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Influence of Etch Process Sequence on CHARM-2 Wafer in Magnetically Enhanced RIE Etcher

Makoto Kobayashi, Hiromi Sakima, Eiichi Nishimura
Tokyo Electron Massachusetts, Inc.
123 Brimbal Avenue, Beverly, Massachusetts, 01915, USA

Abstract

A bare CHARM-2 wafer has been evaluated in a Magnetically Enhanced Reactive Ion Etching (MERIE) apparatus in order to investigate the effect of a magnetic field on the charging phenomena. The monitor device responded, showing some correlation to the magnetic field. On investigation of the mechanism of the response, it appeared the response on the wafer consisted of two factors. One mechanism was demonstrated to be wafer chucking and de-chucking. The other mechanism explored was the MERIE RF plasma itself. It was shown that by optimization of the wafer chucking / de-chucking sequence and RF plasma condition, the response was greatly reduced. Also by utilizing this technique it was demonstrated that a CHARM-2 wafer could be processed without any appreciable fingerprints from the magnetic field. The optimized recipe and sequence were also applied to Tokyo Electron Limited (TEL) internal antenna MOS device which allow the estimation of electron shading effects in order to investigate the correlation between the two types of devices.

1. Introduction

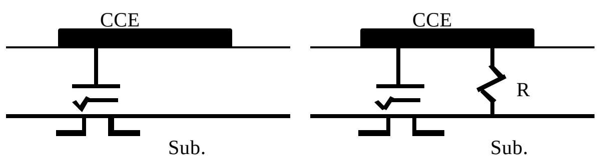
The influence of Plasma Induced damage during the dielectric film etching on various semiconductor devices and processing tools has been discussed frequently. Some Magnetically Enhanced Ion Etching (MERIE) chambers have been regarded to have a potential to cause charging damage. This is usually attributed to the magnetic field that is applied causing a non-uniform self-bias voltage (Vdc) across the wafer [1]. In the meantime, some new charging monitoring methods and products have been developed. These tools and methods facilitate the investigation of charging phenomena and effects that occur during ULSI process. The CHARM-2 wafer [2], created by Wafer Charging Monitor, INC., is one such tool. CHARM-2 wafer testers were used with the TEL Unity 85 dipole-ring magnet (DRM) MERIE system in order to study the charging phenomena in the presence of magnetic fields in this experiment. In the initial condition / baseline process, the monitor device responded significantly with some distinct correlation to the magnetic field flux on the wafer. As the root cause of the response and the solution to the issue was pursued, it was found that the initial response correlated to the magnetic field flux of the magnet can be greatly reduced and possibly eliminated. The optimized process sequencing were applied to the antenna devices which are used to characterize the electron shading damage, in order to verify if the technique from the CHARM-2 study is effective for the different type of charging monitor sample.

2. Experimental

As a plasma reactor, TEL Unity 85 dipole-ring magnet (DRM) system was used in this experiment. The system utilizes circular permanent magnets which are physically rotated around the reactor to achieve good process performance, i.e. etching rate uniformity and selectivity to the bottom layer and photoresist. An electro-static chuck (ESC) is also utilized on the system for a wafer clamping.

The 8-inch CHARM-2 wafers employed 355 sites populated with EEPROM-based polarity-sensitive sensors [3]. In this study the response of two types of sensors were looked at; i.e. potential sensors (**fig. 1-a**) and current sensors (**fig. 1-b**). Potential sensors give magnitudes of the maximum surface voltage that was seen during etching. This is sometimes described as a "peak sensor". The current sensors give the J-V characteristic seen by the charge collection electrode (CCE). Distinct sensors with different preprogramming voltage polarities record both negative and positive voltages and currents. Bare CHARM-2 wafers, which were not coated with photoresist, were used in this experiment.

In order to investigate and cross correlate the effects and results obtained from CHARM-2 experiments, the optimum results were validated on capacitor based antenna type devices as well. "APEX" structures (Tokyo electron Limited, **fig. 2**), were used in this evaluation. This capacitor based damage monitor device has capacitors with hole intensive antenna which are fabricated on the p-type Si substrates. The gate oxide thickness used was 4nm. In order to investigate charge buildup by electron shading effect [4], poly-silicon antenna is covered by 1 m BPSG film and patterned with KrF resist which has some hole size variety (0.25-2.0 m). After exposing the APEX damage monitor to plasma, the leakage current between poly-silicon electrode and substrate was measured with poly-Si electrode to substrate bias set at -5V.



- a **- b**

Figure 1. *CHARM-2 potential sensor (a) and current sensor (b) [3].*

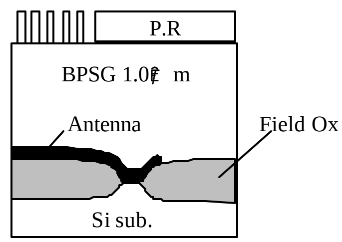


Figure 2. *Antenna device "APEX" structure*

3. Results and discussion

In the first experiment, the CHARM-2 wafers were exposed to a standard contact etch process condition. The etching chemistry was C4F8/CO/Ar/O2, and reactor pressure was 30mT and RF power was 1700W that is generally used for a silicon dioxide etching. Positive and negative potential sensors recorded high potentials distributed non-uniformly across the wafer (**fig. 3-a,b**). Note; the positive potential sensor saturates at +14V. This indicated that a non-uniform plasma existed at some point during the process. Both positive and negative current sensors also responded (**fig. 3-c,d**). To characterize the current response numerically, J (amp/cm^2) at +- 4V are taken into account after this. Both positive and negative current sensors responded as 0.4mA/cm^2 and –0.3mA/cm^2 in this initial condition.

In order to investigate the root cause of these responses, an experiment was designed. One split was run through the ESC chucking but no RF plasma exposure (**fig. 4**). Another split was run with plasma exposure but no ESC chucking voltage applied (**fig. 5**). In the case of chucking only, both positive and negative potentials were recorded but current sensors were little responded. For the other case of plasma exposure without chucking, positive potential was recorded but negative potential was not.

This experiment indicates that there were charging effects which were induced from ESC chucking and RF plasma in this CHARM-2 response. Positive potential appeared to be driven by the effect of both ESC and plasma. Negative potential, however, seemed to be a function of the ESC chucking. As might be expected, CHARM-2 current responses were affected mainly by RF plasma exposure.

At first step of optimizing overall performance, the reduction of potential response was focused on. ESC chucking / de-chucking sequence was explored to reduce both polarity potential responses. It has been reported that wafer cramping system sometimes causes strong charging effect on the VLSI process [5]. In order to understand the experiment, the wafer clamp sequence is described below. For wafer chucking, a DC discharge is generated by +2.5kv DC voltage after the wafer comes into the reactor in order to create wafer chucking force. This DC plasma induces a transient electron flux onto the wafer, and the potential gap between wafer and ESC voltage is said to be a chucking force. This chucking sequence has been labeled "Gas chucking" due to the fact that the DC plasma and gas effectively 'chuck' the wafer. For de-chucking the wafer, RF power is turned off and the conductive lifter pins are brought into contact with the wafer backside. This creates a discharge path through the lifter pins. This sequence is referred "Pin de-chucking".

It was decided to explore replacing the sequence described above with the following new sequence to see if the new sequence would modulate the charging damage effects seen.

For wafer chucking, "Pin chucking" was used which gives the electron injection to the wafer through the lifter pins when the wafer is set onto the ESC. By using this chucking method, it was determined that the negative potential was remarkably reduced. This indicated that a good deal of the negative potential charged up seen was generated by DC plasma strike for wafer chucking.

For de-chucking, "Plasma de-chucking" was explored. Essentially this is described as "ESC chuck voltage off first, then RF plasma-off". This in turn would induce an electron flux onto the wafer during RF plasma strike without chucking voltage present. Thus the remaining charge on the wafer is neutralized in this manner. By using this de-chucking method, positive potential was effectively removed.

At this point, the response of the current sensors through the sequence modification was not reduced, even gradually increased. There was still some component of response which remained as a function of the RF plasma. The results of this series of experiment are shown in **fig. 6**.

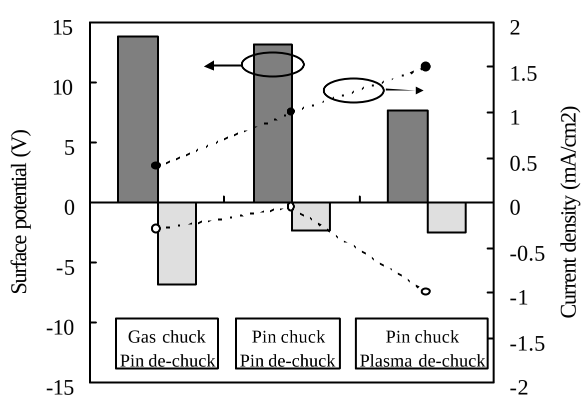
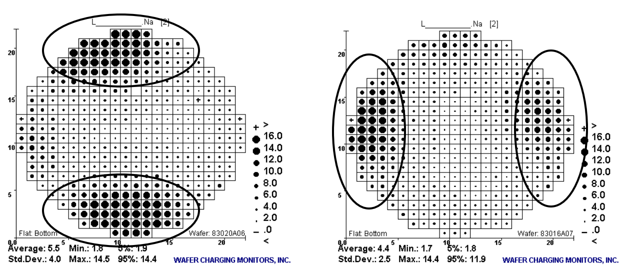


Figure 6. *Change of CHARM-2 responses by changing chuck / de-chuck sequence. Potential sensors are saturated at +- 14V and minimum detective limits are +- 2V*

The next step required was to attempt to modulate the process in an effort to minimize the effects driven by the RF plasma. The positive potential map is illustrated a unique distribution whereby there was a high potential peak on the wafer edge. This indicated an important fact. If the peak appeared during the plasma ignition or throughout the entire process, it likely would not be located in a local area but spread out across the wafer. Keep in mind that the magnet is continuously rotating before and during the etching at 20 rpm. In addition the CHARM-2 wafer monitor records effectively the maximum values which can not be erased once they are recorded or seen. It was theorized that the highly localized peak recorded must have been formed from an instantaneous phenomena, not from continuous plasma exposure. To understand more clearly the phenomena, a different type of modified magnet was used in the next experiment. This magnet was designed to give a unique fingerprint with two sharp potential peaks on the edge of the wafer at the North pole and South pole of the magnet.

In order to find out the moment at which the maximum potential peak was reached the following experiment was performed. The ESC voltage was even cut-off to be able to better isolate and eliminate any potential effects from ESC. The CHARM-2 wafer was exposed to the plasma with the magnet rotation stopped (**fig. 7-a**). Another CHARM-2 wafer was exposed in the same way, but the magnet was rotated 90 degrees before the plasma was turned off. The location of the two peaks had moved 90degree thus following the magnet ending location (**fig. 7-b**). This result indicated the peaks were caused at the transient moment of RF plasma turn off as a function of both the turn off and the magnetic field flux on the wafer.



-a **- b**

Figure 7. *Positive potential response without magnet rotation (a). Magnet was rotated 90degree before the plasma turned off (b).*

In order to eliminate the potential peak, Argon (Ar) plasma in a high pressure (150mT) and low power (300W) was inserted at the end of the RF steps, before RF was turned-off. This "gentle" plasma minimizes the effect of the end plasma transient event. In addition using an inert and controlled chemistry has the added benefit of stabilizing plasma turn off effect as a function of etch chemistry employed in the process. It was demonstrated that the localized potential peak could be eliminated from the positive potential response. Furthermore, negative current response was also effectively reduced. Thus indicating that the negative current response was also driven by the transient at plasma turn off. CHARM-2 responses with the Ar plasma treatment and combined with the best wafer chuck / de-chuck sequence is shown in **fig. 8**. The process sequence included modified chuck / de-chuck sequence and Ar plasma treatment was named "New" process sequence.

In the next boy of work, experiments were set up to distinguish the root causes for the remaining positive potential seen. These responses were considered to be coming from the bulk plasma process when the plasma comes in contact with CCE. Design of experiment (DOE) was carried out in this standard contact chemistry (C4F8/CO/Ar/O2) by changing pressure, RF power, and gas ratio as variables. However, it has not determined main effect to eliminate the responses at this time unfortunately.

Instead, different gas chemistry, CH2F2/O2/Ar which is normally used for Silicon Nitride (SiN) etching, was evaluated because SiN is commonly used for an etching stop layer over metallic electrodes, and the etching might be sensitive to charging damage. In this gas chemistry, CHARM-2 has negligibly low responses especially with high pressure (150mT) and low power (700W). **Fig. 9** shows the CHARM-2 responses of the SiN etch chemistry combined with “New” process sequence. (Note; the contact chemistry (C4F8/CO/Ar/O2) has not achieved to eliminate the responses in this power / pressure stage so far.) This fact suggested there was a strong correlation between gas chemistry (or flow ratio) and the CHARM-2 responses. We intend to investigate the influence in detail hereafter.

Finally, a capacitor / antenna device, “APEX”, which allows to characterize the charging damage induced by electron shading effect was evaluated with the technique obtained from CHARM-2 study. SiO2 layer patterned with photoresist covers this sample. The results are shown in **fig. 10**. X-axis indicates Gate leakage current (Ig , Amp/□m2) and Y-axis indicates Cumulative Frequency (%). Ig was obtained with -5V applied between the antenna and a silicon substrate.
Three kinds of test are indicated in the graph.
“Baseline” … baseline sequence that has strong responses on CHARM-2, shown in **fig. 3**.
“New” … modified sequence that has lowest positive potential response, shown in **fig. 8**.
“Soft condition” … 100mT, 700W, contact etch condition. No CHARM-2 data.

Each sequence was summarized in **Table 1.**

	Process sequence			CHARM-2 response				
	chucking	end process	de-chucking	P.P (V)	N.P (V)	P.J (mA/cm2)	N.J (mA/cm2)	
Baseline	Gas	-	Pin	13.8	-6.9	0.4	-0.3	**Fig. 3**
New	Pin	Ar plasma off	Plasma	5.5	-1.9	1.2	0	**Fig. 8**
Soft condition	Pin	-	Pin	-	-	-	-	-

Table 1. *Process sequence and CHARM-2 responses for each test.*
P.P (mean positive potential), N.P(mean negative potential), P.J (positive current density @ +4V), N.J (negative current density @ -4V).

In terms of results, “New” sequence does not show any advantage in this experiment. For the 2.0 m hole, “Baseline” and “New” sequence show almost the same amount of Ig. “New” sequence may even show some degradation of performance for the 0.25 m hole which is regarded as being effected by shading phenomena. Regarding to the CHARM-2 results, “New” sequence has significantly low response at positive potential, negative potential, and negative current (**Table 1**). However, the positive current response of “New” sequence is higher than “Baseline”. This is understood that both polarity of potentials and negative current were not dominant factors for this antenna device. In addition, the result of positive current of CHARM-2 may have some correlation with the shading damage monitor sample. On the other hand, “Soft condition” consistently demonstrated significantly low Ig in "APEX" evaluation, which is considered one of the most critical parameters for this device. It also has been reported that damage induced by bulk plasma can be reduced by increasing pressure and decreasing RF power [6]. This has been explained by the reduction of stress current density as a function of the reduction of the electron temperature Te [7] which leads to lower shading effect. Bare CHARM-2 wafer used in this experiment does not allowed to detect the shading effect. Further investigation using patterned CHARM-2 wafers [8] might tell the correlation more clearly.

4. Conclusion

The bare CHARM-2 responses in DRM MERIE etching system was quite complex. This series of experiment demonstrated that these responses were modulated effectively by two factors; the ESC chucking / de-chucking sequencing and the RF bulk plasma. The effects from the ESC sequence were eliminated by modifying chucking / de-chucking sequence. Un-uniform distribution of positive potential, also negative current response were improved remarkably by inserting Ar plasma step which has high pressure and low power before RF turn-off. SiN etch process chemistry combined with the best RF sequence and Ar plasma treatment achieved almost no responses. Contact etch chemistry has some remained responses, i.e. positive potential and positive current, which will be explored soon. The work completed also suggested that the both polarities of potential response and negative current response seen in CHARM-2 response seems not to be the dominant factor in case of the samples which are used to characterize the electron shading damage. The positive current response of CHARM-2 wafer appears to indicate some correlation with the results of the shading damage monitor device, which is needed a further exploration.

5. Acknowledgment

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6. References

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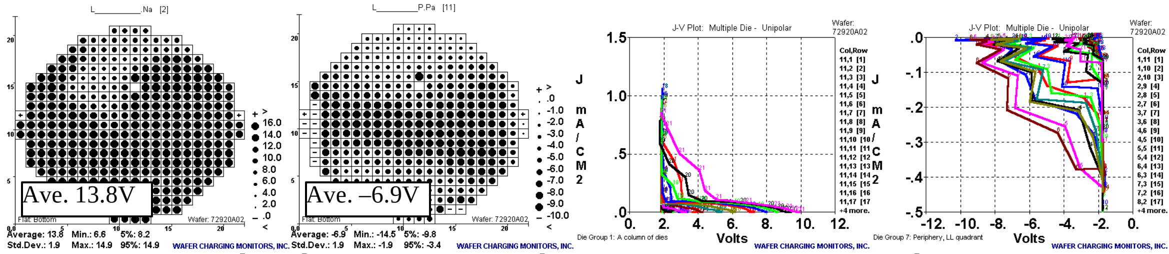
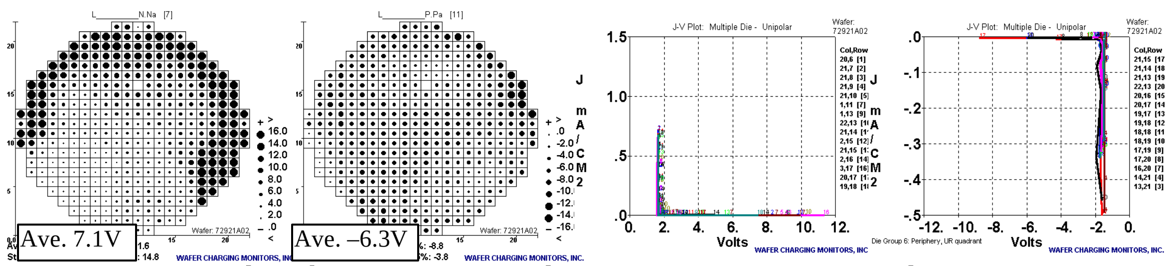


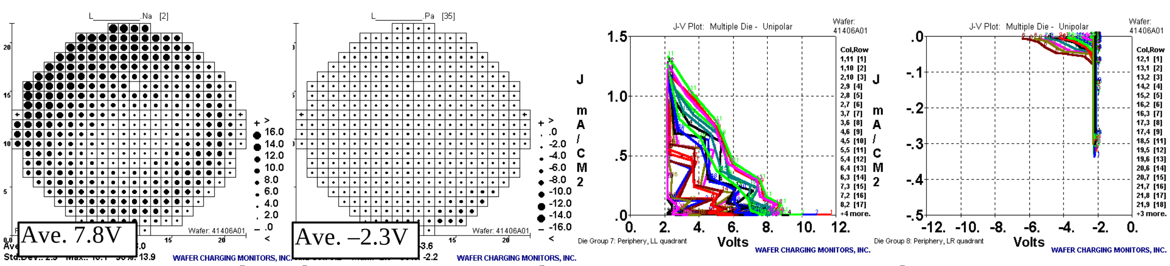
-a. Positive potential -b. Negative potential -c. Positive current -d. Negative current

Figure 3. *CHARM-2 responses with baseline process sequence and condition (30mT, 1700W, C4F8/CO/Ar/O2)*



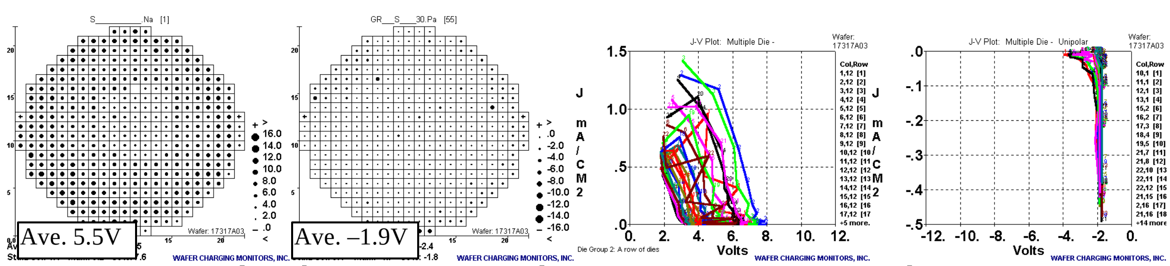
-a . Positive potential -b. Negative potential -c. Positive current -d. Negative current

Figure 4. *CHARM-2 responses with ESC chucking (no RF plasma exposure). Both potential responses were appeared.*



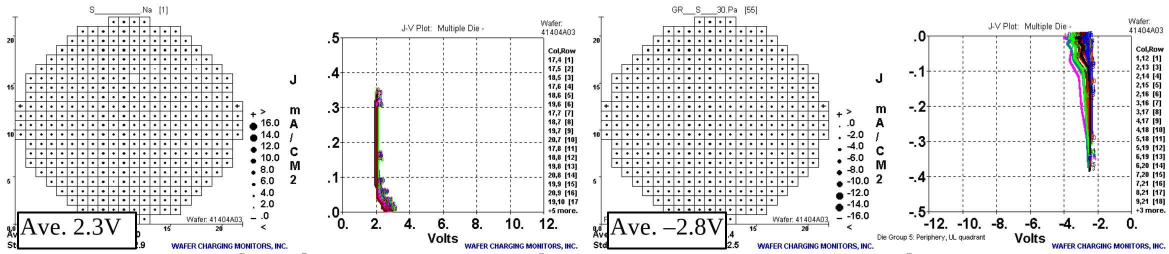
-a. Positive potential -b. Negative potential -c. Positive current -d. Negative current

Figure 5. *CHARM-2 responses with RF plasma exposure (no ESC chucking voltage). Negative potential response was not appeared.*



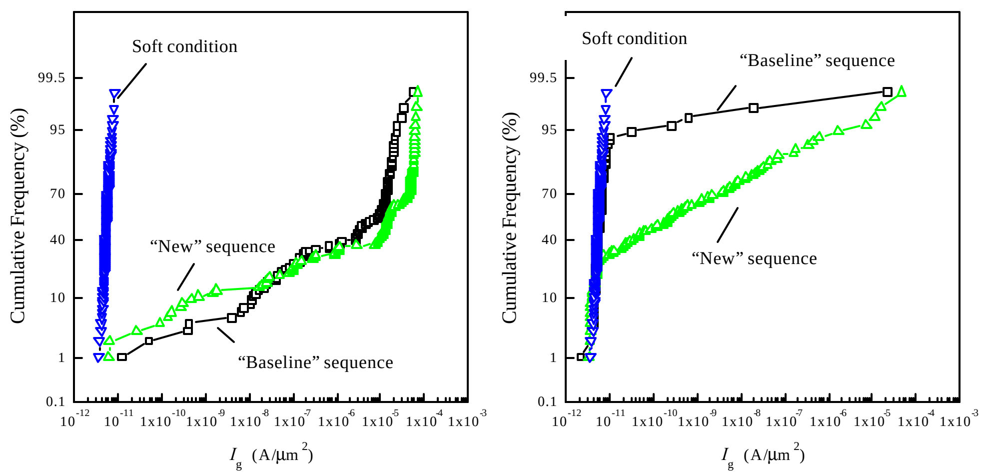
-a. Positive potential -b. Negative potential -c. Positive current -d. Negative current

Figure 8. *CHARM responses with "New" process sequence (30mT, 1700W, C4F8/CO/Ar/O2) Localized potential peak has removed by adding Ar plasma step before turn-off the plasma.*



-a. Positive potential -b. Negative potential -c. Positive current -d. Negative current

Figure 9. *CHARM-2 responses with CH2F2/O2/Ar chemistry (150mT, 700W, “New” sequence)*



-a. *2.0□m Hole sample*
(2.5K holes, antenna ratio=7854)

-b. *0.25□m Hole sample*
(5K holes, antenna ratio=245)

Figure 10. *APEX results with 2.0um holes (a), 0.25um holes (b)*