Opportunities and Challenges to Sustainable Manufacturing and CMP

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ABSTRACT

Today the requirements for reducing the impact of our manufacturing activities are increasing as the world awakes to and addresses the environmental impacts of our society. Energy consumption, greenhouse gas emissions, materials availability and use, environmental impact levels, etc. are all topics of interest. Semiconductor manufacturing in general and process steps such as CMP are not exempt from this and, in many cases, the industry has led the efforts in reducing impacts. This paper will first review some of the drivers for sustainable manufacturing, then define some of the terms that will be useful for determining the engineering aspects of sustainability and sustainable manufacturing, as well as metrics for assessing the impact of manufacturing in general and CMP in particular. An assessments of CMP will be given to illustrate the potential for "design for the environment" in CMP and related processes. Consideration will be given to research opportunities, including process modeling, that this focus provides to CMP researchers, consumable suppliers and industry.

INTRODUCTION

The move towards sustainable systems and development is accelerating due to the input on the challenges facing the planet from a large number of directions – from scientific societies to consumers. How this movement is perceived by manufacturers and responded to by the engineers engaged in production is not clear. The definitions are varied and, often, not scientifically based. The metrics for comparison or quantification not defined. The relationship between environmental, societal and business aspects of sustainability and engineering principles governing manufacturing are not clear. However, it is important that efforts be made to help define these terms, derive these metrics and help establish these critical relationships. This is important to meet the demands of government, consumers, and the competitive market. From a business perspective, the uncertainty about some of these issues pose real risks to businesses. Finally, as educators, it is important to develop a clear set of engineering principles and tools to equip our students to fully participate in addressing these challenges.

Whether or not one agrees with the predictions about global warming, the generation of greenhouse gases, etc. it is clear that energy and resources of production are costly and the costs are likely to increase. Costs of control and disposal of materials used in production, along with the normal environmental health and safety requirements, are likely to increase as well. Scarcity of water and other materials, independent of environmental concerns, is another risk to industry. Lester Brown underlined the importance of this as follows [1]:

> "Today, we need a shift in how we think about the relationship between the earth and the economy. This shift is no less fundamental than the one proposed by Copernicus back in 1575. This time, the issue is not which celestial sphere revolves around the other -- but whether the environment is part of the economy -- or the economy is part of the environment."

One of the issues is the definition of "sustainable manufacturing." No clear definition exists. We will begin with a short discussion of sustainability in the context of manufacturing and, then, discuss efforts in semiconductor industry, with a specific focus on chemical mechanical planarization (CMP), to "green" the processes.

SUSTAINABLE MANUFACTURING AND GREEN MANUFACTURING

Sustainability is usually used in reference to development (see, for example, the Brundtland Commission report of the UN [2]). Brundtland states that "Sustainable Development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." It is not obvious how to apply this directly to manufacturing but we could consider several categories of "sustainability." These categories depend on whether or not the resource consumed, or impact, is renewable or the impact can be accommodated by the environment. Materials and other resources extracted from the earth, like coal and oil, are not usually considered to be "renewable". So electricity generated from these resources is not renewable. Solar and wind based energy would be considered renewable. Impacts can be sustainable if the environment can "absorb" the impact as part of the natural processes. Hence, there is a limit to the amount of CO_2 (and other green house gases (GhG)) or other contaminants put into the atmosphere based on the atmosphere's ability to accommodate this input. Exceeding this level is not a sustainable situation. Some resources may appear to be sustainably used but are scarce. For example, water is "renewable" in a specific area if not used beyond the ability of the aquifier or water sources to replenish that taken from the system. So, recycling water used in an industrial process may be a sustainable solution. Of course, one needs to consider the energy and material used in treating the water as part of any recovery system.

The use of "exergy" to assess sustainability of a process or system has been proposed, for example, [3]. Exergy is defined as the measure of the usefulness of value or quality of a form of energy (thermal or chemical) and measures the "maximum amount of work which can be produced by a system or flow of matter or energy as it comes into equilibrium with a reference environment", [3]. It is helpful to identify causes of inefficiencies. But, rather than expecting an impossible efficiency, it compares the system or flow the thermodynamically maximum – for example Carnot efficiency. It reflects the irreversibilities associated with the process or system.

Hence, it seems as if it will be necessary to use a combination of assessment tools and definitions, depending on the specific materials and resources consumed and the impact that consumption has, in the course of the process, on the environment. The subject is still under intense discussion. For the purposes of this paper, we will assume that improvements that reduce energy or material/resource consumption (including water) and/or reduce the impact of the process or system on the environment are "more green" than other processes and systems and are "better." How much better and whether or not the improvement is worth it in terms of the energy or materials/resources consumed (and their impacts) to make the improvement is an outstanding question. This requires engineering metrics to make these assessments and this is part of the challenge.

GREENING OF CMP

The semiconductor industry has been proactive in improving processes and systems to reduce energy and material use and the process impacts. This started with the natural attempts to reduce the cost of ownership in any way possible for processes that use exceptionally expensive materials (solid, liquid and gas) in production either as process chemicals or for cleaning and control. In addition, many of these materials are harmful and environmental health and safety programs have been aggressively developed. Documents such as Semi S23-0705 Guide for Conservation of Energy, Utilities and Materials [4] offer useful guidelines to the industry and address continuous improvements. The ITRS 2005 industry road map anticipates 40% less energy per cm^2 in 2010 from 2005 baseline for Fab tools consumption. But the challenge to the industry is immense.

In the US, in 2004, the semiconductor industry emitted 4.7 Million metric tons of CO_2 eq in global warming gas (GWG) emissions [5]. Based on a global capacity of 2 million wafers per month [6] (and we realize that may be substantially different in today's economic environment) this is the equivalent of approximately 30 million metric tons of CO_2 equivalent of direct emissions annually and approximately 130,000 million kilowatt hours of electricity consumed per year [7].

If we drill down to CMP as part of semiconductor fabrication we see that the actual energy consumption of CMP per wafer is relatively small (less than 0.5%) [6]. This is dwarfed by other processes, like litho, and facilities use. Use of ultrapure water by CMP is quite large (estimated at almost 18% of fab usage) and second only to wafer clean. Technology predictions indicate additional interconnect layers and, hence, additional CMP [7]. But there are a lot of opportunities for improvement, or "greening", of CMP.

There are a number of approaches to achieving sustainable manufacturing, or at a minimum, green manufacturing that have applicability to CMP. Allwood [8] lists five basic options as:

- Use less material and energy
- Substitute input materials: non-toxic for toxic, renewable for non-renewable
- Reduce unwanted outputs: cleaner production, industrial symbiosis
- Convert outputs to inputs: recycling and all its variants, and
- Changed structures of ownership and production: product service systems and supply chain structure

To some extent, all of these are applicable to semiconductor manufacturing in general and CMP in specific. As mentioned earlier, the first option, use less material and energy, has been a driver in process improvement in the semiconductor industry to some extent for a long time. To achieve greener production and, in the extreme, sustainable production, requires reducing the gap between the amount of energy and resources used and the impact of that usage to a more efficient production. Or, as stated in a recent EU study on energy efficiency in manufacturing, moving from maximum gain from minimum capital to maximum value from a minimum of spent resources [9]. This is a logical follow-on from what Lester Brown pointed out earlier. This gap will be filled with a combination of technology "wedges" that, combined, achieve the goal of sustainable production [10]. These wedges consist of specific improvements or modifications in the process or system meeting certain requirements, including that the cost of the materials and manufacturing (in terms of energy consumption and green house gas emissions, etc.) associated with the wedge cannot exceed the savings generated by the implementation of the wedge technology over the life of the process or system in which it is employed. Another requirement is that the cost and impact of the technology must be calculable in terms of the basic metrics of the manufacturing system (that is linking green house gas emission, etc and process metrics like yield, throughput, lead time, etc.).

A key requirement in this "greening" is the development and application of engineering metrics for ascertaining the life cycle cost of the technology or changes anticipated and evaluating alternatives and different scenarios of implementation. Background on the nature and structure of these metrics is given in [11]. These metrics rely on a clear determination of the goal of the metric (for example, water scarcity or energy independence, metric type (for example, return on investment in green house gas reduction or consumption factor), manufacturing scope (for example, process/tool, line, plant, or supply chain) and geographic scope (for example, local or regional or international). Some common metrics include: Energy payback time, Water (or materials, consumables) payback time, Greenhouse gas return on investment (GROI), and Carbon footprint.

We present in the following section some examples of potential improvements following this discussion of greening CMP.

RESEARCH OPPORTUNITIES

If we review CMP relative to the whole semiconductor manufacturing process we see that, relative to energy, CMP impacts are seen in ultrapure water (UPW) use and associated energy for production and delivery but little impact on GhG "in process" and little influence on energy use overall. CMP consumables not considered in these studies

- abrasive (manufacture and delivery), disposal
- slurry fluids (manufacture and delivery), disposal
- pad manufacture and delivery

These could be important in a complete analysis as is the embedded energy and materials in fabrication, delivery, installation and maintenance of the tool.

We need to first view CMP over the entire scale of its impact, from the meter sized machine and pad to the nanometer sized abrasive particle at the pad/wafer interface. Doing so, we can identify a number of areas for improvement. Following the five basic options for making a process more sustainable outlined above as they apply to CMP, we can find a number of possibilities as:

- Use less material and energy
  - more efficient motors/reduce "idle" time running
  - increase pad life/reduce conditioning/optimize conditioning
  - reduce slurry use
  - more efficient wafer cleaning/reduced use of UPW
  - alternative cleaning methodologies

- Substitute input materials: non-toxic for toxic, renewable for non-renewable
  - alternate slurry chemistry (or non-slurry planarization)
  - greater role of pad topography

- Reduce unwanted outputs: cleaner production, industrial symbiosis
  - fixed abrasive pads to reduce pad loss/slurry waste
  - reduce water use (e.g. during "idle")

- Convert outputs to inputs: recycling and all its variants
  - recycle slurry aggressively (designed for reuse)
  - recover energy from operation (spindle or platen motor)
  - end of life strategies for tool and consumables

- Changed structures of ownership and production: product service systems and supply chain structure
  - lease of CMP tools (i.e. tool manufacturer takes "cradle to grave" responsibility for tool
  - lease slurry and pads

Many of these areas are actively being explored already. Mapping these possibilities onto the research domain specific research opportunities include:

- Modeling of CMP can contribute to design for manufacturing (DfM) strategies to insure optimum use of the process
- Consumable "design" for extended pad life or reuse
- defined surface features for optimized contact
- defined surface features for ideal contact frequency (as in copper CMP)
- variable compliance (e.g. MEMS-based or electro-rheological actuators)
- "designer slurries"
- Wafer cleaning to reduce material/water and energy use
- Tool control to reduce set up and tuning with changeover and for idle
- Novel conditioning techniques for extending pad life
- Kinematics for reduced footprint
- Design of tool for "refitting" and scaling to new technology and devices

- Alternate planarization techniques for increased efficiency
- *In situ* metrology/sensors for process control

These are challenging as the process research must track a continuously changing set of requirements as industry follows their roadmap.

CONCLUSIONS

Even if it is not straightforward to define sustainable processes or systems, a sustainability focus offers opportunities for all aspects of CMP. At the least, greening of the CMP process is a benefit. As engineering, we should define the terms before others do it for us!
We need engineering metrics for analysis of "trade-offs" and proposed improvements to the process so we are sure that, from a life cycle perspective, there is a net gain. And we need to make sure our focus on energy does not obscure other potential risks associated with resource use, notably water. Some aspects of this work are not clear, for example, how to include the impacts on society. But, there are many excellent research / development topics to pursue by our community. To be successful, this requires collaboration between academics and industry and , for sure, this won't be solved by only one researcher or group.

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