WHITE PAPER

TOROIDAL REMOTE PLASMA SOURCES FOR CHARGE-SENSITIVE ON-WAFER APPLICATIONS

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ABSTRACT

Charging of silicon wafer surfaces by energetic plasma species is a serious concern as on-wafer structures and devices become smaller and more sensitive. The MKS toroidal remote plasma source (RPS), when incorporated into a semiconductor process tool, delivers primarily neutral radical reactants to a wafer surface, with little to no potentially damaging charged species. This report describes the experimental verification of that claim using an industry-standard wafer charging monitor. MKS Paragon® and R*evolution® Remote Plasma Sources were characterized using Ar, N_2, O_2, and H_2 under typical process conditions. These tests demonstrated the potential for safe use of these RPS devices in charge-sensitive on-wafer applications. Experiments produced no detectable charge flux, while minute potential and ultraviolet sensor signal changes allowed exploration of the impacts of gas species, showerhead, and argon ignition in producing process differences.

INTRODUCTION

The accumulation of charge on a silicon wafer surface can occur when exposed to electrically charged plasma species. This can cause plasma process induced charging damage (PID) that is a serious concern for semiconductor device fabrication as on-wafer structures and devices become smaller and more sensitive [1] [2]. For example, in the fabrication of advanced 3D device structures using radical-enhanced selective etching processes, it is important that neutral radicals are delivered to the wafer surface without associated damage from charged species. Theoretically, a toroidal plasma source such as the MKS toroidal remote plasma source delivers primarily neutral radical reactants while limiting the flux of potentially damaging charged species. Measurements of positive and negative potentials, charge flux and ultraviolet (UV) exposure can be used to estimate the likelihood of charge damage to very sensitive devices.

In its simplest form, a toroidal plasma source forms a closed loop of plasma. In MKS' implementation, this plasma loop is the secondary circuit of a transformer-coupled power scheme [3]. Ferromagnetic cores direct the fields which form the looped plasma. The same phenomena which create the loop of plasma inhibits the ability of charged particles to escape the plasma. However, neutral plasma species are not constrained, making toroidal sources ideal for processes which require neutral radicals. For example, cleaning processes in semiconductor device fabrication require neutral O or F radicals [4]. Although toroidal RPS are not expected to significantly contribute charged species, any on-wafer process can present a concern for device damage and should be thoroughly characterized.

Charging damage in embedded device structures manifests as changes in the electrical properties of the device arising out of charge transport through the gate oxide and trapping at the oxide-silicon interface. The magnitude of the charging damage can be proportional to the amount of charge transported, depending on the inherent sensitivity of the device. The extent of damage caused by surface charging primarily depends on the current density, and as such, minimizing charge flux is an ideal approach for minimizing PID in on-wafer plasma processes [7]. Understanding the factors influencing charge transport is thus critical for the characterization of a potential charging source. In plasma processing, there are two oxide charge transport mechanisms that must be considered: Fowler-Nordheim tunneling and UV-assisted conduction [2] [5] [6]. Fowler-Nordheim tunneling consists of charge tunneling through a potential barrier in the presence of a very high electric field. UV-assisted conduction can happen at a lower electric field strength, with UV energy providing the excitation needed to overcome the barrier to charge transport. Differentiating these mechanisms requires the use of multiple types of sensors to measure surface-substate potentials, charge flux, and UV dose.

In this White Paper, we report on the results of analyses using an industry-standard wafer charging monitor to provide experimental verification of the preferential delivery of neutral radical reactants over charged species from MKS Instruments' Paragon and R*evolution Toroidal Remote Plasma Sources.

METHODS

The charge monitor employed in this study was the CHARM®-2 Monitor Wafer with a grid of embedded sensors evenly distributed over the surface of a 200 mm SiO_2 wafer. The electrical properties of these sensors change during exposure to plasma conditions. Combining the observed results and ranges from all sensors reveals the potential for charging damage and possible tunnelling mechanisms [8].

All experiments were performed in the same process chamber, with the charge monitor wafer held at 100°C and with 60 s collection times. The wafer pedestal was not biased, and the Paragon or R*evolution RPS was the only potential source of charged species. Use of showerhead, RPS unit (AX7710 or AX7696 with KF40 outlets), and process gases were varied. RPS powers were in the 2-6 kW range. Higher pressures can inhibit ion transport so experiment pressures were at the low end of the standard operating window of the unit (1-10 Torr). When in use, the quartz showerhead had a graduated circular multi-hole pattern reducing the cross section for flow to ~38%.

Sensor results are shown as a wafer map (a graphical representation of the sensor values and positions) or as the corresponding sensor averages or thresholds. Multiple sensors with varying measurement ranges are embedded on the wafer. When the most sensitive sensors are not activated, results are assigned the value of the sensor threshold (denoted with a < or > sign). With prolonged use of the monitor wafer, the thresholds can migrate slightly; the threshold at time of measurement is given in tabulated results. The dynamic range of the charge potential sensors are effectively ±1 V to ±25 V with sensor saturation at ±30 V [8]. Current density could be obtained in the $\mu A/cm^2$ to the mA/cm^2 sensor range, with damage concern shifting from unlikely to very likely over that range. Exact values where damage can occur are impossible to speculate for all device architectures, but sensor ranges are intended to allow for process optimization [9].

A second CHARM-2 monitor wafer was required after the first one was irreparably damaged following exposure to an inductively coupled plasma source (300 W). The hydrogen process experiment used this second monitor wafer; all sensors are equivalent apart from wafer lot-to-lot variation which has the potential to affect UV signal attenuation. For verification, optical emission spectroscopy (OES) was performed for the UV wavelengths collected by the CHARM-2 monitor wafer. Comparative UV measurements per process gas (OES vs CHARM-2 monitor wafer) were determined as having minimal difference between monitor wafers used.

RESULTS

On-Wafer Charging

MKS' Paragon and R*evolution toroidal RPS units were characterized for different gas species (Ar, N_2, O_2 and H_2) under standard process conditions. The main goal of this study was to verify that MKS' toroidal remote plasma sources do not contribute damaging on-wafer charges. Each experiment placed a monitor wafer in the test chamber and representative process conditions were established within the chamber. Specific process values and thresholds are presented in Tables 1, 2, and 3. A process was considered safe from destructive charging when charge flux sensors on the monitor wafer did not activate under any RPS process conditions; this indicated no detectable charge transport within the sensors. For all experiments and conditions employed with toroidal RPS, current density based on thresholds were between +1.2 μA/cm² and -0.9 μA/cm². These data, below threshold values, indicate very safe processes with respect to charge transport in SiO_2. In contrast, a remote 300 W Inductively Coupled Plasma (ICP) source using similar process conditions produced enough charging to permanently damage a monitor wafer. Typically, current density in the single μA/cm² range is unlikely to cause damage; 10-100x that amount could affect very sensitive device designs, and in the mA/cm² range (as experienced with the ICP source), damage is a critical concern. The ICP source resulted in potentials on the monitor wafer that were significantly over saturation value and more

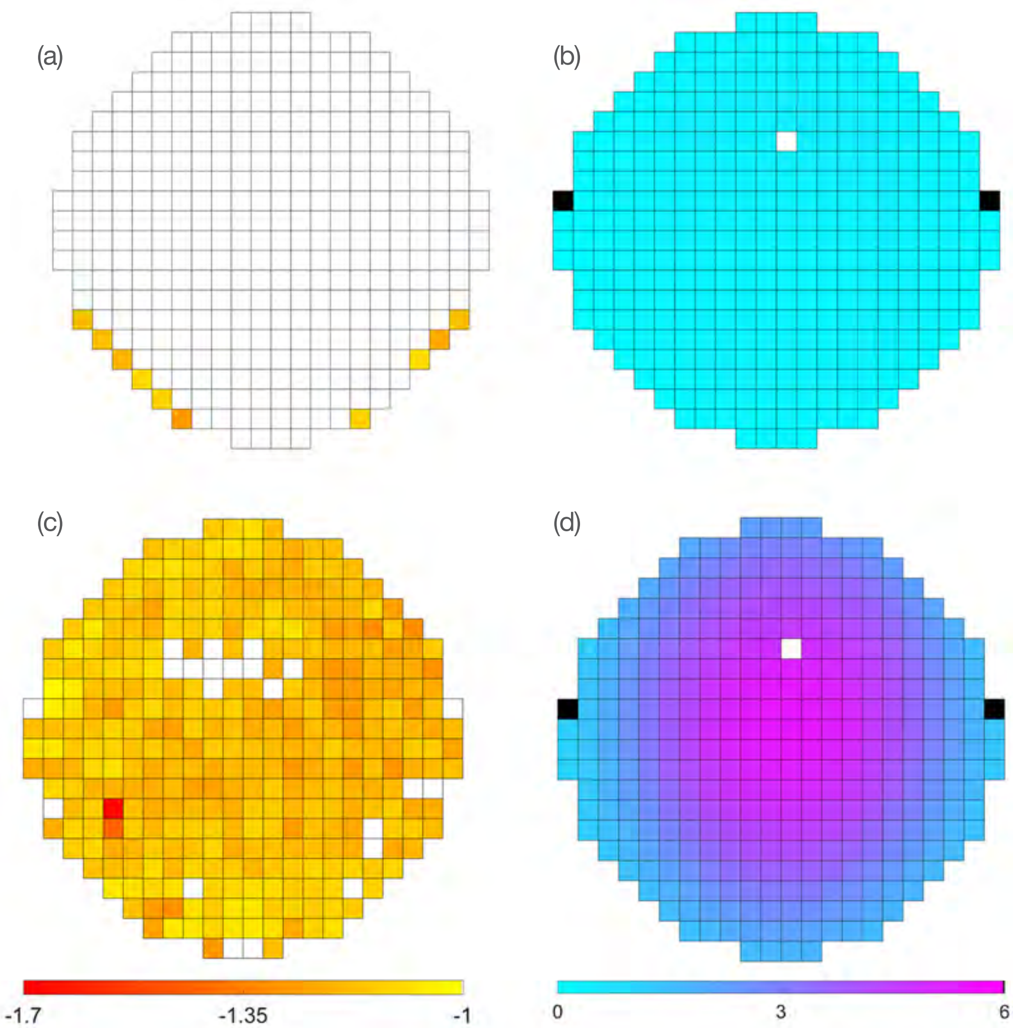

Figure 1 - Measurement Results: Effect of Quartz Showerhead. MKS Paragon Remote Plasma Source with 5 slm Argon at 2 Torr for 60 s. Wafer at 100°C. (a) Negative potential wafer map [V], showerhead. (b) UV signal wafer map [relative response], showerhead. (c) Negative potential wafer map [V] without showerhead. (d) UV wafer map without showerhead.
Note: White squares are inactivated sensors or sensors with values less than the sensor threshold. Black squares contain no UV sensors.

than an order of magnitude greater than those seen for the RPS units. From our data, tunneling-based transport is considered unlikely since the values of the potentials are too low (between +1.8 V and -1.3 V) to provide the electric field necessary to tunnel through the SiO_2 potential barrier. UV-assisted conduction is also unlikely because the UV signal combined with the potentials are too low to be significant. While neither charge transport nor significant charging was detected, enough data was collected to explore the effects of RPS unit, process gas, showerhead, and ignition scheme.

Effect of Showerhead

It is interesting to consider the effect of a showerhead on potential charging. Examination of wafer charging with and without a quartz showerhead under the same argon conditions produced the two sets of wafer maps shown in Figure 1. In these four wafer maps, the yellow-red scale indicates negative potential sensors, and the blue-purple scale shows the relative UV response. Additional sensors, including charge flux sensors, did not activate. The average values and thresholds of this comparison are presented in Table 1. In Figure 1 (a) white indicates inactivated sensors; there is a slight signal on the wafer edge. This can be compared with the results obtained when there is no showerhead present in the system (Figure 1 (c)). Without the showerhead, the activated sensors reach slightly larger potential values (-1.3 V vs -1.0 V). This result indicates that the showerhead blocks some charges hitting the wafer surface. Argon plasma species are limited to negatively charged electrons, positive Ar ions, or neutral Ar atoms. Since only negative potentials were read by the monitor wafer, the results show that electrons are the main charged species impinging on the wafer surface. The showerhead noticeably blocks and dissipates the UV (Figure 1 (b)).

Thus, even without the showerhead, the effect of argon is insufficient to cause charging concerns. This is true for all aspects of the argon process, including argon ignition. In terms of isolating ignition, the difference between an RPS unit which ignites in argon and switches to a process gas and one where the ignition takes place in the process gas is worth exploring.

	MKS Paragon® RPS 2 Torr, 5 slm Ar	
	No Showerhead	With Showerhead
Current Density [μA/cm²]		
Positive	< 1.1	
Negative	> -0.7	
Potentials (5% max average) [V]		
Positive	< 1.6	
Negative	-1.3	-1.0
UV Dose		
Relative Response	3.25	0.29

Table 1 - Comparison of charging and UV responses with and without a showerhead in Ar experiments performed at 2 Torr, and 5 slm Ar flow using MKS Paragon Toroidal Remote Plasma Source. Average values or sensor thresholds are tabulated.

Influence of Argon Ignition vs Process Gas Ignition

Depending on the specific RPS under consideration, ignition is not always possible in process gases. Adding an argon ignition step may be an issue if Ar ions influence the final process results. We performed a comparison between two RPS units that demonstrated that argon ignition has a minimal effect in MKS RPS processes using nitrogen processing recipes. The R*evolution RPS can ignite in process nitrogen gas and the results from a 1 Torr, 1 slm N_2 60 s process is mapped in Figures 2 (a) and (b). Ignition in Ar is needed to run the same process in a Paragon RPS. The results of a 1 Torr, 2 slm, argon ignition (exaggerated to 2 seconds) followed by the same 60 s, 1 Torr, 1 slm nitrogen process is shown in Figures 2 (c) and (d). The averages of the negative potentials are given in Table 2. For the R*evolution RPS, the potentials read were < 5% of the threshold (Figure 2 (a)), whereas the potentials with Ar ignition were slightly higher, but still comparable to the pure Ar Paragon RPS runs (different conditions) of Figure 1 (a, c). More negative charging occurs in the Ar ignition processes, but values are still well below the level of concern for charge transport.

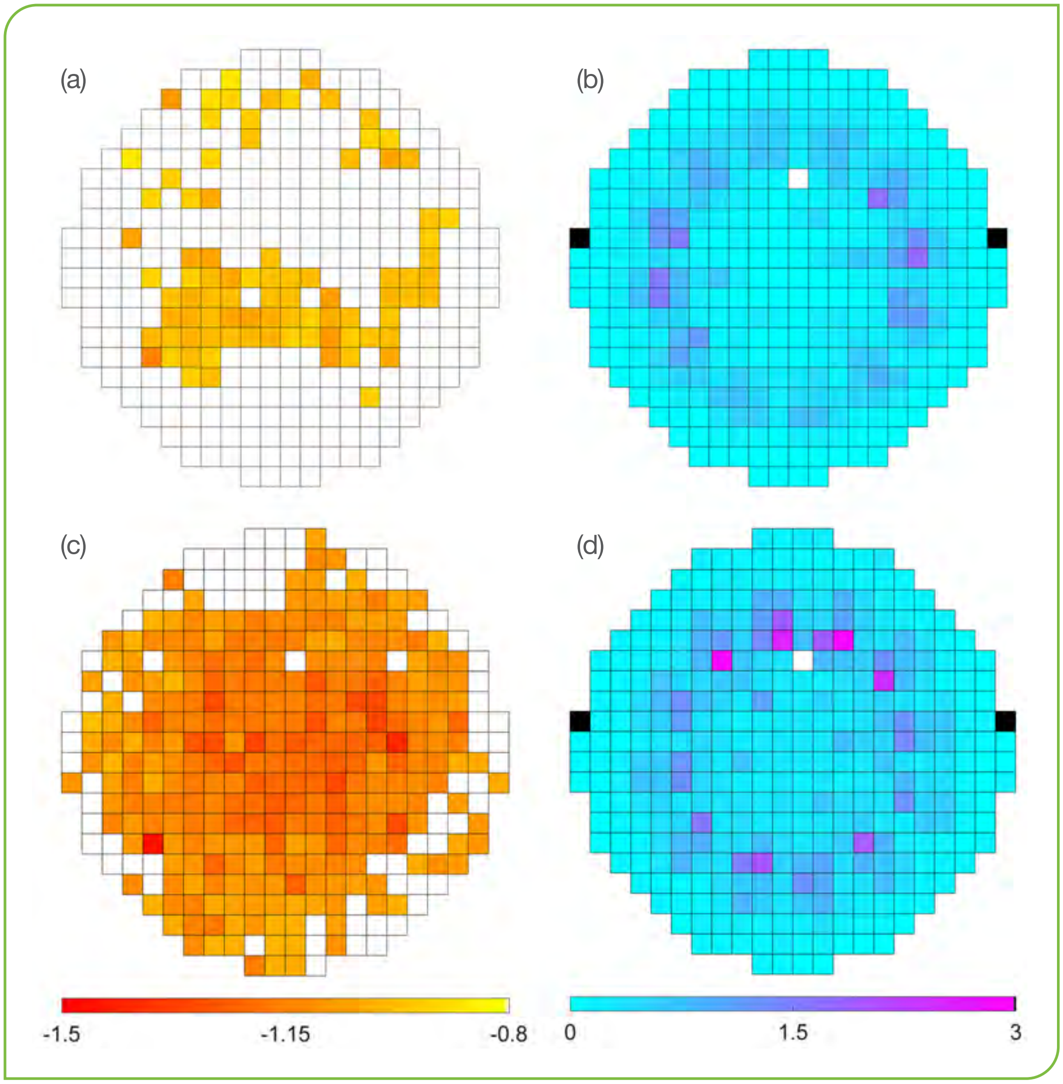

*Figure 2 - Argon Ignition. (a, b) R*evolution RPS is direct ignition in N_2 process gas. (c, d) Paragon RPS ignites in Ar and then gas is transitioned to N_2 process. Negative wafer potential maps with voltage scale (a, c). Relative UV sensor signal (b, d).*

UV patterning due to the quartz showerhead can be seen with the addition of nitrogen gas to the process (Figure 2 (b, d)). Additionally, in Figure 2 (b) there is a diffuse UV background that is not present in Figure 2 (d). This is probably due to the Ar ignition; Figure 1 (b) displays such a diffuse background for slightly different conditions. Overall, the UV signal seems to be a summation of a diffuse Ar ignition background with the showerhead patterned N_2 component. The effects of argon ignition are seen to be very limited at the processing conditions explored.

Influence of Gas Species

Other process gases also reproduce the showerhead pattern. Figure 3 presents the comparison between H_2, N_2 and O_2 for the same R*evolution remote plasma source and conditions. The average values are in Table 3. Qualitatively, the relative intensity of $H_2/N_2/O_2$ is consistent with OES exploration of the range of UV sensor collection. Once again, no charge transport is detected using the MKS RPS regardless of process gas chemistry. The relative and minimal charging on the monitor wafer differs in polarity, depending on the process gas.

	MKS Paragon® RPS 1 Torr, 2 slm Ar ignition 1 Torr, 1 slm N_2	MKS R*evolution® RPS 1 Torr, 1 slm N_2
Current Density [µA/cm²]		
Positive	< 1.1	< 1.0
Negative	> -0.7	> -0.6
Potentials (5% max average) [V]		
Positive	< 1.6	< 1.5
Negative	-1.3	> -1.0
UV Dose		
Relative Response	0.33 [1]	0.20

*Table 2 - Comparison of Paragon and R*evolution ignition (quartz showerhead used).*
[1] UV is normalized by total process time; time of Ar ignition must be accounted for in the process.

	MKS R*evolution® RPS		
	1 Torr, 1 slm N_2	1 Torr, 1 slm O_2	1 Torr, 1 slm H_2
Current Density [µA/cm²]			
Positive	< 1.0		< 1.2
Negative	> -0.6		> -0.9
Potentials (5% max average) [V]			
Positive	< 1.5		1.8
Negative	> -1.0	-1.1	> -1.2
UV Dose			
Relative Response	0.20	0.01	0.98[2]

*Table 3 - Comparison of process gases (quartz showerhead used) for MKS R*evolution Remote Plasma Source.*
[2] Different CHARM-2 monitor wafer. UV response is not guaranteed comparable between wafer lots, different Borophosphosilicate Glass (BPSG) thickness above the UV sensor is possible, which could result in different attenuation/signal. Qualitatively, relative intensity of $H_2/N_2/O_2$ is consistent with OES exploration of range of UV sensor collection.

Hydrogen produces primarily positive charging, while with nitrogen and oxygen charging is negative. This trend correlates with the electronegativity of the gases. It is also noteworthy that the relative size and lifetime of these plasma species affects their ability to pass through the chamber and obstacles (e.g., showerhead) and reach the wafer surface. Pressure also directly affects ion transport through the system. Our results suggest that pressures greater than 1 Torr would further decrease the small amount of charging observed under these process conditions. Pressures below 1 Torr are outside of RPS specification and were not explored. Verification of the degree of charging is needed for lower pressures, especially for long lifetime ionic species.

CONCLUSION

The decisive result of this study is that no charge flux sensors activated while testing with MKS RPS devices. This finding meant there was no detectable charge transport and therefore no possibility of damaging on-wafer electrical structures. Since there are orders-of-magnitude differences between the charge flux sensor thresholds and any wafer charging levels that may be of concern, our tests demonstrated no reason for charge damage to exist when using MKS toroidal remote plasma sources under standard operating conditions. This conclusion is further reinforced by the very limited accumulation of charge potentials or UV even reaching the monitor wafer. Because MKS' RPS are designed to deliver neutral chemical radicals to the wafer surface rather than a charged ionic species, these results are as expected. However, given the large variations in the sensitivity of semiconductor devices to on-wafer charging, it is always prudent to obtain experimental verification of the charging levels in a new process. After testing revealed charging damage is highly unlikely, we used the data to evaluate the very small changes in the levels of charged species and UV radiation relative to the different processing conditions. The effect of a quartz showerhead on diffusing argon UV signals and

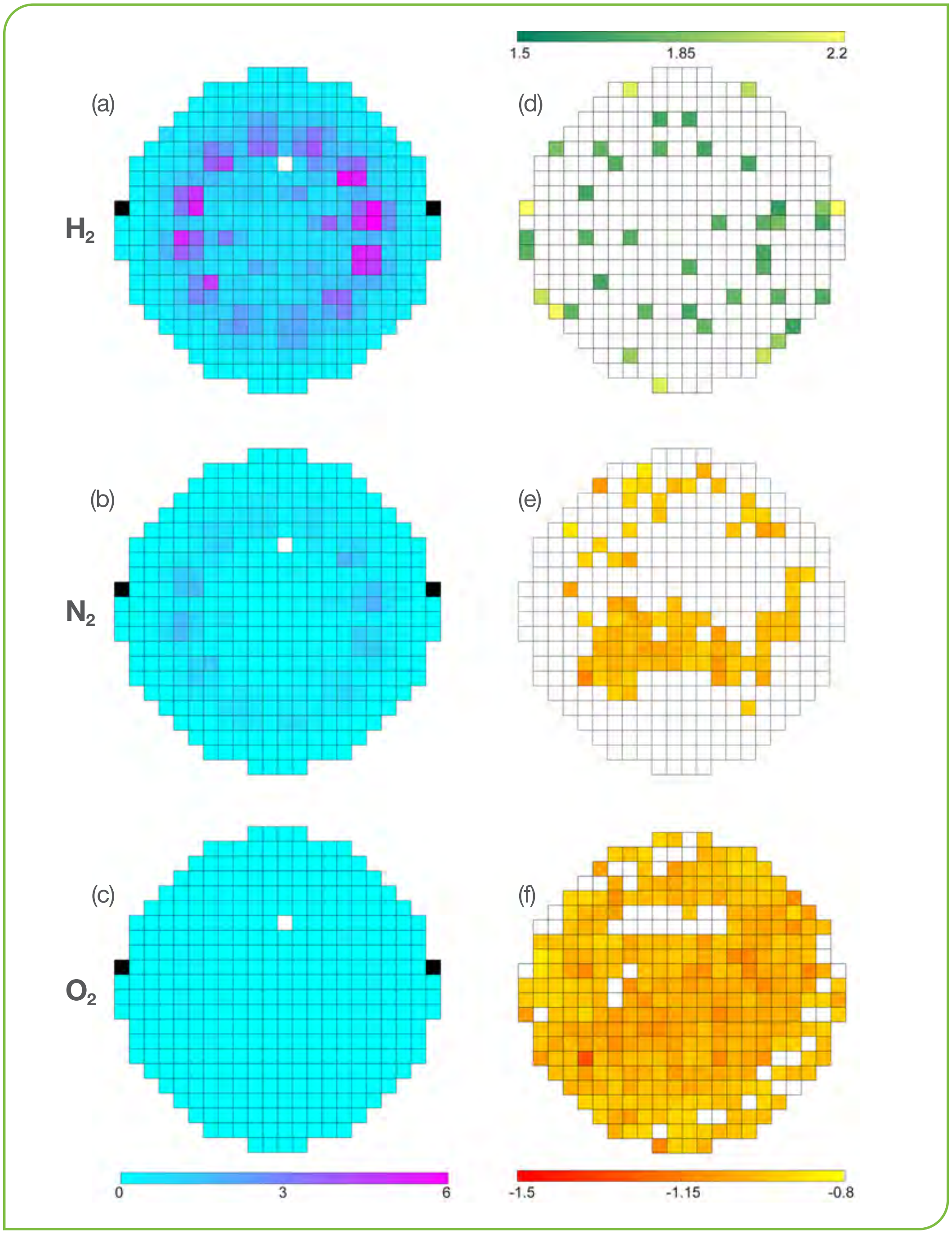

*Figure 3 - MKS R*evolution RPS with quartz showerhead; 1 Torr, 1 slm of process gases. Hydrogen sensor maps of UV (a) and positive potential values (d) utilized new CHARM-2 monitor wafer (see methods). Nitrogen sensor maps (b) and (e) are the same data as Figure 2 (b) and (a). Oxygen sensor maps of UV (c) and negative potential values (f). UV data are all on the same scale. Incremental color changes of potential maps are similar, with color representing negative or positive potentials reached and appropriate color scale.*

the differences in UV showerhead patterning when using various process gases were observable. There were slight differences in charge potentials between gases as well. We also verified the limited effect of the addition of an argon ignition step to nitrogen-based plasma processing. The alleviation of concerns for argon ignition-based charging opens the opportunity to consider RPS devices with various ignition schemes interchangeably.

Overall, the results show that the use of MKS toroidal remote plasma sources produce very safe processes with insufficient on-wafer charging to damage sensitive embedded devices.

These results allow MKS to confidently recommend toroidal Remote Plasma Sources for charge-sensitive applications.

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