The Greening of CMP: Improvements in Chemical and Material Efficiencies and Life Cycle Management

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Abstract

The reliance on chemical mechanical planarization (CMP) for integrated circuit (IC) manufacture has increased. CMP has a large environmental footprint, primarily due to the amount of materials consumed for a typical process of record (POR) and the associated waste generated. Improving the process efficiency will reduce the environmental footprint and decrease the cost of ownership.

An estimate of the solid waste generated just from chemical mechanical polishing (CMP) for a typical 200 mm wafer fab is 300 metric tons per year.[1] More than a million gallons of slurry are consumed per year along with hundreds of millions of gallons of water. Since less than 10 percent of the slurry delivered to the pad actually participates in the polish process, and the remaining 90 percent is sent directly to waste, integrated device manufacturers (IDMs) are literally dumping about $20 million per year per 200 mm fab down the drain.[1] Slurry cost dominates the cost of ownership (CoO) for CMP, as shown in Figure 1; it is no surprise that the CMP process has arguably become the most expensive wafer process in IC manufacture. A growing reliance on CMP has the number of CMP steps increasing nonlinearly as the industry marches toward the 22nm technology node and beyond. An opportunity exists to reduce the environmental footprint of CMP through gains in consumable utilization efficiency. With over half of the CoO resulting from consumables, improving the utilization efficiency of consumables will reduce the CoO for CMP.

By analyzing the CMP slurry utilization life cycle within the fab, slurry waste can be generated in the supply system as well as in the polishing tools. ATMI has developed a slurry mixing and delivery system, the CMPlicity™ System, to address common wasteful mixing and delivery methods by using their patented no-waste, NOWPak® container technology, long used for delivery of photoresist.[2] The efficiencies achieved are claimed to reduce slurry waste by 15 percent. Within the process modules there have been continuous

improvements in both pad design and slurry dispensing that are claimed to afford similar 15 percent reductions in slurry. However, none of these approaches addresses the largest source of inefficiency within the CMP consumable life cycle; that being the rotational polishing tool itself that can direct more than 90 percent of the delivered slurry off of the pad to the drain. The fundamental mechanics of rotary CMP systems necessitate the platen and wafer rotate in the same direction to ensure uniform relative motion and removal mechanics (Prestonian). These conditions result in centrifugal flow fields on the platen surface, augmented by rotational drag at the carrier perimeter, effectively sweeping slurry toward the edge of the platen, as shown in Figure 2. This macro scale flow combined with the reser-

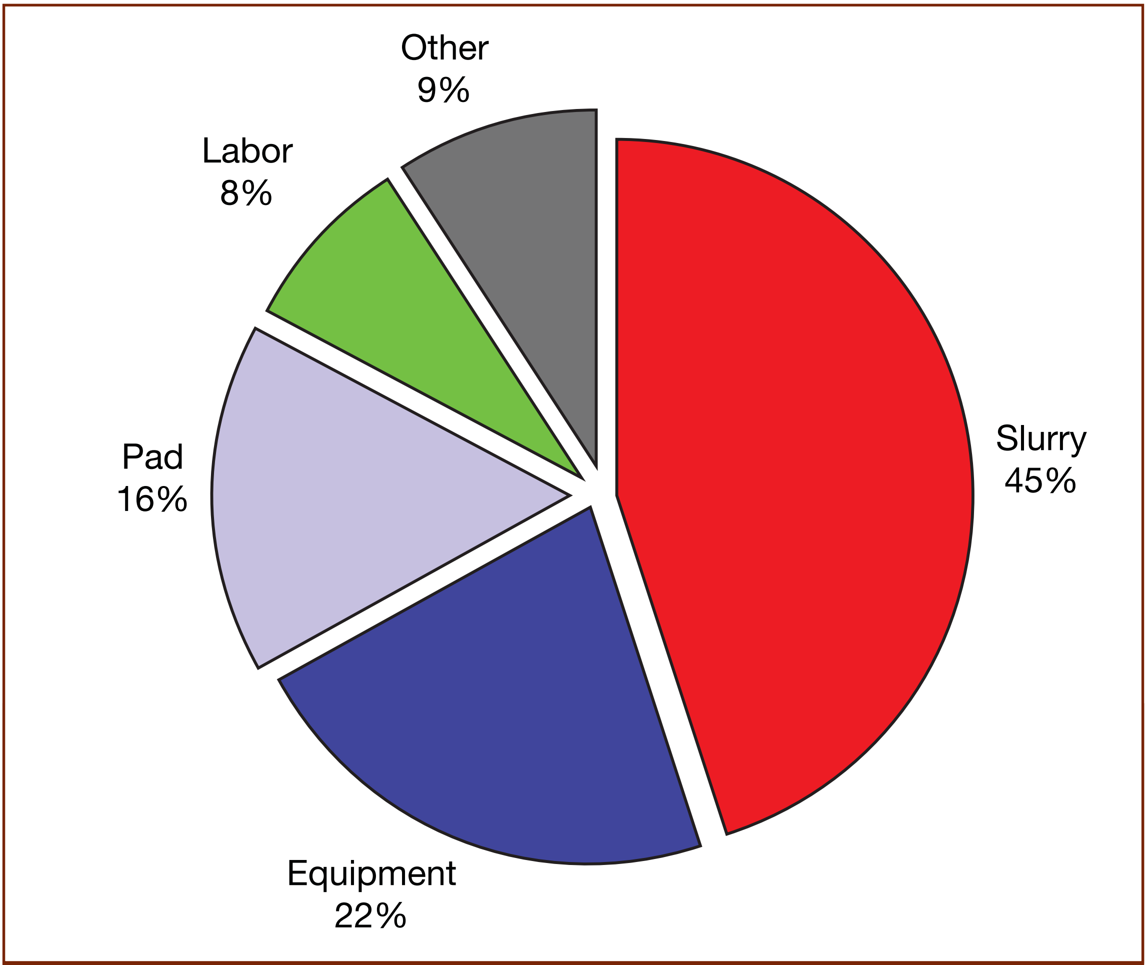

Figure 1. Typical CMP Cost Breakdown *(Courtesy of Araca, Inc.)*

voir of material, mostly spent, contained in the texture of the pad leads to very inefficient transport. Some tool suppliers attempt to physically mix the fresh slurry and spent material with a diamond disk conditioner and some with variable slurry outlet locations. Users have also developed creative approaches such as diverters and dams in an attempt to improve the mixing of fresh slurry with spent slurry and by-products. Universally, users compensate by overfeeding fresh slurry and excessively conditioning the pad surface in an attempt to stabilize the slurry film distribution. This inefficiency and the associated compensation methods have shown to be a significant root cause of process instability, and the major source of consumption due to the inadequate exchange of fresh slurry for spent material trapped on and in the pad. None of these methods has reduced the residence time significantly. None can provide tuning or control of residence time, as once the pad is saturated, the spent material acts as a barrier to replenishment.

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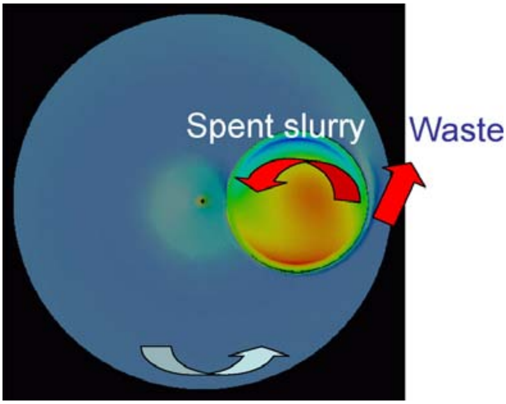

Figure 2. Inefficiencies of Slurry Utilization on a Rotary CMP Tool *(Courtesy of Araca, Inc.)*

RHEM and others have shown that the polish process by-products (i.e., spent slurry, wafer film compounds, pad debris, etc.) are drawn by the rotation of the wafer back toward the center of the pad, as shown in Figure 2. This recycles by-products back under the wafer with each platen revolution. In fact, the concentration of debris on the pad reaches its maximum exactly when one is trying to achieve the final surface finish. The increase in large particle counts as the polish process proceeds is well-documented and they are known to be responsible for microscratches. The mean residence time for slurry under the wafer has been estimated as >30s, which for some pads indicates that the initial slurry to contact the wafer remains there for more than 50 percent of the total process time.[3] This “saturation” is a significant reason for the typical high slurry flow rates required in a POR, and sets the floor as further reductions lead to (large-particle) scratch-related defects. The small amount (<10 percent) of delivered slurry that participates in the polish process is constantly being diluted by process by-products and debris. Consequently, in an attempt to achieve a constant material removal rate, excess slurry must be delivered to the pad to create enough mixing turbulence within the saturated pores to "stabilize" the rate decay from buildup of process by-products and to wash the surface of large-particle debris. In addition, as the chemical reaction by-products are accumulated on the pad (i.e., Cu-BTA, CuO, etc.), otherwise referred to as "pad staining," they inhibit the desired wafer film reaction, resulting in an inability to reach a steady-state condition for material removal. The pad groove configuration can contribute to a higher slurry flow requirement to achieve this "pseudo-equilibrium" due to reservoirs of static slurry and by-products within the grooves. Advanced groove designs can help slightly reduce average residence time and slurry consumption, yet they have limited effectiveness, as they do little for closed cell pore residence and, as importantly, contaminant residence. Lastly, it has been shown that pad grooves impart nanotopography on the wafer, which will cause additional design and fabrication challenges for advanced nodes.[4]

In addition to generating significant polishing consumable waste, the typical POR for CMP also consumes large amounts of ultra pure (UP) water, to the tune of more than 25 liters per wafer pass. A typical polisher uses a 5 gallon per minute flow rate of UP water and the pad is flushed with high pressure for 5-25 seconds between wafers. Wafers are typically sprayed with UP water while being transferred from one platen to another. Wafers may sit in an overflow rinse bath while being queued for the cleaning station. The reason for the rinsing of the pad and wafer during transfer is to remove slurry in preparing for the next polish step. As an example, after the Cu polish, different slurry is used for the barrier polish, and when mixing the two different slurries, coagulation or agglomeration could occur, resulting in large particles that will generate scratches. Microscratches will cause yield and/or reliability issues depending on the process level where they occur.

Advanced groove designs can help slightly reduce average residence time and slurry consumption, yet they are not very effective, as they do little to affect closed cell pore residence.

The composition and aggregate of these materials and the removed films pose an evolving environmental, health and safety challenge. In addition to abrasives (silica, ceria, alumina, etc.), slurry also contains an oxidizer (H_2O_2); an acid or base to set pH at about 3 or 10; an emulsifying agent to minimize slurry agglomeration; a surfactant to improve surface wetting; an antifoaming agent to prevent foaming due to the surfactant; a biocide to prevent bacterial growth in acidic slurries; and a metal passivating agent. Many PORs include a buff process either using slurry or a formulated product, which adds more chemicals to the waste stream. Some PORs include a pad cleaning step using a formulated product that contains a metal chelating agent (citrate, oxalate, EDTA, etc.). Unfortunately, Cu chelating agents are also effective in chelating with Pb and Fe, increasing the concentration of metals in the waste stream and its toxicity. In addition to the bulk material going to waste, there is the contribution of abrasively generated nanoparticles of various wafer materials as well as agglomerated and decomposed slurry abrasives in the form nanoparticles. Much has been written about the unusual toxicity of nanoparticles resulting from the surface area or activity. Zinc oxide and iron oxide, while not toxic in bulk, have very unusual toxicity when in nanoparticle form. Since cell functions are on the nanoscale, toxicity is tremendously enhanced when foreign nanoscale material is introduced to cells. It is not yet possible to determine which materials in nanoparticle form may be hazardous to human cells, so it is recommended that nanoparticles be handled with extreme care. The predominant contributor to CMP solid waste is slurry; however, since newer technologies tend to introduce new materials and processes to meet device demands, the solid waste stream from CMP now contains about half of the elements in the periodic table, due to films removed from the wafer (many of which can be toxic). Much of this will go directly into the waste water discharged to municipal systems in existing fabs.

The pad surface manager (PSM^{TM}) was developed to remove spent slurry and

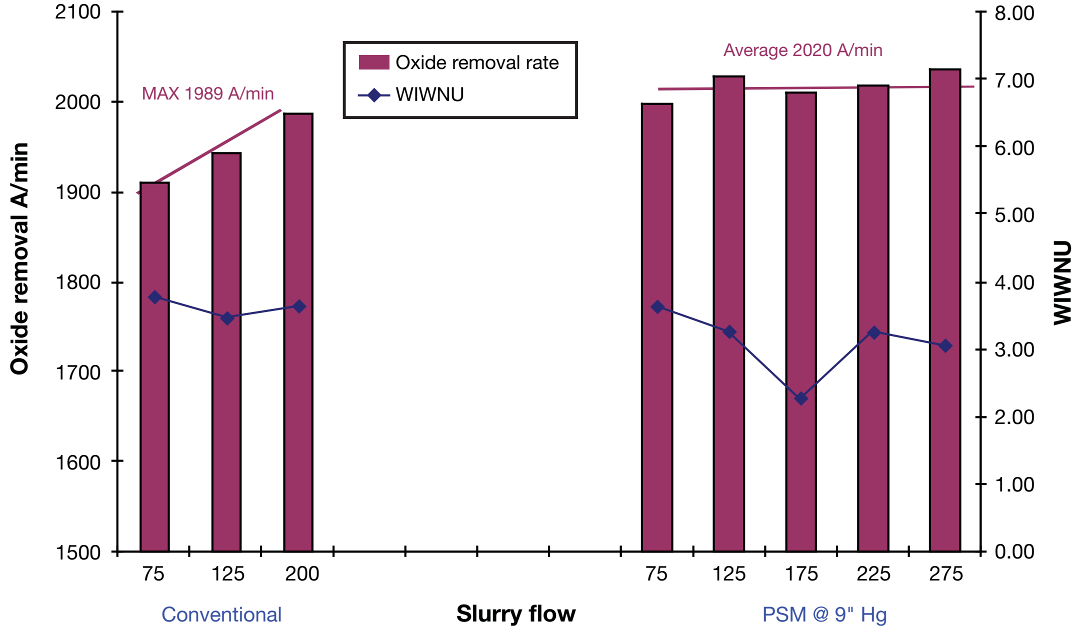

Figure 3. Impact of PSM on Oxide MRR and Slurry Flow Rate

waste from the pad in situ to prevent recycling of the polish by-products back under the wafer to lower wafer defectivity.[5] The concept gives users control of the "liquid" residence time via programmable evacuation of spent slurry film from the pad surface and texture, allowing for the controlled exchange of these consumables. The evacuation functions independent of the dressing abrasion, so the requirement of using the conditioner for slurry mixing is eliminated. The PSM was designed to be a bolt-on replacement for the CMP tool's conditioner arm with a stand-alone control system for liquid, gas and chemical dispense. The PSM can condition the pad and also act like a carpet cleaner and remove waste from the pad, allowing fresh slurry to be delivered to the wafer. Since the CMP process is now operating in a replenishment mode instead of in a dilution mode, equivalent material removal rates (MRRs) can be achieved at consistently lower slurry flow rates, as shown in Figure 3. The data in Figure 3 is for a thermal oxide polish using a perforated pad. Similar reductions in slurry flow rate have been observed for grooved pads, by controlling the evacuation force so as not to clear the fluid reservoir contained in the grooves. As seen in Figure 3, equivalent or higher MRRs were achieved with a slurry flow rate of 75 ml/min. vs. the POR of 200 ml/min. without PSM. Also note that the change in slurry flow rate with PSM had a negligible impact on the MRR, unlike the POR without PSM, which showed an increasing MRR with increasing slurry flow rate. PSM allows for a 60 percent reduction in slurry flow rate, yielding an equivalent reduction in solid waste generated from the CMP process. This has a significant impact on the environmental footprint as well as the CoO. Furthermore, since the PSM is removing spent slurry and polishing by-products from the pad, the water rinse requirements are significantly reduced, saving UP water as well.

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Capturing this spent waste stream allows for in-line instrumentation to analyze the effluent for a variety of attributes (i.e., solids content, pH, conductivity, ion content, etc.) This instrumentation enables users to perform remediation, direct the waste stream to an appropriate drain or collection point, or send this denser stream on to a solids separation operation.[5] Intelligent routing allows one to recycle rinse or idle water for less critical processes or for subsequent pad rinsing, thus reducing the consumption of UP water and further reducing the environmental footprint. In addition, instrumenting the effluent allows more precise detection of the MRR and end point, thus reducing the overpolish requirement. This can have a significant impact on dishing and erosion. It has not yet been quantified; however, reductions in dishing, erosion and Cu recess are expected to further improve the device electrical performance. This can be significant since it is estimated that 10 percent of the U.S. energy budget is used for powering computers.[6] Low-power designs will require better z-thickness control.

Much has been developed to improve the environmental footprint of CMP. There have been tool developments (improved slurry distribution on the pad), improved slurry delivery systems, improvements in pad design requiring less slurry to achieve acceptable quasi-steady-state MRRs, and development of the PSM. Utilization of all these improvements can lead to an improvement in CoO and EHS by targeting the root cause of waste. PSM enables management of the tribological conditions of the polishing process – lubrication, chemistry, solids and pad texture – and affords feedback of the chemical status which provides for a much higher level of control.

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