8th International Symposium on Plasma- and Process-Induced Damage
April 24-25, 2003,Corbeil-Essonnes, France

Investigation of Electron-Shading Effects during High-Current Ion Implants

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***Abstract*-Charging characteristics of As^+, BF_2^+, and B^+ high-current ion implants, performed at different energies and different plasma flood system settings, were measured using bare and resist-covered CHARM®-2 wafers patterned with a six-field mask containing holes ranging from 2 um to 0.5 um (clear and resist-covered fields were also used). The results show significant differences in the charging characteristics of high-current ion implanters compared to contemporary plasma-based process tools. The differences appear to be independent of ion energy, but depend on the set-up conditions of the plasma flood system used to limit positive charging caused by the ion beam. In contrast to plasma tools, the implants typically exhibited positive and negative potentials independent of hole size. The positive and negative current densities measured in the resist holes were also independent of hole size (and significantly higher than in the clear field). However, a 500 eV B^+ implant with modern plasma flood control produced positive and negative potentials that scaled with hole size, as expected for electron shading, but with current densities below CHARM®-2 detection levels. This establishes an existence proof that optimal plasma flood can achieve near perfect current balance between the positive charging from the ion beam and the negative charging from the flood plasma. Altogether, these results suggest that charging damage in high-current ion implanters should be controllable when implant mask and device features are scaled down.**

I. INTRODUCTION

Because contemporary ion implanters use plasma flood systems[1] to neutralize ion beam induced positive charging, the purpose of this work was to investigate whether electron-shading effects play a role in implant charging.

It is well known that the presence of photoresist on wafers profoundly affects wafer charging damage during high current ion implants. Significant observations about this were made in early studies which used "antenna" capacitors as detectors [1]. Understanding of the physical mechanisms came from the use of the EEPROM-based CHARM®-2 monitors, which allowed in-situ measurements of peak potentials and peak charge-fluxes experienced by device structures on the surface of a wafer [2]. Early experiments with CHARM®-2 monitors covered with uniform [3] and patterned resist films [4] showed large increases in positive charging associated with the presence of resist on CHARM®-2 sensors during high current ion implants. Experiments employing resist layout types used on CMOS product wafers [5] confirmed the large increases in positive charging in the presence of resist patterned with a dark-field mask [6]. However, the resist feature sizes used in [6] were on the order of 100s of microns, which are significantly larger than contemporary device design rules. The purpose of the present work was to quantify charging phenomena associated with resist patterns using contemporary feature sizes.

II. EXPERIMENTAL PROCEDURES

In all present experiments, CHARM®-2 wafers were patterned with 1.2μm resist using a six-field resist mask. 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, the resist covered the entire die, but holes were patterned on the charge-collection electrodes (antennas) of the potential and charge-flux sensors using 2μm, 1.5μm, 1μm, and 0.5μm design rules. The wafers were exposed to standard As^+, BF_2^+, and B^+ implants. Un-patterned (no resist) CHARM-2 wafers, placed on the opposite side of the wheel, were used with each implant as implant monitors.

The first experiment compared standard As^+ and BF_2^+ implants performed in the AMAT 9500 high-current ion implanter equipped with a first-generation plasma flood system (PFS) to control wafer charging. The As^+ implant (As1) was 80 keV, 2e15/cm^2, at a beam current of 10 mA and peak current density of 0.48 mA/cm^2. The BF_2^+ implant was 50 keV, 2e15/cm^2, at a beam current of 6.5 mA and peak current density of 1.26 mA/cm^2. The PFS was set to arc current of 4 A, and 1.2 sccm of Ar for both implants. The arc voltage was 30 V, and the guide tube voltage was -10 V.

Since qualitatively similar results were obtained for both As^+ and BF_2^+ implants, the second experiment

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[1] Even in when plasma flood is not used, the impact of the ion beam with background gases generates a weak plasma.

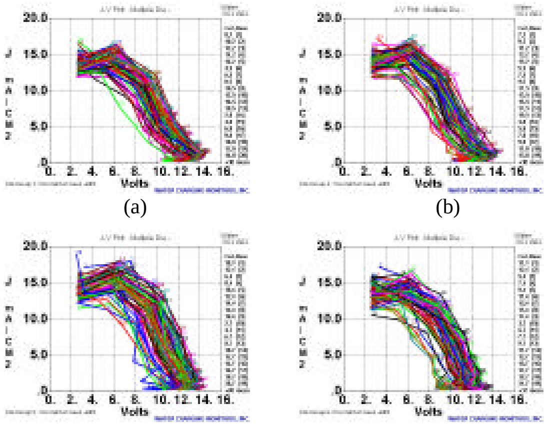
compared 80 keV, 2e15/cm^2 As$^+$ implants performed in the same AMAT 9500 at two different PFS settings. One implant (As2) was performed at a beam current of 10 mA, peak current density of 1.09 mA/cm^2, and flood arc current of 2 A (low setting). The other implant (As3) was performed at the same beam current, peak current density of 1.15 mA/cm^2, and flood arc current of 5 A (high setting).

To investigate the effect of low ion energies and plasma flood set-up conditions, which affect the output and electron temperature of the flood plasma, the third experiment compared implants performed in the AMAT xR LEAP Q ion implanter equipped with a second-generation high-density plasma flood system (HD-PFS) [7]. The 500 eV, 1e15/cm^2 B$^+$ implants were performed at a beam current of 1.4 mA and beam current density of 0.1 mA/cm^2. One implant used the standard, recommended HD-PFS mode (A/D mode), which provides a high-density, low electron temperature plasma, whereas the second implant used the "bias" mode, which provides a significantly higher electron temperature, lower density plasma. Both implants used 0.5 A, 30 V flood arc, guide tube voltage of 0 V, and 0.8 sccm of Argon.

The J values in the J-V plots shown here were obtained by dividing the collected currents by the area of the resist openings. Consequently, the J values represent the positive or negative current densities measured in the resist holes. The J-V graphs show J-V plots from the same field over the entire wafer.

III. EXPERIMENTAL RESULTS

The positive J-V plots obtained from the 80 keV, 2e15/cm^2 As implant (As1) implant are shown in Figures 1a-1d. Figures 1a-1d are nearly identical, indicating that the positive current density is independent of the size of the resist hole. Similar results were obtained for the 50 keV, 2e15/cm^2, BF$_2^+$ implant [8].

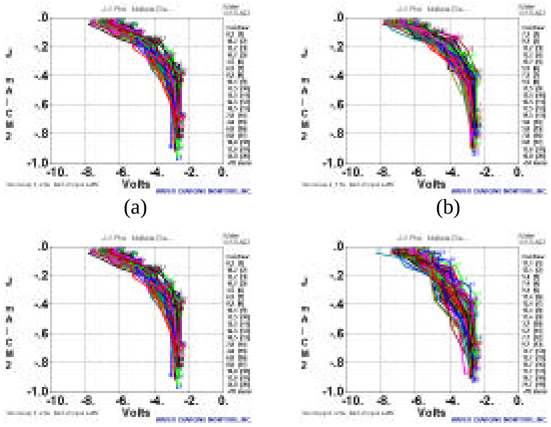


(a) (b)

(c) (d)

Figure 1. Positive J-V plots recorded during the As1 implant: (a) 2µm holes; (b) 1.5µm holes; (c) 1µm holes; (d) 0.5µm holes.

The corresponding set of negative J-V plots obtained from the As1 implant is shown in Figures 2a-2d. Figures 2a-2d are nearly identical, indicating that the negative charging is also independent of the size of the resist hole. Similar results were obtained for the BF$_2^+$ implant [8].

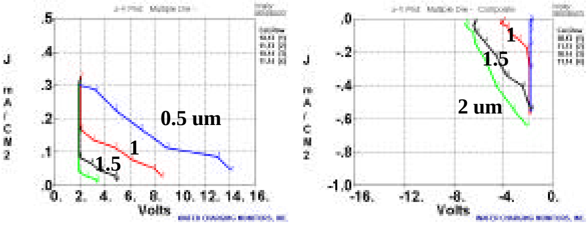


(a) (b)

(c) (d)

Figure 2. Negative J-V plots recorded during the As1 implant: (a) 2µm holes; (b) 1.5µm holes; (c) 1µm holes; (d) 0.5µm holes. (The asymptote at ~ -2.5 V comes from non-responding sensors, and should be ignored.)

The most striking observation from these experiments is that both positive and negative current densities measured in the resist holes are independent of the size (or, equivalently, the aspect ratio) of the resist holes. This is completely different from what is observed in plasma tools, which show a strong increase in positive charging (and a strong decrease in negative charging) with decreasing hole size [9]. Example J-V plots, obtained in a non-uniform plasma tool (which would most resemble a high-current ion implanter), using the same resist patterns, are shown in Figures 3a-b.

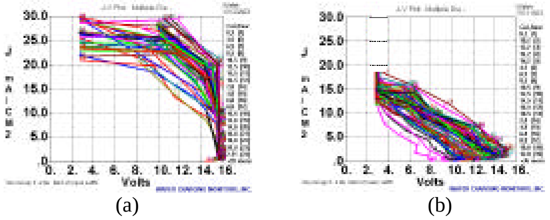


(a) (b)

Figure 3. J-V plots for 2µm, 1.5µm, 1µm, and 0.5µm holes obtained in non-uniform plasma etcher: (a) positive J-V, (b) negative J-V.

The two different PFS settings used in the second experiment also produced positive and negative current densities which were independent of hole size, as in the first experiment. However, the low setting produced higher positive potentials and current densities, shown in Figure 4a, than the high setting, shown in Figure 4b. This behavior was expected, and illustrates how increased PFS output reduces beam-induced positive charging.

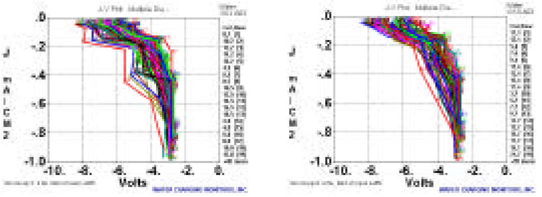
Although the peak potentials shown in Figure 4b are still relatively high, and the positive current densities are very high, they may not necessarily cause device damage. It must be remembered that charging in high current ion implanters occurs in pulses, as the wafer moves past the beam on a rotating wheel. The resulting depletion layers under n-channel devices, and the reverse-biased N-well junctions under p-channel devices, can support relatively high positive voltages and prevent positive current flow through gate oxides [10] thereby protecting devices from even relatively high positive charging.



(a) (b)

Figure 4. Positive J-V plots recorded in 2 um holes during (a) the As2 (low PFS setting) implant - charge-flux sensors are saturated at ~16V, truncating the J-V plots; (b) the As3 (high PFS setting) implant.

Moreover, the increased flood required to significantly reduce positive charging, as shown in Figure 4(b), does not generate negative current densities which would damage n-channel devices. Although the negative potentials are sufficiently high to inject current into contemporary gate oxides, as shown in Figure 5, the low-level damage caused by negative charging is annealed out during the high-temperature implant activation step.

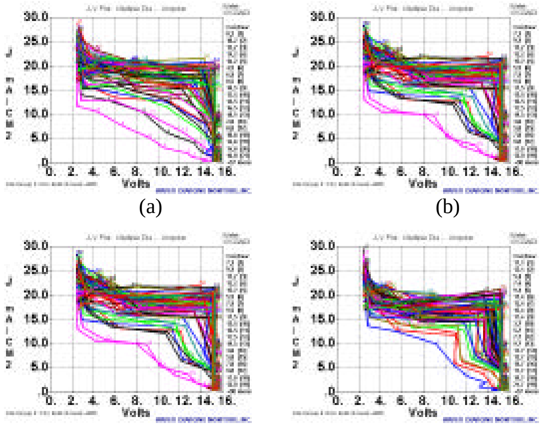


(a) (b)

Figure 5. Negative J-V plots recorded during the As3 (high flood) implant: (a) 2µm holes; (b) 0.5µm holes. (The asymptote at ~ -2.6 V comes from non-responding sensors, and should be ignored.)

As the above results were obtained during high energy implants, it was speculated that different results might be obtained when implant ion energies are lower, approaching ion energies encountered in etching plasmas. However, the positive and negative J-V plots from the 500 eV B^+ implants in Figures 6 and 7 show that when the HD-PFS flood system is set in the "bias" mode (not recommended by AMAT), the results are similar to those obtained for the high energy implants in the PFS-equipped AMAT 9500: again, both positive and negative J-V plots are independent of hole size. It should be noted that the "bias" mode is believed to provide a lower-density, higher electron temperature plasma than the standard A/D mode.

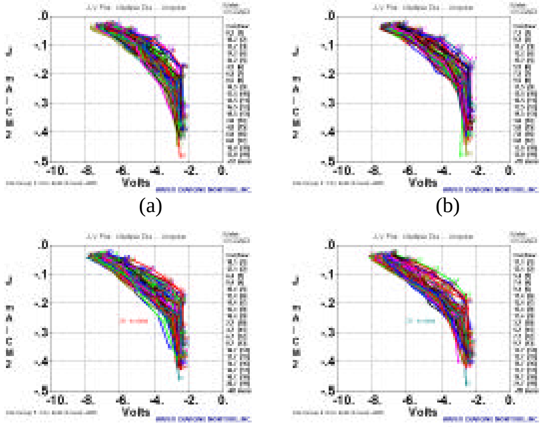
In contrast, both positive and negative potentials from the 500 eV, B^+ implants done in the HD-PFS recommended A/D mode showed a dependence on hole size, as shown in Figure 8. The positive potentials in Figure 8(a) increased with decreasing hole size, while the negative potentials in Figure 8(b) decreased with decreasing hole size, in accordance with the "electron-shading" effect [11].



(a) (b)

(c) (d)

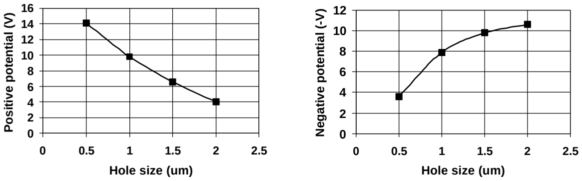
Figure 6. Positive J-V plots recorded during 500 eV B^+ implant using HD-PFS "bias" flood set-up: (a) 2µm holes; (b) 1.5µm holes; (c) 1µm holes; (d) 0.5µm holes.



(a) (b)

(c) (d)

Figure 7. Negative J-V plots recorded during 500 eV B^+ implant using HD-PFS "bias" plasma flood set-up: (a) 2µm holes; (b) 1.5µm holes; (c) 1µm holes; (d) 0.5µm holes. (The asymptote at ~ -2.2 V comes from non-responding sensors, and should be ignored.)



(a) (b)

Figure 8. 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.

In the A/D mode, both positive and negative current densities were below CHARM-2 detection levels (thus no J-V plots are possible), indicating excellent charge neutralization. The HD-PFS A/D mode is thought to provide a higher-density, lower electron temperature plasma, and has demonstrated more robust control of charging damage than the first-generation PFS [7].

IV. DISCUSSION OF RESULTS

In high-current ion implanters, positive charging of wafer surface arises primarily from the emission of secondary electrons generated by the implanted ions[2]. Ideally, a plasma flood system provides a source of low-energy electrons which neutralize positive potentials and current density in a self-regulating manner. As evidenced by our results, to what extent this actually occurs depends on the design and set-up of the plasma flood system. Because the plasma flood system is controlled independently of the ion beam, it is in fact possible to provide insufficient negative charge, or excess negative charge – and anything else in between – relative to the positive charging caused by the ion beam. With the exception of the 500 eV B^+ implant using the HD-PFS recommended A/D setting, the results presented here indicate incomplete neutralization of the ion beam-induced positive charging[3].

The following mechanism explains the results obtained in the high-energy implants and the 500 eV B^+ implant using the “bias” mode. The positively charged resist [3] collects the secondary electrons produced by the beam at the bottom of the resist hole and repels the (low-energy) plasma ions, resulting in a positive current density $J_b(a+\gamma)$, where J_b is the beam current density, a is the un-neutralized fraction of the ion beam (between 0 and 1), and γ is the secondary electron emission coefficient. This process is independent of feature size (at least for small features).

To achieve very low positive charge flux in the resist holes when under the beam, as in the case of the optimally-neutralized 500 eV B^+ implant, the resist surface should be nearly uncharged, so as not to impede electron transport into the resist hole, or not to attract secondary electrons out of the resist hole. Indeed, the positive potential sensors under the resist show a very small response, indicating only slight positive charging of the resist surface. This was achieved by a more dense, lower electron temperature, plasma produced by the HD-PFS standard A/D mode. The higher density plasma, in turn, leads to the observation of the electron-shading effect on the extremely sensitive potential sensors, as shown in Figure 8.

V. CONCLUSIONS

Wafer charging characteristics of high current As^+, BF_2^+, and B^+ implants were evaluated using CHARM-2 wafers covered with patterned 1.2μm resist. Positive and negative current densities measured in 2μm, 1.5μm, 1μm, and 0.5μm holes indicate that, because plasma flood and ion beam parameters are *independently* controlled, it is possible to achieve a nearly perfect balance between flood and beam charging, as evidenced by lack of response on the CHARM-2 charge-flux sensors. The observation of electron-shading effects in the 500 eV B+ optimally flooded implant constitutes the first report of electron-shading in an ion implant system. The surprise is that electron-shading was observed as an artifact of plasma flood operation, not implant energy, as was initially conjectured. Because nearly perfect neutralization of the beam-induced charging is possible with the use of properly designed and properly set-up plasma flood system[4], **c**harging damage in high-current ion implanters should not be a problem as implant mask and device features are scaled down[5].

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[2] Typically, the beam is arranged to be nearly charge-neutral to prevent beam blow-up, which would cause dose non-uniformity.

[3] As discussed in the previous section, this will not necessarily cause device damage.

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

[5] Absolute confirmation of this requires charging evaluation of high energy implants done on the AMAT xR LEAP Q ion implanter equipped with the high-density plasma flood system (HD-PFS). These are planned for the future.