Halo 45deg implant, PR Strip, Piranha Clean, RTA, Litho, Implant N LDD, NMOS Halo 45deg implant, PR Strip, Piranha Clean, RTA, CVD USG and Nitride, USG and nitride Etchback, Litho, NMOS S/D Implant, PR Strip, Piranha Clean, RTA, Litho, PMOS S/D Implant, PR Strip, Piranha Clean, RTA, Ar sputtering etch, Co and TiN Sputtering Dep, RTA, Strip Ti and Co, PECVD Nitride, HDP-CVD PSG, CMP PSG, Litho, Etch PSG, PR Strip, Ar Sputtering etch, Ti and TiN Sputtering Dep, Tungsten CVD, W TiN and Ti CMP
Inter-connect	PECVD Barrier/Etch Stop, IMD Dep, PECVD Barrier/Etch Stop, IMD Dep, Via Litho, Via Etch, Strip PR, Trench Litho, Trench Etch, Strip PR, Ar sputtering etch, Ti Liner, TiN Barrier, Cu CVD Seed Layer, Cu ECP, Copper Anneal, Cu CMP and Clean
Passivation:	PECVD nitride, Bump Contact Litho, Nitride Etch, Polyamide coating, Ship to test and package, Strip Polyamide, Ar sputtering etch, Cr, Cu and Au liner, Pb tin alloy coating, Litho Contact, Etch Pb-tin alloy, Strip PR, Lead tin alloy reflow

B. Results

Process-level measurement techniques allow a picture of the exact chemicals and compounds emitted at the process output and post-POU stage. The full profile of post-POUA emissions on a per-wafer basis is given in Figure 1 and Table 1. In Figure 1, the percentage split of only the top nine gaseous emissions are shown. The overwhelmingly large mass fractions of utility nitrogen and water omitted for clarity. Table 1 lists all material emissions including nitrogen and waste water.

Because the library is focused on process dependent flows, rather than facility level emissions, differences due to the fabrication process sequence may be represented for comparison.

We proceed with a comparison of this 6-layer device and an 8-layer device of otherwise the same specifications (130nm node copper CMOS, 300mm wafer). All emissions are at the post-POUA, and will be further abated in the facility house scrubber and acid waste neutralization systems. It should be noted that POUA outputs are not representative of actual emissions to air.

TABLE V. COMPARATIVE LCI FOR LAYER COUNT

	6 Layers	8 Layers
Process and Facilities Electricity (KWhr/die)	1.56	1.87
Post-POA Emissions		
Global Warming Potential (MTCE/die)	2.89×10^{-3}	2.94×10^{-3}
Hazardous Air Pollutants (g/die)	4.02×10^{-1}	4.21×10^{-1}
Criteria Air Pollutants (g/die)	2.01×10^{-1}	2.26×10^{-1}
Volatile Organics (g/die)	5.90×10^{-1}	6.97×10^{-1}
Other Chemicals (g/die)	1.38	1.41

IV. DISCUSSION

A. Discussion of Results

The LCI library is composed of individual generic process steps, an approach which has been advanced in previous literature [6][1][13], and these steps are grouped into modules for (i) Silicon on Insulator (SOI), (ii) Shallow Trench Isolation (STI), (iii) gate, (iv) interconnect, (v) passivation and (vi) bonding pad. Beneficial qualities of a structure of individual process steps grouped into modules include:

- Tractable: The model can be updated and changed as individual process steps or POU abatement technologies change
- Parametric: The design can be changed to represent different device types, e.g. with different layer counts
- Secure: The model protects sensitive or proprietary information while communicating data pertinent to environmental impact analysis

The current results are compared with a previous study of a 130nm technology 6-layer copper CMOS chip, produced on a 200mm wafer.[2]

TABLE VI. COMPARISON TO PREVIOUS LCI

	Intel Pentium 4 (Northwood) [2]	Current Study
Electricity (KWh/die)	3.5	1.56

Differences in the results for energy use in these two studies are attributable to discrepancy in the boundaries drawn around the systems and methods of data collection, as well as possibly the abatement technologies used in the facilities under study. Because there is little information given about data collection methods for energy figures in the previous study, comparison is difficult. It is clear that types of electricity consumption that are included in the fab-wide inventory are not included in the current account. Additional forms of electricity consumption in and around the fab, for which data was not available in the current study, include: wafer handling, chemical purification, house scrubber, AWN and fluorine and ammonia waste systems, UPW heating (for some process steps), office HVAC as well as lighting in the sub-fab and office space.

Material emissions are not comparable between the current and previous LCI, because the current study reports post-POUA emissions while the previous reports facility-level emissions, presumably from the facility abatement systems.

Process dependent information is the focus of the model, and the library is thereby most effectively used for comparison between production sequences, rather than for solitary inventory assessment.

B. Conclusions

In this study we associate material and energy data at the equipment and facility level with individual process steps. By collecting and organizing the data in this manner, different process flows and thereby a range of devices may be analyzed. The equipment-centric, module-based model structure is tractable, parametric and secure and is useful for comparative assessment of the environmental implications of semiconductor fabrication.

The library presented is primarily useful for comparative life cycle inventory assessment of process sequences. Given the boundaries drawn, the inventory gives a detailed view of chemical emissions but under-reports electricity use per wafer. Additional consumption should be included in the model to allow a more thorough view of electricity use in the fab and more representative result for actual total energy demands for production.

Finally, it is important that the origin of life cycle inventory data be transparent. Comparison with an existing life cycle inventory of a comparable device is hindered by the limited information concerning data acquisition from the facility under study. It is reasonable to posit that a good deal of information relevant to life cycle analysis, such as methods

of data collection, can be shared while not violating intellectual property security.

C. Future Work

The inventory presented in this work represents only the energy and material flows for device processing. Significant environmental impacts upstream of the facility, particularly energy required for chemical production and purification as well as facility infrastructure will be included in a forthcoming cradle-to-gate inventory. Also, for the purpose of life cycle assessment of a device, the chemical emissions from facility abatement must be measured or estimated using previously measured DRE to show the actual emissions to air. Environmental impact assessment of these impacts, as well as the use phase and end-of-life issues, would complete the LCA of the product.

The library constructed for this study is intended for future use in comparative life cycle analysis of new and existing process technologies. Possible prospects for future study include strained silicon, 3-D gate structures or other novel production technologies.

ACKNOWLEDGMENT

This work has been supported by the US EPA under grant number RD-83145601 and Applied Materials Inc. Special thanks to Sebastien Raoux, Mehran Moalem, Rafika Smati, Barry Page, Morteza Farnia and Mike Woolston.

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Figure 1. Post-POUA emissions per wafer

Figure 1 shows the largest nine components in the emissions inventory excluding water or nitrogen. For all emission components by mass refer to Table VII.

TABLE VII. EMISSIONS INVENTORY

Post-POA Emissions (g/wafer)	
H3PO4	3.963 x 10 ⁴
Utility N2	3.395 x 10 ⁴
Alumina Slurry A	1.385 x 10 ⁴
NH3	6.114 x 10 ³
CO2	5.574 x 10 ³
IPA	3.442 x 10 ³
O2	3.078 x 10 ³
H2SO4	2.502 x 10 ³
Process N2	1.341 x 10 ³
H2O2	873.162
Other	2922.680
Aqueous cleaner A	463.000
Silica slurry A	437.500
Silica slurry B	437.500
Aqueous cleaner B	294.667
HF	227.907
NF3	132.295
ethyl lactate	124.913
HCl (gas)	124.377
PP glycol monomethyl ether acetate	120.038
Ar	85.546
HCl (liquid)	79.232
lamine solvent	72.016
N2O	68.196
Formaldehyde (CH2O)	49.246
NH4OH	48.904
m-Cresol	31.238
p-Cresol	30.925
SiF4	25.239
BTA	18.001

CF4	9.382
NO	7.050
CO	6.120
WF6	5.982
NO2	4.580
F2	2.854
Pt	2.613
HF (gas)	2.402
BF3	2.060
H2	1.686
CuSO4	1.200
BTBS	1.068
SiH4	0.771
BCl3	0.762
C2F6	0.720
C2F4	0.540
COF2	0.428
CHF3	0.351
Cu	0.349
C4F8	0.220
AsH3	0.207
CH4	0.188
MMA	0.171
C4F6	0.090
Cl2	0.072
SiCl4	0.038
TMS	0.017
C4F8	0.010
DMA	0.007
DCS	0.001
PH3	0.0004
He	0.0001