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TECHNICAL NOTE

HIGH-THROUGHPUT PHOTORESIST STRIP USING A TOROIDAL RF PLASMA SOURCE IN ASHERS

ABSTRACT

New requirements in photoresist strip processes are placing conflicting demands on dry asher tools, which must achieve high throughput while avoiding damage to fragile materials and complex structures on wafers. Low-field toroidal RF plasma generator technology provides faster etch rates with no increase in plasma damage for single-wafer ashers when compared to traditional conventional microwave or inductively-coupled plasma (ICP) sources.

Advanced photoresist strip processes with high wafer throughput and negligible substrate damage are critical for successful device fabrication at the 90 nm node and below. Cutting-edge devices can require from 22 to 30 or more masking steps, each with an associated photoresist strip removal process. Some steps contain uniquely fragile materials and complex structures that are incompatible with the existing levels of process-induced surface damage and defect generation. For example, the use of low-κ dielectrics forces photoresist strip processes to minimize or, preferably, eliminate film removal, moisture and chemical infusion into film pores, surface compositional change and surface structural damage. Additionally, strip processes at 90 nm and below face aggressive nanoscale topographies that are susceptible to damage. Finally, advanced strip processes will have to meet extremely demanding uniformity, repeatability and wafer throughput standards. All of these fabrication methods produce conflicting process requirements; processes must have very aggressive strip rates without etch- or damage-inducing exposure of the substrate to the plasma.

Photoresists are composed of polymers with a hydrocarbon backbone. The material properties of resists and their residues vary due to differences in the chemistry of the pendant groups on this backbone. Common to all photoresists is the fact that an insoluble, cross-linked hydrocarbon residue remains on the substrate after processing. After the etching or ion implantation step, the photoresist is removed and the wafer is cleaned before subsequent processing. Photoresist residues can be removed via a physical mechanism such as simple dissolution using an organic solvent, or through chemical reactions (usually oxidation) of the resist that produces gaseous byproducts such as CO_2. The latter technique is commonly referred to as "ashing."

Photoresists may be exposed to highly-reactive chemicals, ion bombardment and high temperatures, depending on the process. This may modify the surface and bulk chemistry and material properties of the residue. These (and other) differences in resist chemistry have led to the need for three different approaches to photoresist removal: 1) organic strippers; 2) oxidizing-type aqueous strippers; and 3) dry strippers [1]. The first two approaches are liquid-based and, until recently, have been commonly used for photoresist removal. However, liquid approaches are becoming less desirable in advanced device production due to incompatible chemistries (i.e., the use of hydroxylamine-based strippers in the presence of copper and certain low-κ's [2, 3, 4, 5], CD losses due to fluoride interactions with SiO_2 vias [3]), material transport and topological limitations [5], and damage caused by surface tension effects [6]. The incursion of water and other chemical species into porous low-κ materials with subsequent outgassing is also a significant problem for liquid-based stripping. Sidewall polymers from etching also tend to be highly resistant to wet-stripping chemistries. These and other problems cause plasma ("dry-ashing") techniques to be preferred for polymer and residue removal in fabrication processes at reduced

geometries. Dry ashing typically employs high (>100° C) wafer temperatures and atomic oxygen to remove the resist and polymer residues by the interaction of oxygen atoms or electronically-excited oxygen molecules with the organic material [6, 7].

Prior to the introduction of single-wafer photoresist ashers, barrel and other relatively unsophisticated designs removed photoresist residues by exposing substrates directly to plasma [8]. This was highly effective for the inexpensive treatment of large batches of wafers. Eventually, however, research on more advanced device structures showed that direct exposure of these structures to plasma produced unacceptable damage [9, 10, 11]. Advanced strip processes, therefore, must avoid direct plasma exposure. This places conflicting demands on next-generation dry ashers. Wafer throughput requires high removal rates and short process times, which are difficult or impossible to achieve without direct plasma exposure. Additionally, the increasing number of masking steps in modern fab lines places greater demands on the ashing tools for reduced contamination, tighter process uniformity and greater process repeatability. Barrel and other direct exposure ashers cannot meet these demands.

ADVANCED STRIPPER TOOLS WITH CONVENTIONAL PLASMA SOURCES

Advanced, high-throughput commercial photoresist strippers can be configured with multiple process chambers, robotics and other features to handle more than one 300 mm wafer at a time. These tools can achieve 160 wafers per hour throughput for normal ashing processes, with somewhat lower throughputs experienced in lower-temperature high-dose implant (HDI) processes (See Figure 1).

In conventional systems, remote ("upstream") microwave excitation is used to create neutral, reactive oxygen species that are fed to the wafer surface without direct exposure of the substrates to the plasma within the source. Resist strip rates that range between 3 and 6 microns per minute are possible using such equipment,

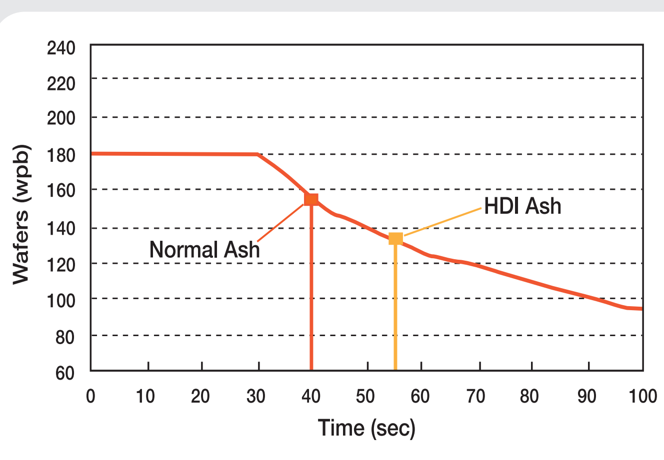

Figure 1 - Wafer throughput for an advanced photoresist stripping system with multiple processing stations.

and appropriately designed baffles produce acceptable (±7 percent) strip uniformities over the wafer surface. This configuration is very repeatable in terms of wafer-to wafer strip performance. Advanced tools permit high-pressure wafer bake-out in order to eliminate “popping” of high dose implanted photoresist. ISBP (in situ bake process) is a patented heat-treatment process in which the wafer is ramped up to a high temperature (250°C) at 760 Torr. The pressure on both sides of the implant crust is almost the same, thus avoiding "popping."

ADVANCED DOWNSTREAM PLASMA SOURCES

An intelligently-designed remote RF plasma source can yield dramatic improvements in resist stripping. Figure 2 shows a schematic of MKS’ low field-torodial R*evolution® Remote Plasma Source. Within the plasma source, 400 kHz RF power is inductively coupled through ferrite cores into plasma that is confined within a toroidal quartz chamber. This design is based on an electrical transformer principle where the output of the RF power section connects to the primary coil and the current flowing in the toroidal plasma becomes the secondary. The result is an efficient method for sustaining the plasma while maintaining very low electric fields of 5 to 10 V/cm. The source operates efficiently over an extremely wide range of gas flows and pressures, and generates reactive

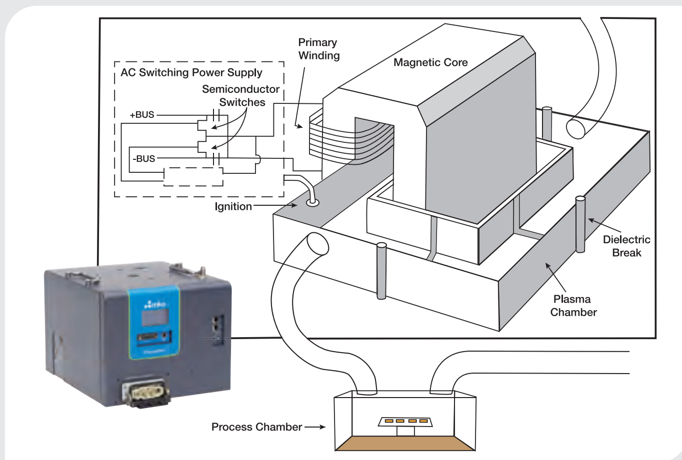

*Figure 2 - Schematic of MKS' R*evolution, an advanced low-field toroidal RF plasma source*

species in O_2, N_2, H_2, H_2/N_2, and H_2/He gases. Plasma power is adjustable up to 6 kW, creating a wide window that allows for process tuning for maximal excitation under high gas flow conditions. Figure 3 shows the ion density within a toroidal RF source at a loop current of 60 A. Plasma density and electron temperature within the source are typically $n_e = 10^{13}$ cm^{-3} and $T_e = 2.5^{-3}$ eV, indicating very efficient coupling of the RF power into the plasma. The plasma chamber is made of high-purity quartz. The use of quartz significantly reduces losses of atomic gases such as oxygen, hydrogen and nitrogen through wall recombination. Surface recombination rates of atomic gases on quartz are 100 to 1000 times lower than on most metals and dielectrics. This results in higher reactive gas output.

Toroidal RF sources are uniquely suited for high-throughput photoresist stripping in advanced device fabrication. The transformer configuration and 400 kHz RF frequency efficiently couple power to the plasma, yielding high plasma densities and high concentrations of reactive species. The low electric fields result in minimal ion bombardment of the chamber walls and excellent gas stream purity using the remote toroidal source. In non-toroidal ICP plasma sources, the electric fields are much higher, resulting in ion bombardment that sputters the quartz and contaminates the gas stream. ICP mass spectrometry (ICP-MS) and x-ray photoelectron spectroscopy (XPS) analysis of wafers processed in a photoresist strip tool using a remote toroidal RF source under conditions producing strip rates 2 to 3 times greater than in the same system equipped with a microwave source showed extremely low (~1 x 10^{10} cm^{-2}) particulate, quartz and metal contamination with the toroidal source.

Higher ion densities within a toroidal plasma source do not produce high charge densities at substrate surfaces. Figure 4 compares downstream ion densities of an RF toroidal source and a conventional microwave source. Both produce nearly identical ion densities at the substrate surface, but the toroidal RF source yields significantly higher strip rates.

The high gas flow within toroidal sources promotes high concentrations of radicals at the wafer surface. Since

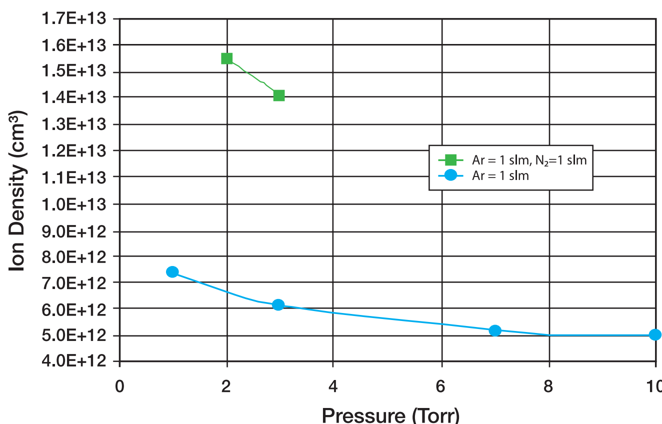

Figure 3 - Plasma densities in a toroidal plasma source at plasma loop current of 60 A.

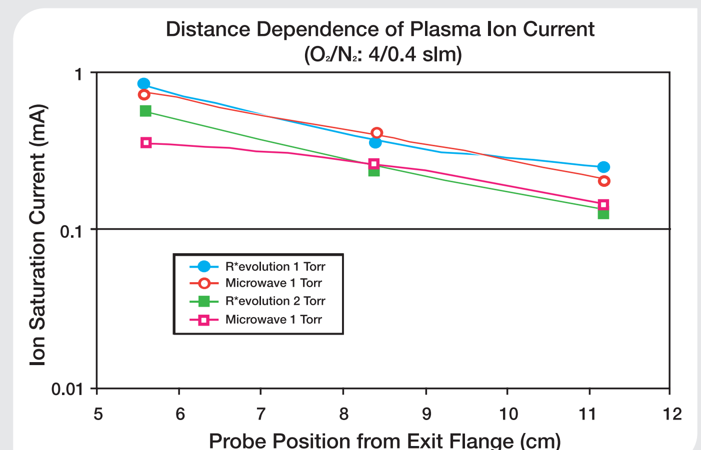

Figure 4 - A comparison of ion densities downstream from an RF toroidal source vs. ion densities downstream of a microwave plasma source.

radicals decay rapidly through reactions with the chamber walls, high gas flow produces short residence times for radicals in the gas stream, minimizing decay. High concentrations of radicals at the substrate surface produce high strip rates. Figure 5 shows that strip rates close to 12 microns per minute are possible with the toroidal source, while a maximum of ~6 microns per minute is observed with microwave sources under similar conditions. Strip uniformities are excellent and typically better than those observed with microwave sources. The ability to adjust the plasma power makes it easier to tailor strip processes to a given set of resist materials properties.

Compared to conventional microwave plasma sources, toroidal RF sources are also less expensive, occupy less space (a valuable attribute for consolidation into resist strip tools) and are simpler to integrate.

COMBINING ADVANCED STRIPPER TOOL WITH TOROIDAL RF PLASMA SOURCES

MKS' remote toroidal RF plasma sources have been evaluated on high throughput photoresist strip tools in production environments. The evaluations show practical operational ranges for gas flow, pressure and power are wider than with nontoroidal ICP sources. Ashing rates are higher than those obtained using microwave or non-toroidal ICP sources in identical equipment. For example, the toroidal RF source gives a much higher ashing rate (10 microns per minute) and better uniformities (6 percent maximum-minimum) with I-line photoresist when compared with equivalent equipment configured with a microwave source. Additionally, a plasma damage measurement (PDM) tool was used to test on-wafer particle charge accumulation in production trials. The particle charge accumulation with remote toroidal RF sources is less than half that observed in similarly-configured downstream microwave systems, and nearly as low as in ozone-based (plasma-free) systems (Figure 6). Further, particle contamination with remote toroidal RF sources was evaluated over two months of production data. The particle count was low and steady, and typically less than one-third of the process specification.

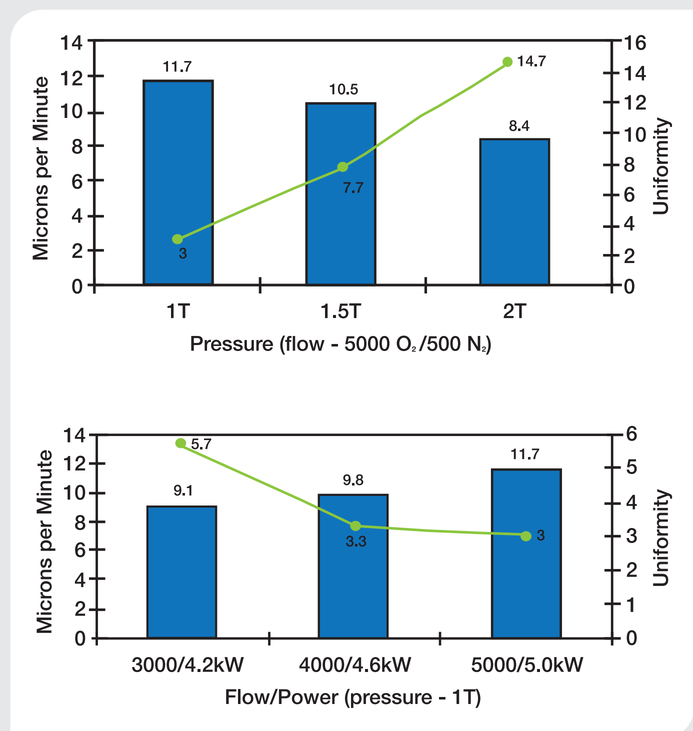

Figure 5 - Strip rates and uniformities achieved using a toroidal RF plasma source.

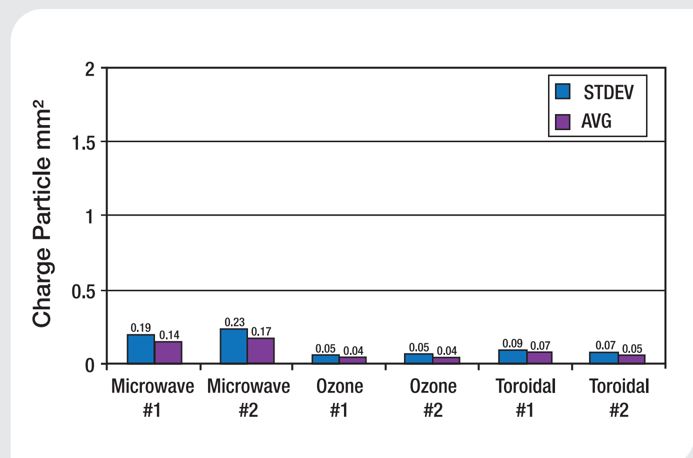

Figure 6 - On-wafer charged particles vs. source type in the advanced stripper configuration shown in Figure 1.

Higher ash rates reduce process time, giving higher throughput and better productivity. Production line tests show reductions of 35 to 40 percent in process times with overall improvements of 10 to 15 percent in productivity for all ashing application (Table 1).

FUTURE DIRECTIONS

The inclusion of fluorine in the process gas stream in toroidal RF systems is being evaluated. The addition of fluorine radicals to the process gas stream is effective for removing implant hardened resist. It improves the reaction kinetics of reactive oxygen neutrals with resist and post-etch crust. The high gas flow in remote toroidal RF sources provides a wide scope for the delivery of higher concentrations of chemically-activated neutrals to substrate surfaces. This potential for manipulation of the stripping chemistry is very attractive for the development of process alternatives in advanced, high-throughput strippers.

In light of the above discussion, it is apparent that the most efficient configurations for an advanced, high-throughput photoresist stripper is one combining very high rate processes, such as those possible with remote toroidal RF sources, and extremely high physical throughput. The combination of advanced strippers and toroidal RF sources offers a unique potential for the development of sophisticated new resist-stripping processes that can address the toughest resist removal problems. For example, the high radical flux downstream of the toroidal RF source yields reasonable ash rate even at lower substrate temperatures. This allows the development of new strip processes in which rate reductions normally observed at reduced wafer temperatures are compensated for by the increased flux of reactive species made possible by the high gas flow in the remote toroidal RF source. This new capability significantly opens the operating range for ashers. For example, Figure 1 shows strip rate data for HDI processing obtained with equipment platforms containing two or three chambers and high-throughput robotics for wafer handling as well as the remote toroidal RF source. It is seen that even at the reduced temperatures employed for HDI strip processes, high wafer throughput (nearly 140 WPH) can be maintained with this equipment combination. It is anticipated that wider operational windows will enable development of novel ashing processes for advanced device fabrication.

Process	Process Time (sec)	
	M/W 1.0	FCIP 1.0
ACTIVE	40	25
N & P Well	53	33
N+, P+	53	33
Normal Etch	40	20
Contact Etch	40	25
Total	226	136

Table 1 - A comparison of strip process times using downstream microwave plasma (M/W 1.0) at toroidal RF sources (FCIP 1.0).

CONCLUSION

The relative simplicity and high performance of remote toroidal RF plasma sources offer a number of process and integration advantages in advanced high-throughput photoresist strip. These sources are proven, robust technologies. Remote toroidal RF sources deliver much higher concentrations of reactive neutrals to the wafer surface than do conventional microwave sources and display strip rates that are at least 2 to 3 times greater than those possible using the microwave sources. This increase in strip rate is accomplished without any increase in plasma damage to the substrate.

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