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In this issue ...

From the Editor ...

• **Electron shading effects in plasmas and high-current ion implanters:** In this issue, we summarize key findings from our P²ID'02, IIT'02, and P²ID'03 papers, which examined electron shading effects in uniform and non-uniform plasmas and high-current ion implanters, using identical resist patterns. This latest work is full of surprises! You will want to update yourself on these important phenomena. (For complete details, you may obtain copies of the original papers from WCM.)

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New and exciting ...

Automated ChargeMap™ is released!

The latest version of ChargeMap – the CHARM-2 data analysis and interpretation software - generates the appropriate wafer maps, J-V plots, and a complete report of all findings **automatically**. The new report format now includes **extensive explanations of the results, and their relevance to charging damage**.

ChargeMap now also includes the DamageMap™. Given the gate oxide breakdown voltage, DamageMap produces a wafer map of charging **currents**, the **real cause** of charging damage. **DamageMap maps may be compared directly to product yield wafer maps**, to determine if a particular processing tool is responsible for **damage to product gate oxide.**

The new ChargeMap also verifies the integrity of the calibration, program, and measure data files to ensure a fool-proof assessment of the charging characteristics of your process tools.

Electron shading effects in plasmas and high-current ion implanters ...

The countless CHARM-2 experiments that we reviewed over the years of working with our customers clearly demonstrated that if plasma non-uniformity (observed with bare CHARM-2 wafers) was minimized, damage to devices was also minimized. This observation was consistent with antenna capacitors experiments reported in the charging literature. However, as our customers pointed out to us, the potentials recorded by bare CHARM-2 wafers were often too low to cause damage to their gate oxides – *yet device damage was still observed!* We emphasized that the potentials and current densities recorded by bare CHARM-2 wafers were lower than the potentials and current densities experienced by devices on patterned wafers as a consequence of the electron-shading effect. But it was clear from the conversations that our customers were often skeptical, and wished they could know the potentials and current densities experienced by devices on their product wafers.

The extensive investigations of charging effects on resist-patterned wafers, summarized here, were done primarily to provide the experimental evidence to show how results obtained on bare CHARM-2 wafers relate to potentials and current densities experienced by devices on resist-patterned product wafers. As you will see, the presence of resist patterns typically creates a worst-case situation for charging. However, bare CHARM-2 wafers still provide the proper information to help minimize that charging.

To study pattern-induced charging effects, a special-purpose six-field mask was developed to pattern resist on CHARM-2 wafers. In one field, the resist was completely removed from the entire die. In another field, the resist completely covered the entire die. In the remaining four fields, holes were patterned on the charge-collection electrodes of CHARM-2 potential and charge-flux sensors using 2µm, 1.5µm, 1µm, and 0.5µm design rules. CHARM-2 wafers were patterned using 1.2µm resist, and processed in plasma oxide etchers and high-current ion implanters. Un-patterned (bare) CHARM-2 wafers were also used in each experiment as process monitors.

Uniform vs. non-uniform plasmas

Typical results obtained in an etcher exhibiting excellent plasma uniformity - where a bare CHARM-2 wafer showed no response - are illustrated in Figure 1, which shows the positive current density measured in the 2µm, 1.5µm, 1µm, and 0.5µm resist holes. (In each pattern, the measured current was divided by the total area of the resist holes, to obtain current density in the holes, in A/cm^2.)

A large increase in positive potentials and positive current density was observed when hole size decreased, consistent with the "electron shading" effect. (Conversely, negative potentials and negative current density *decreased* when hole size decreased, as expected.) This behavior is due to negative charging of the inside top of resist holes, which prevents plasma electrons from entering the holes to neutralize the positive ion flux.

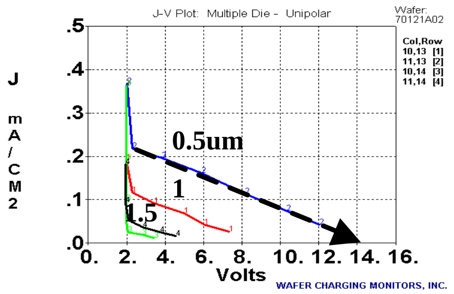


Figure 1. Positive J-V plots for 2µm, 1.5µm, 1µm, and 0.5µm holes in a uniform plasma oxide etcher. (The vertical asymptote at ~ 2V comes from non-responding sensors, and should be ignored.)

As shown in Figure 1, the peak positive potentials developed in the 0.5µm holes, are sufficient to cause conduction in contemporary gate oxides. (Extrapolation of the 0.5µm J-V plot to J=0 shows peak positive potential of ~14V.) Unfortunately, because electron-shading is a general effect that arises from the presence of resist patterns in plasmas, this is the best that can be done at the process level! This means that even uniform plasma oxide etchers are capable of causing damage in contemporary technologies, and that antenna design rules are the only resource that can be employed to reduce damage to acceptable levels.

How does this compare with results obtained in a non-uniform plasma which, as we know, is more damaging? Let's look at Figure 2, which shows the positive J-V plots for the 0.5µm holes at different locations from the center of the wafer in a non-uniform plasma, and Figure 3, which shows the positive J-V plots obtained on a bare CHARM-2 wafer at the same die locations.

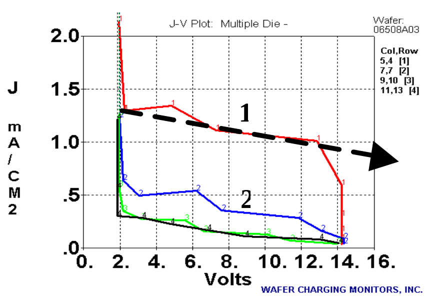


Figure 2. Positive J-V plots for 0.5µm holes at different locations from the center of the wafer. (The irregularities in the J-V plots are due to spatial charging variation within a die.) Sensors are saturated at ~14V, truncating the J-V plots at ~14V.

The bottom two J-V plots in Figure 2 are due to electron shading only, since they come from a region of the wafer characterized by a uniform plasma (as evident from Figure 3, where the corresponding J-V plots for these locations appear as no-response, vertical lines). The bottom two J-V plots in Figure 2 are also similar to the 0.5µm plot in Figure 1 for the uniform plasma tool.

However, even slight plasma non-uniformity, which gives rise to the barely noticeable J-V plot 2 in Figure 3, causes increased charging stress, as shown by plot 2 in Figure 2. As might be expected, greater plasma non-uniformity, indicated by J-V plot 1 in Figure 3, gives rise to still greater charging stress, as shown by plot 1 in Figure 2. In fact, the extrapolation of plot 1 in Figure 2 to J=0 suggests positive potentials of ~50V ! (The dynamic range of the potential sensors is ~14V on this CHARM-2 wafer, causing plot 1 to be truncated at 14V.)

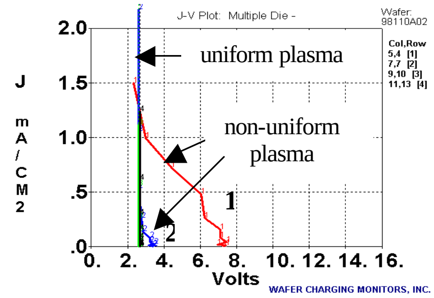


Figure 3. Positive J-V plots from a bare wafer at the same locations as shown in Figure 2. (Vertical lines at ~ 2.5V are due to non-responding sensors.)

This huge increase in positive charging occurs because electron-shading effect and plasma non-uniformity are independent effects, each of which contributes to the overall charging stress! Consequently, much higher potentials and charging currents are developed during etching in regions of plasma non-uniformity, which requires much more conservative antenna design rules to limit damage to acceptable levels. Conversely, to minimize damage during wafer manufacturing (when designs cannot be changed), plasma non-uniformity needs to be completely eliminated!

Since "electron shading" is a general effect that arises from the presence of resist patterns in plasmas, other etchers – such as polysilicon or metal etchers – also behave in a similar way.

These results also demonstrate that, for the purpose of minimizing damage on patterned product wafers, it is sufficient to work with bare CHARM-2 wafers as detectors, because eliminating the plasma non-uniformity detected by bare CHARM-2 wafers will automatically minimize the charging stress on resist-patterned product wafers.

When there is no resist -- sputter pre-cleans

What if there is no resist pattern on the wafer? Electron shading effects can still be present and cause more severe charging than recorded by bare CHARM-2 wafers. For example, during the sputter pre-clean step in metal depositions, negative charging of the inside top of high aspect ratio vias in an oxide layer will cause electron shading. In this case, the electron shading is caused by the wafer topography itself. As a consequence, product wafers will experience more severe charging stress during sputter pre-cleans than will bare CHARM-2 wafers – analogous to the oxide etching examples. Consequently, to minimize damage during sputter pre-cleans, plasma non-uniformity needs to be completely eliminated!

PFS-equipped high-current ion implanters

The results obtained in plasma tools made us wonder what happens in high current ion implanters. After all, many implanters use plasma flood systems (PFS) to control wafer charging. Do these implanters behave like plasma tools? The pursuit of this answer led to some real surprises!

We began our investigation of resist-pattern-induced charging during implantation with experiments using standard, high-energy, production As^+ and BF_2^+ implants performed in the AMAT 9500 high-current ion implanter equipped with a first-generation PFS. The positive J-V plots obtained from the 80 keV, 2e15/cm^2 As^+ implant are shown in Figures 4a-4d. The huge increase in positive charging in the presence of resist patterns is evident from a comparison of Figure 4a (bare wafer) with Figures 4b-4d (resist-patterned wafer). Again, it is apparent that the bare CHARM-2 wafer provides a measure of non-ideal performance, which must be minimized to minimize charging damage, but the actual charging stress experienced by resist-patterned wafers is much greater. Moreover, figures 4b-4d are nearly identical, indicating that the positive current density is independent of the size of the resist hole. The corresponding set of negative J-V plots obtained on patterned wafers from the As^+ implant were also nearly identical, indicating that negative charging was also independent of the size of the resist hole. Similar results were obtained for the 50 keV, 2e15/cm^2 BF_2^+ implant.

What a surprise! Both positive and negative current densities measured in the resist holes were independent of the size (or, equivalently, the aspect ratio) of the resist holes. This was completely different from what was observed in plasma tools!

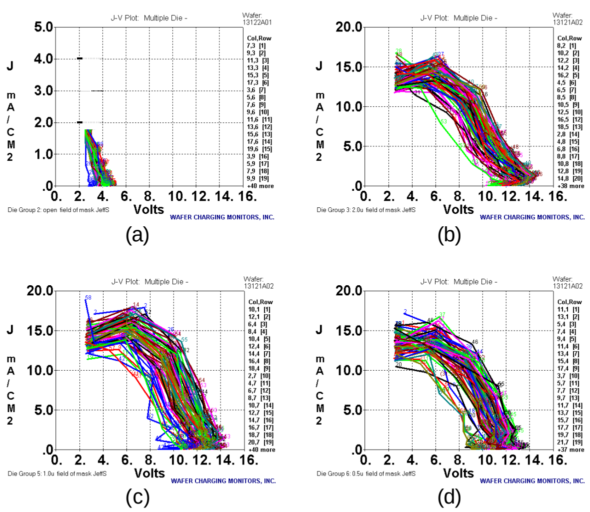


Figure 4. Positive J-V plots recorded during high-energy As implant: (a) bare wafer (note different J scale); (b) 2µm holes; (c) 1µm holes; (d) 0.5µm holes.

The above As^+ and BF_2^+ results suggested incomplete neutralization of the ion beam-induced positive charging, based on the following argument: in the case of insufficient negative charge, the positively charged resist collects the secondary electrons produced by the beam at the bottom of the resist hole. This results in a positive current density at the bottom of the resist hole, whose magnitude is independent of hole size, because it is a product of the beam current density and the secondary electron emission coefficient, both of which are independent of hole size.

To confirm that insufficient charge neutralization was, indeed, the cause of the feature size-independent charging in Figures 4b-4d, the second experiment compared two 80 keV, 2e15/cm^2 As^+ implants performed in the same AMAT 9500 at two different PFS settings -- one low, and one high.

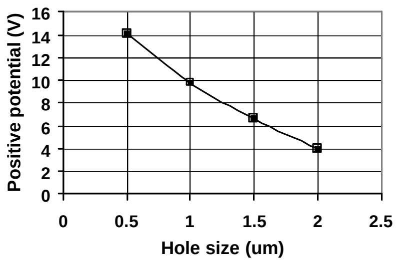
Consistent with past experience, comparing these two implants showed that the low PFS setting produced higher positive potentials and lower negative potentials, while the high PFS setting produced lower positive potentials and higher negative potentials. But, to our surprise, even the high PFS setting (which we expected to provide sufficient neutralization, and exhibit electron shading) produced positive and negative potentials and current densities which were again *independent of hole size!*

To explain these results, we now started thinking about ion energies. Maybe the much higher ion energies used in the implants were responsible for the feature size-independent charging observed so far. We wondered what would happen if implant ion energy approached ion energies used in etching plasmas. Maybe the feature size-dependent charging observed in plasmas would then be observed during ion implants.

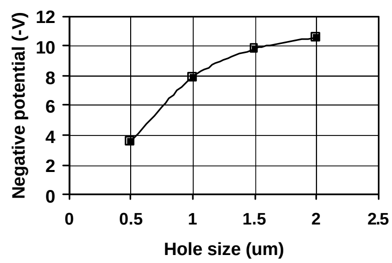
Consequently, in the third experiment, we decided to look at *low* ion energies. We compared two 500 eV, 1e15/cm^2 B^+ implants performed in the AMAT xR LEAP Q ion implanter equipped with a second-generation high-density plasma flood system (HD-PFS). One implant used the standard, recommended HD-PFS mode (A/D mode), which provides high-density, low electron temperature plasma, whereas the other implant used the "bias" mode, which provides a significantly higher electron temperature, lower density plasma.

The results obtained with the "bias" mode (not recommended by AMAT) again showed both positive and negative J-V plots that were independent of hole size. However, in the results obtained with the A/D mode (recommended by AMAT), both positive and negative potentials showed a marked dependence on hole size, and the positive potentials, shown in Figure 5(a), increased with decreasing hole size, while the negative potentials, shown in Figure 5(b), decreased with decreasing hole size, in accordance with the "electron-shading" effect. Moreover, in the A/D mode, both positive and negative current densities were below CHARM-2 detection levels (thus, there were no J-V plots), which indicated superb charge neutralization.

To achieve the very low (undetectable) positive charge flux in the resist holes under the beam, the HD-PFS had to achieve a nearly uncharged resist surface, which would neither impede electron transport into the resist holes nor attract secondary electrons out of the resist holes. This was, indeed, confirmed by the positive potential sensors under the resist, which showed a very small response, indicating only slight positive charging of the resist surface. This superb charge neutralization is attributed to the low electron temperature plasma of the HD-PFS standard A/D mode, while the slight electron-shading effect shown in Figure 5 is thought to result from the higher density plasma of the HD-PFS standard A/D mode.



(a)



(b)

Figure 5. Positive and negative potentials recorded during 500 eV B^+ implant using the recommended A/D plasma flood set-up: (a) positive potentials; (b) negative potentials. Current densities were below CHARM-2 detection levels.

The HD-PFS results thus indicate that, because plasma flood and ion beam parameters are *independently* controlled, it is possible to achieve a nearly perfect balance between electron flood and beam charging, and thus to avoid charging damage, with the use of **properly designed and properly set-up** plasma flood system[1]. The surprising result was that electron shading was observed as an artifact of PFS design (HD-PFS vs. PFS) and set-up (A/D mode vs. "bias" mode), rather than PFS output (high or low) or ion energy (high or low), as was initially conjectured.

Summary

The different results obtained with the older AMAT 9500 high-current ion implanter equipped with a first-generation PFS vs. the AMAT xR LEAP Q ion implanter equipped with a second-generation HD-PFS illustrate the improvement in the understanding and design of implanter plasma flood systems. The AMAT 9500 examples also demonstrate that production-worthy implants are often ***not*** optimally neutralized. On the other hand, the AMAT xR LEAP Q results show that even a properly designed HD-PFS may not provide optimal neutralization, if it is not properly operated.

The on-going evolution and improvement in plasma uniformity and charging performance of plasma tools has been evident to us through the years, as well. However, because ions and electrons in plasma tools are not de-coupled to the same extent as in ion implanters, *even with uniform plasmas* the electron-shading effect will continue to hamper the charging performance of plasma tools, and pose problems that will need to be solved to avoid charging damage.

[1] Other types of charge-control systems were not evaluated.

ACKNOWLEDGMENTS:

It is a real pleasure to acknowledge the extensive collaboration with our colleagues, which led to the unified understanding of pattern-induced charging effects in ion implanters and plasma tools described in this Bulletin. We are particularly indebted to Dr. Jeffrey Shields of Microchip Technology, who designed the resist mask used in these experiments, and who coordinated many of the experiments described here. Special thanks go to Dr. Sonu Daryanani of Microchip for performing the first two implant experiments, and to Dr. Larry Larson and Todd Rhoad of SEMATECH for arranging the second round of implants. We also thank Dr. Michael Current and Dennis Wagner for planning the second round of implant experiments, and Dr. Michael Vella for his ideas about PFS operation.

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