PART TWO OF TWO

Plasma doping: Progress and potential

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Plasma doping is the leading candidate to replace today's beam-line ion implantation, which is being pushed to the limit by the need for ultra-shallow junctions. Cluster-compatible hardware is envisioned to provide simpler, more economical, higher-throughput wafer processing. Part one of this article, in the September issue of *SST*, reviewed the status of plasma doping, cited device data, and touched on process and equipment issues. Part two discusses potential problems, including charge damage, equipment requirements, and economic factors.

Charging

Any process tool that exposes the wafer to high-density plasma has the potential to generate a lot of charging damage. Most recent tests, however, have indicated that there is minimal damage to thin gate oxides under plasma-doping (PD) conditions [22]. Several factors can be hypothesized as contributing to this apparently benign effect. The use of short pulses of positive ion implantation (II) separated by relatively longer exposure to low-energy electrons from the plasma generates a self-limiting situation. Very short positive pulses have relatively low charge/unit area (about 1×10^{11} ions/cm^2 = 16nC/cm^2) that will not produce significant electric fields in any dielectric (E ~ 1.8kV/m), so that one pulse will not introduce any significant leakage into the dielectrics. After this short pulse, a much longer time is allowed for the low-energy plasma electrons to neutralize the surface charge. PD has, in effect, a built-in plasma flood, much akin to the most recent and successful neutralization method used in beam-line implantation. Studies have shown that as long as the pulse frequency is kept below a threshold value, the plasma is able to fully neutralize the charge accumulated in the pulse.

Wafer heating

This is a potentially serious problem, as many applications assume the use of photoresist coatings on the wafer, limiting the maximum temperature to 100–150°C. The high power in a conventional high-current implanter is one of the basic reasons that these instruments have traditionally used a batch of wafers mounted on a spinning disk or wheel to spread the beam power over a larger area. There are three factors that have evolved over the last few years to mitigate this problem. First, the increasingly shallow junctions mean that the implant energy is lower for each device. A 1×10^{15} atoms/cm^2 dose at 5keV, if delivered to a wafer 0.8mm thick, will only raise the temperature by 6°C, even if no heat leaves the wafer during the process. Second, the cross-sectional areas of beams in implanters have been growing, so that the power density is reduced. PD represents the ultimate in this trend, as the beam is as large as the entire wafer. Finally, cooling technologies have improved significantly. Conventional centrifugal loading onto elastomer pads typically produces contact thermal conductances on the order of 20mW/cm^2-°C, while modern gas-cooled electrostatic clamps have demonstrated conductances as high as 300mW/cm^2-°C. Preliminary measurements of the wafer temperature during PD indicate that the temperature remains below 60°C. Other recent studies have demonstrated that no damage occurs to photoresist features or dimensions during PD implantation [31, 32]. Hence, we feel that PD tools may not need any cooling at all, but if it becomes necessary to allow much higher energies or doses, or if required maximum temperatures drop still further, the technology is available to address the problems.

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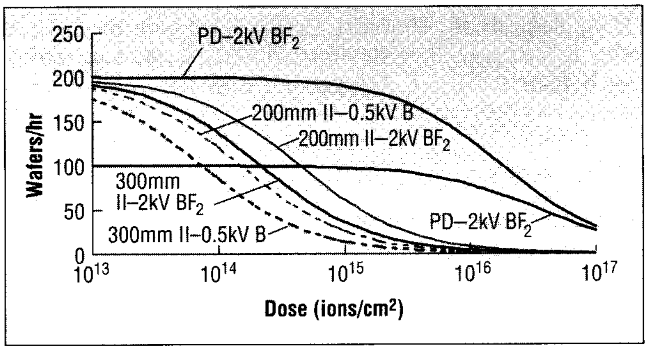
Contamination

Many aspects of modern IC manufacturing are extremely sensitive to contamination. The NTRS roadmap calls for continued reduction in metal contamination from 5×10^{11} atoms/cm^2 in 1999 to $<1\times10^{9}$ atoms/cm^2 in 2009, while conceding that there is no known solution. Conventional ion implantation has always benefited from the presence of a long beam tube and a mass analysis system that separates the dirty ion source from the process chamber where the wafers are held. In PD, this insurance is eliminated and the source and process chambers are one and the same. Hence, there is a very valid concern, but once again PD benefits from a number of factors and thus we believe that this is not a showstopper. Indeed, as discussed previously in this paper and several other studies, PD adds very low levels of transition metals, which are comparable with those of many of today's conventional beam-line implanters, and improvements continue, as with beam-line implanters [32].

The plasma density in a PD system is much lower than that in a high-brightness source used for a beam system. Therefore, the walls of the chamber are at much lower temperature and can be made out of materials (such as aluminum or silicon) selected to minimize their impact as contaminants, rather than refractory metals such as molybdenum or tungsten that are typically minority carrier lifetime killers in silicon. Furthermore, since there is no beam line, the risk of sputtering metals off the walls of the beam line disappears. In a PD system, the only area that is subject to sputtering by ions with the implant energy is the wafer platen itself, and appropriate design can minimize the transfer of deleterious materials to the wafer. In addition, silicon coating of components prone to sputtering is a technology that is widely used in today's beam-line implanters.



Comparison of throughput between beam-line II (200mm and 300mm) and PD processes.

Cross-contamination is another serious issue with ion implantation, and will become more ubiquitous with PD. We feel that the basic design of PD systems will encourage their use in species-specific applications. Thus, in contrast to beam-line systems which are often switched between one dopant and another between wafer lots, or even within one lot, we think that PD chambers will be reserved for a single chemical dopant and that a complete PD tool might be composed of several such dedicated chambers. Many users of beam-line implanters already do this dedication, even though it does imply a larger investment in capital equipment.

Other damage issues

For the PD process to be compatible with device processing, no significant sources of damage can exist. Charging and photoresist degradation have been addressed. In addition, other areas of concern have been examined, including Si and SiO_2 etch and excessive crystalline damage. PD wafers show minimal disturbance of SiO_2 when proper processing conditions are chosen, and much of this "etch" can be attributed to changes in the index of refraction. AFM inspections of bare Si wafers reveal that no significant silicon etching occurs during PD implants and that the mean square roughness values are consistent with values typical of unimplanted bare Si wafers [22]. Finally, cross-sectional TEM analyses have revealed no extended defects or end-of-range dislocation loops in as-implanted or annealed wafers, and rapidly annealed wafers appear to have the same crystalline quality as unimplanted, control wafers [32]. Therefore, no processing issues appear to be showstoppers for PD.

Equipment issues

The basic elements of a PD system have been established through the work of several research teams and contain the following subsystems. The vacuum subsystem may be the single largest-cost item and will include a turbo pump and a mechanical pump to achieve base pressures in the range of 1×10^{-8}torr (1×10^{-6}Pa) and operating pressures in the range of 10mtorr (1.4Pa). A mass flow of about 2sccm will require a pumping speed of about 150 liter/sec, well within the range of available modern pumps. This will produce a mean residence time of less than one second, leading to good control of gas composition.

The plasma generation system is one that has seen intensive development in many applications such as etch, CVD, and others. A low-pressure gas is readily ionized and can produce a plasma with any power that couples effectively to the charged particles. Thus electric fields (DC, pulsed, RF, or microwave) and magnetic fields (RF) have been used to generate plasmas. Optical excitation is also possible, but is less efficient. Most existing PD systems use either inductively coupled RF, or microwave ECR. The technology and the components are readily available.

Plasma confinement plays an important role in several equipment considerations. Maintaining a minimum interaction between the plasma and the walls will reduce contamination problems. This will also cut the ion recombination rate and thus minimize the power required to sustain the plasma. It is also a major influence on plasma uniformity. The subject of plasma confinement has been intensively investigated by the large number of researchers developing controlled fusion systems. Again, the technology and the equipment are well understood and readily available. The same is true of the other parts of a PD system. Wafer-handling and control systems, and toxic-gas-handling and other subsystems can be readily adapted from other semiconductor process tools.

Cost of ownership

PD systems have the potential to be much smaller, simpler, and cheaper than beam-line systems. The high-temperature source, complex and fragile beam generation electrodes, beam guide, mass analysis magnet, and many other parts are simply deleted. Furthermore, if the assumption of a single dopant species is integral to the design, gas-handling systems can be drastically simpler. The design simplicity can also be leveraged to improve reliability with all the improvements in uptime and utilization that this enables.

Meanwhile, the throughput for high-dose, low-energy processes will be higher than in conventional beam-line systems. The figure shows a comparison of the throughput of a hypothetical PD system against a conventional beam-line II tool. Depending on the number of process chambers, the details of the process chamber volume and loadlocking scheme, and other factors, throughputs of between 100–200 wafers/hr for ULE high-dose implants should be accomplishable.

Hence, we estimate that PD systems may have a much lower cost of ownership than beam-line systems. In addition, these serial processing tools satisfy the "flexible manufacturing" paradigm shift that is occurring, and the development of a doping tool with smaller granularity has long been requested by process engineers.

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These are all fundamental reasons why we believe that PD tools will be the high-dose, low-energy ion implanters of the future.

At the crossroads

Plasma doping first appeared as a "possible solution" in the 1994 SIA Roadmap. It was felt at that time that standard beam-line implanters could not manufacture the 60nm junctions needed by 1999 as the energy needed was too low for efficient extraction from the ionizer. SEMATECH followed this direction by directing resources toward work relevant to the manufacturing demonstration of this technique. The outcome of the concerted efforts corroborated the viability of plasma doping as an alternative doping method. When the 1997 Roadmap was issued, PD was clearly listed as the leading candidate. The remaining issues of note were the development of a dosimetry technique as accurate and reliable as that used in beam-line implanters, and the continuing demonstration of its successful application in semiconductor processes through device demonstrations. The data acquired since then have clearly indicated that PD is the functional equivalent of beam-line II for low-energy implantation, but it has also been noted that there is no specific process benefit that puts it head and shoulders above beam-line technology. Dosimetry has continued to be an issue. While SPC-type tests show reasonable performance, there has still been no universal dosimetry method showing performance that actually is comparable to low-energy beam-line processes. This includes the fact that there is not as complete a technical linkage between fundamental machine parameters and the machine performance.

The 1999 International Roadmap for Semiconductors will be issued later this fall. It is likely that PD will be listed as the only

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technique that is directly competitive with low-energy beam-line implantation through the 70nm microprocessor gate length node. It should be noted that low-energy beam-line implantation tools have continued to evolve during the last five years and that a process tool change typically only occurs when the incumbent technique is expected to be incapable of achieving the new requirement.

The present status of PD is that suppliers generally have developed a plausible design and have done several demonstrations of the technology in the R&D labs. They are prepared to deliver early alpha- or beta-level tools but the proper market window for a true manufacturing machine is not clear. From the users' viewpoint, several would-be showstoppers such as charging and contamination have been tackled and the feasibility of the technique has been demonstrated. The biggest benefits of PD will likely be productivity and economics. These attributes are attractive to the manufacturing community, but are not as appealing to the engineering community, which is concerned about dosimetry and loss of effective control.

The Plasma Doping Users Group was formed in 1998 to spearhead PD activities. In addition to holding meetings worldwide, the group operates a web page (http://www.cityu.edu.hk/ap/plasmausers/home.htm) to facilitate information exchange among users as well as to post meeting information and articles. ■

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