A LCA Approach for Making Greener Semiconductor Products

Presented by
Tao Zhu, Graduate Student
Department of ChEE
University of Arizona
Current Environmental Situation

The semiconductor industry is a relatively clean industry.

The entire electronic equipment industry (semiconductor or otherwise) in 2000 accounted for only **35 million pounds** of total releases. This is less than the total of the **TWO largest electric utility facilities in the US** (roughly 40 million pounds combined).

In Arizona the semiconductor industry is responsible for roughly 3% of releases from the entire electric utility and electronic equipment manufacturing facilities categories.
"Chip making is sometimes called a 'clean industry' because of the images of technicians in white lab suits working in ultra-clean rooms with shiny pristine silicon wafers. But it is estimated that on the average day of operations at a chip-making plant four million gallons of wastewater are produced, and thousands of gallons of corrosive hazardous materials, like hydrochloric and sulfuric acid, are used. However, there have been few instances of hazardous spills."

source: SpaceDaily, Agence France-Presse
However, in semiconductor manufacturing, there is but one product, with a large number incoming material streams and outgoing waste streams.
For example, in petroleum manufacturing, almost all of the incoming raw material finds its way into some product. There is little waste.

The semiconductor manufacturing industry must find ways to reduce the amount of raw materials used, while also finding uses for the effluent materials whose purity is no longer acceptable for chip manufacturing.
Current Analysis Tools

Although we are "clean", are we sustainable?

Different sustainability measures:

Target Method from Agere/NJIT.

EcoIndicator95.

No consensus yet on how to measure sustainability as defined by the Brundtland report.
Current Analysis Tools

Preliminary studies from NJIT show that silicon wafer manufacturing is very far from being sustainable according to the Target Method.

Therefore:

We need to be proactive in developing sound policies to more toward sustainability so the industry can survive future periods of resource depletion.

We also need to proactively shift public perception of our industry through publicizing our efforts at becoming even cleaner (although we are "clean" already!)

NSF/SRC Engineering Research Center for Environmentally Benign Semiconductor Manufacturing
Problems and Opportunities

Rapid Technology Change

Rapid Growth

Need for:
- Proactive approach
- Anticipating problems
- Solving problems
- Avoiding problems
- Pre-competitive cooperation

NSF/SRC Engineering Research Center for Environmentally Benign Semiconductor Manufacturing
Elements of ESH

What are the elements of ESH conscious design?

Optimize for global optimum for environment, health, safety, and economics

Design plant for future decommissioning

Design products for ease in recycling

Design processes for robustness and ease in changing to more environmentally benign formulations

NSF/SRC Engineering Research Center for Environmentally Benign Semiconductor Manufacturing
LCA: Details and How to Carry It Out

LCA is an analytic tool for quantifying the environmental impacts of all processes used in converting raw materials into a final product. It consists of three parts, life cycle inventory, impact assessment, and life cycle improvement.

Life cycle studies have been used to understand three types of problems:

- Assessments of single products to learn about their eco-profiles.
- Comparisons of process routes in the production of substitutable products of processes.
- Comparisons of alternative ways for delivering a given service or function.
Pros and Cons

An LCA study is not very objective because.

✓ LCA is based on a number of assumptions and choices
✓ LCA methods are still being developed and refined
✓ There will always be uncertainties related to data and methods

However LCA is a good tool because

✓ No other analytical tools are available yet
✓ An assessment will always be subjective
Strength and Weakness

Good side

- The whole life cycle (avoid sub-optimisation)!!
- Conversion to potential environmental impacts!!
- Compare different I/O on the same scale!!
- Cleaner products
- Informed choices
- Prioritise
- Strategy - can be integrated in DfE and EMS

NSF/SRC Engineering Research Center for Environmentally Benign Semiconductor Manufacturing
Strength and Weakness

Problems with LCA **Cost, time, effort**

- Here and now
- Time consuming
- Data are difficult to collect
- Difficult to interpret and evaluate
- Not very transparent
- Does not pay back here and now
Example of Screening LCA: scCO₂

Using carbon dioxide at high temperature and pressures, known as supercritical carbon dioxide (scCO₂), in place of hazardous materials, replaces the solvents as well as the tremendous quantities of ultra-pure water that are used to wash those solvents away.

Some research that has been underway:

- GTi manufactures a patented scCO₂ drying system
- The Los Alamos SuperScrub™
- Thrust B seed project in ERC center: Densified fluid cleaning of semiconductor wafer surfaces

[NSF/SRC Engineering Research Center for Environmentally Benign Semiconductor Manufacturing]
scCO$_2$ Properties

- $T_c = 304.19$ K, $p_c = 7.38$ MPa
- Cheap
- Inert
- Physiologically safe
- Ecologically harmless
- Non corrosive
- Non flammable
- High diffusion coefficient
- Low viscosity coefficient
Common Usage of scCO$_2$

- Decaffeinating of coffee, tea
- Extraction of fragrances
- Dry cleaning application
- Remove bitterness from beer

Supercritical CO$_2$

NSF/SRC Engineering Research Center for Environmentally Benign Semiconductor Manufacturing
Scope of Boundaries Included

- Produce CO\textsubscript{2} (if applicable)
- Collecting CO\textsubscript{2}
- Processing CO\textsubscript{2} (purify, pressurize, preheat, heat)
- Using scCO\textsubscript{2} on wafer cleaning
- Collect CO\textsubscript{2} after use
- Use - reuse
- Disposal - recycling

Transportation has been excluded from the boundaries

NSF/SRC Engineering Research Center for Environmentally Benign Semiconductor Manufacturing
scCO$_2$ - Los Alamos SuperScrub™ process.
Expected Results of Economic Aspects

The initial capital costs for scCO₂ systems are usually higher than other alternatives by a significant amount.

- High-pressure cleaning chamber and the valves and instrumentation required for the system.
- No vendors that mass produce scco₂ systems yet.

NSF/SRC Engineering Research Center for Environmentally Benign Semiconductor Manufacturing
<table>
<thead>
<tr>
<th>Cost Component</th>
<th>Items Considered</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Equipment</strong></td>
<td>Depreciation, moving equipment, rearranging equipment footprint, training</td>
</tr>
<tr>
<td><strong>Consumables</strong></td>
<td>Utilities, chemicals, supplies, waste management</td>
</tr>
<tr>
<td><strong>Maintenance</strong></td>
<td>Maintenance labor, parts, vendor contracts, vendor training, computer system</td>
</tr>
<tr>
<td><strong>Labor</strong></td>
<td>Operators</td>
</tr>
<tr>
<td><strong>Support personnel</strong></td>
<td>Higher support personnel, engineering, supervision, contractor labor</td>
</tr>
<tr>
<td><strong>Administrative costs</strong></td>
<td>Insurance, taxes, interests</td>
</tr>
</tbody>
</table>

*NSF/SRC Engineering Research Center for Environmentally Benign Semiconductor Manufacturing*
Expected Results of Environmental Aspect

- DI water uses up many resources
- scCO₂ has to use a lot of energy to operate
- Because of the high operating pressures of scCO₂, we may lower yield or productivity by damaging wafer structures
- High pressure could induce hazardous problems

The quantifying of each category and underlying categories need future work
Impacts and Results Discussion

Process and equipment developments are making scCO$_2$ more competitive

- Reducing the requirements for continuous carbon dioxide flow
- Producing effective cleaning at lower temperatures and pressures
- The construction of equipment with less expensive materials.
- scCO$_2$ could be the most environmentally benign based on LCA results even with its high energy costs

NSF/SRC Engineering Research Center for Environmentally Benign Semiconductor Manufacturing
A More Complex Process: \( \text{NF}_3 \) in Cleaning

Use life cycle assessment as a tool for selecting among manufacturing strategies and for selecting within a strategy for improved ESH impact – In chamber cleaning, is use of \( \text{NF}_3 \) or \( \text{C}_2\text{F}_6 \) “globally” better (cradle to grave)

- Using LCA can reveal better trade-off decision opportunities
- All units are involved in the ‘whole picture’ and been investigated, so we can improve ‘sub-optimisation’
- LCA will look globally at ESH impacts like ozone depletion, resource depletion, toxicity, etc
- Externalities like transportation, upstream manufacturing activities, and downstream usage all become important
Forms of Fluorine

Fluorine containing species that enter and leave semiconductor manufacturing processes are normally gases:

- **HF**: *an extremely hazardous acid*
- **NF<sub>3</sub>**: *a toxic gas*
- **PFCs, HFCs, CFCs**: *multiple hazards, ozone depletion*
- **NH<sub>4</sub>F**: *a salt*
- **BF<sub>3</sub>**: *a toxic gas*
- **CF<sub>4</sub>**: *a colorless, odorless, nonflammable, gas*
- **SiF<sub>4</sub>**: *a colorless, corrosive, gas*
- **SF<sub>6</sub>**: *a colorless, nontoxic, nonflammable, gas*
- **WF<sub>6</sub>**: *a toxic, corrosive, nonflammable liquid*
- **ArF**: *a toxic gas*
- **KrF**: *a toxic gas*
- **F<sub>2</sub>**: *a toxic gas*
## Trade-offs Between CFC and NF₃

<table>
<thead>
<tr>
<th>Issues</th>
<th>NF₃</th>
<th>C₂F₆</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost</strong></td>
<td>Expensive</td>
<td>Less expensive</td>
</tr>
<tr>
<td><strong>Impact</strong></td>
<td>Immediate toxicity concerns</td>
<td>Green house gas with long impact on environment</td>
</tr>
<tr>
<td></td>
<td>Long term impact unknown</td>
<td>Strong structure, long life time results in accumulation in atmosphere</td>
</tr>
<tr>
<td><strong>Usage</strong></td>
<td>Faster cleaning than C₂F₆ so may reduce some impacts.</td>
<td>Produces CFCs</td>
</tr>
<tr>
<td></td>
<td>Produces more F, causing problems in ductwork?</td>
<td></td>
</tr>
<tr>
<td><strong>Treatment</strong></td>
<td>Use burner box followed by scrubbing.</td>
<td>Use plasma to break CFCs to harmless and manageable species, then to scrubber. Will produce much CO₂ during treatment.</td>
</tr>
<tr>
<td></td>
<td>Scrubbers were optimized for CFC control! Problem?!?</td>
<td></td>
</tr>
<tr>
<td><strong>Manufacturing</strong></td>
<td>Ammonia + fluorine, cupper</td>
<td>Uses non-renewable hydrocarbons, metal-fluorine compounds Complex chemistry with many steps</td>
</tr>
</tbody>
</table>
Data Needed for Complete Evaluation

- Production methods of NF$_3$, CFCs
- Possible mechanism that is happening during the production and usage
- Input, output inventories data, emission
- Abatement strategy of NF$_3$, CFCs
- Energy usage of producing NF$_3$, CFCs
- ESH information of NF$_3$, CFCs
Difficulties Doing NF$_3$ Analysis

1. How can proprietary information be used? Information is difficult to share – competitive advantages!

- Is it possible to create a “black box” approach to aggregate data (UT Austin cluster tool approach).
- Possibly use slightly outdated “data” from recently discarded processes to provide snap shots of environmental impacts from similar manufacturing steps?

Can the industry create a standard database format for sharing information that is:
- Non-proprietary.
- Still useful?
Difficulties Doing NF$_3$ Analysis

2. Can we estimate data for LCA to avoid proprietary information sharing?

- Use patents to build representative LCA data? (Too many uncertainties).
- Use a semiconductor industry standard – a “standard wafer” like information furnished by Philips.

Could be used as baseline data for external (academic) use.
Conclusions

✓ Life cycle assessment is becoming a useful tool for the semiconductor industry
✓ The methodology needs more work to become fast and robust
✓ We have to generate a uniform database to facilitate LCA, shortening the time span to meet industry needs
Acknowledgements

✓ NSF/SRC to provide funding for this project
✓ Professor Paul Blowers
✓ Professor Farhang Shadman
✓ International Sematech
✓ Motorola for future collaboration
✓ Jeremy Zarowitz for EPA TRI data

NSF/SRC Engineering Research Center for Environmentally Benign Semiconductor Manufacturing