Correlation of Plasma-Induced Charging Voltage Measured In-situ by Microelectromechanical Sensors with Device Degradation

Kiran Pangal and J. C. Sturm

Department of Electrical Engineering, Princeton University
Princeton, NJ 08544

ABSTRACT

The plasma-induced charging of surfaces during semiconductor processing has been measured noninvasively and *in situ* using microelectromechanical charge sensing devices. We have shown that this sensor reading can be used to predict degradation in Metal-Oxide-Semiconductor (MOS) capacitors. The charging voltage scales with oxide thickness and is found to be a strong function of input rf power, chamber pressure and type of gas used in the plasma.

INTRODUCTION

Plasmas are being used extensively in modern integrated circuit manufacturing. During plasma processing, the wafer is subjected to bombardment from electrons, ions and photons. These fluxes lead to electrostatic charging of wafer surface, which result in degradation of gate dielectrics [1,2].

We have fabricated a device that can noninvasively measure this charging *in situ* in real time in the plasma reactor. We can also use this method to quickly map charging across the electrode. The charging is measured *in situ* by measuring the deflection of microcantilever. The measurement was then correlated with plasma-induced gate oxide degradation of MOS capacitors.

A conducting micro-cantilever, suspended above, and electrically isolated from a conducting surface, can act as a charge-sensing structure. If the cantilever surface were to be charged, the substrate would mirror the charge, resulting in an electric field between the cantilever and the surface below and therefore the cantilever would bend as shown in fig. 1. The deflection can be measured by the shift in the reflected spot of a laser beam caused by the change in angle of reflection of the laser beam. The charge on the cantilever can then be inferred from the deflection.

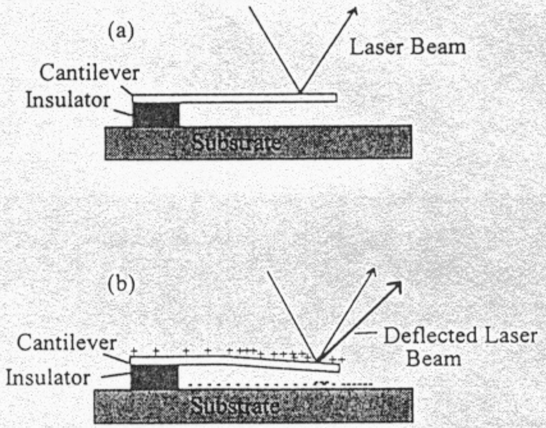

Fig.1. Microscopic charge-sensing structure for (a) uncharged and (b) charged surfaces.

Simple cantilevers might be difficult to use since the angle of deflection varies along the length of the cantilever, and focusing a laser beam onto a small portion of the cantilever inside an etching reactor might be difficult. We therefore modified the cantilever and fabricated paddles,

1997 2nd International Symposium on Plasma Process-Induced Damage.
May 13-14, Monterey, CA.

wherein a large area or pad is connected to the support by thin arms (Fig. 2). These structures had a nearly constant angle of deflection over most of the reflecting area, and the reflecting area was also enhanced. Various sizes of these structures were made so that each paddle detects a particular range of voltage.

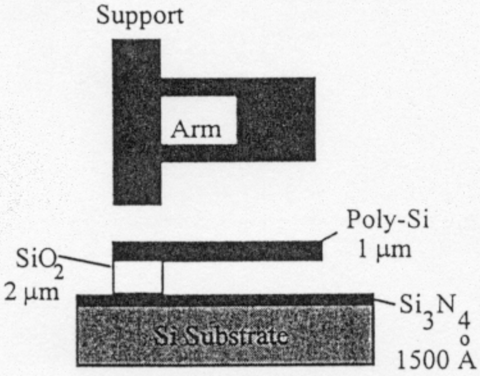

Fig. 2. Top and side views of the paddle structure

The fabrication of the paddle structure and cantilevers was reported earlier [3]. The MOS capacitors were fabricated on n and p type (100) substrate with 5-20 Ω-cm resistivity. Gate oxide of different thicknesses (100, 125 Å) were grown after a standard RCA clean at 850 °C. All capacitors had an aluminum gate with 200 nm thick field oxide and the ratio of area of metal on the field oxide to that on the gate oxide was about 0.42 . The capacitors were annealed after metallization at 400 °C in forming gas for 30 min.

EXPERIMENTAL

Prior to exposure to plasma, the devices were externally calibrated by observing the deflection in response to an applied electrical voltage applied between the polysilicon on top of the support and the substrate.

Figure 3 illustrates the experimental set-up used to measure charging in-situ in the plasma reactor chamber. A He-Ne laser beam is directed into the reactor chamber through a quartz window on the top electrode. The unfocused laser beam covers several paddles of the same size and the reflected beam is projected onto a screen. When the plasma is on, charging occurs, and the reflected spot moves. The plasma-induced charging voltage can then be computed from this shift.

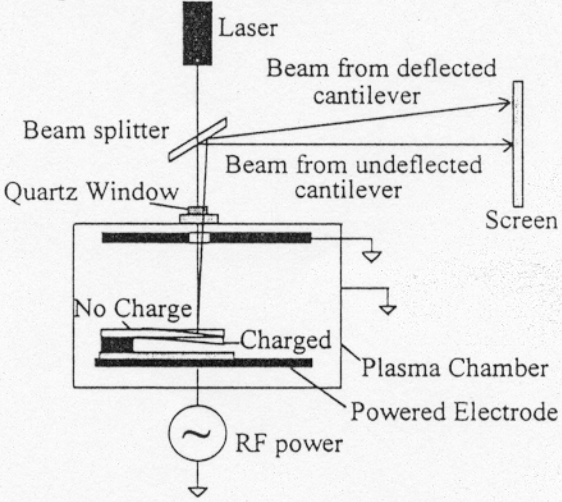

Fig. 3. Experimental setup used to detect charge in plasma, showing reflected beam from charged and uncharged sensor.

Some of the cantilevers deflect far enough suffer "pull-in" [4] and touch the substrate when exposed to plasma. These cantilevers remain stuck even after the plasma is off. This can easily be checked with an optical microscope. The charging voltage can be then estimated by having a range of paddles with different pull-in voltages, and noting which ones have pulled-in. Charging voltages inferred by this technique match those measured directly. This method requires no optical ports and charging voltage across the electrode can be estimated.

We have measured the plasma-induced charging voltage by these two methods in a parallel-plate diode type reactor with an electrode diameter of 24 cm with spacing between electrodes being 5 cm. The gases are injected into the chamber through a shower head in the top electrode.

RESULTS AND DISCUSSION

The *in situ* method was used to measure the plasma-induced charging voltage at the electrode edge (9.5 cm from the center). The charging voltage was found to increase as RF input power was increased (Fig. 4(a)). We also measured charging voltages at different points on the electrode by the *ex situ* method. The charging voltage was found to be lower at the center compared to that at the edge (Fig. 4(b)).

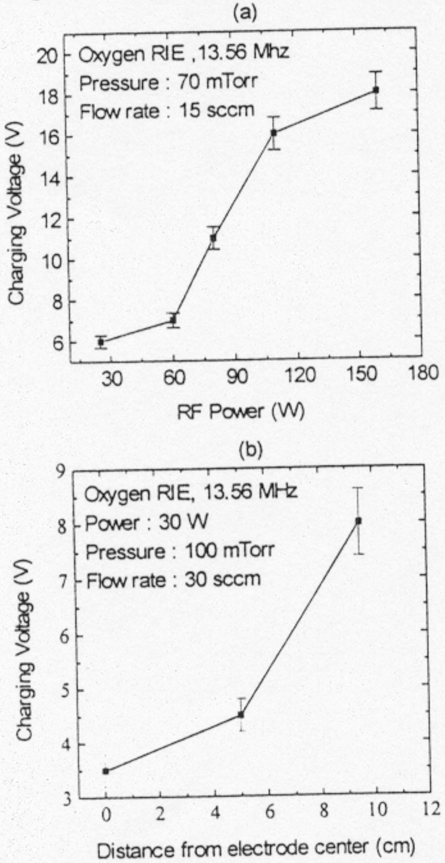

Fig. 4. (a) Charging Voltage as a function of input rf power, (b) Charging Voltage as a function of position on the electrode.

We then exposed the MOS capacitors to plasma, varying the rf power, time of exposure and the chamber pressure. The quasi-static (QS) capacitance vs. voltage (C-V) was measured after a fixed interval of time (14 min.). The QS C-V curve reflected the degradation of the gate oxide and this degradation scaled with the sensor reading. Figure 5(a) shows the QS C-V curves of various devices exposed to Argon plasma at different rf powers for 1 min and fig. 5(b) shows the corresponding interface state density, clearly showing that the degradation of gate oxide scales with rf power.

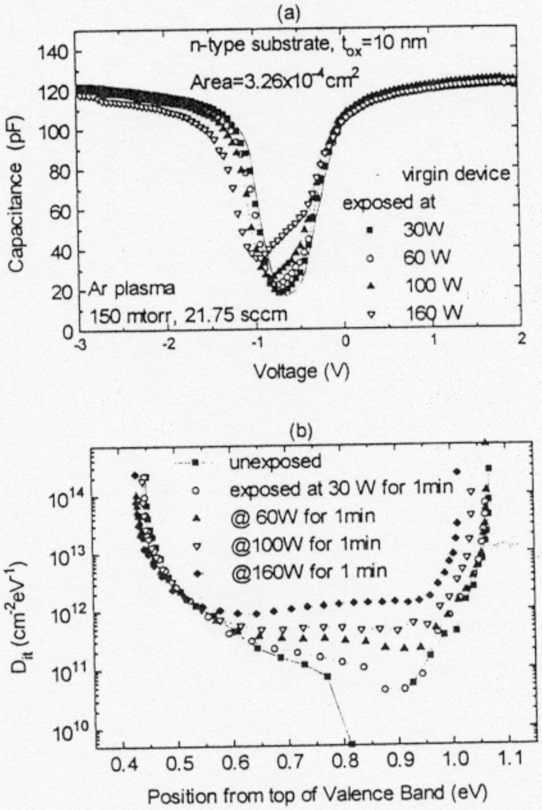

Fig. 5 (a) Quasi-static C-V curves of devices exposed at varying rf powers for 1 min, (b) corresponding interface state density as a function of position in the band gap.

As reported in earlier work by others [5], we matched the plasma-induced damage with that caused by DC bias stressing of the MOS capacitors. By varying the DC stress, we could estimate the electrical voltage on the gate during the plasma exposure by comparing QS C-V curves. We found that negative bias stress on the gate gave QS C-V curve which most closely resembled that measured after plasma exposure (Fig. 6). Similar results were found for MOS capacitors with p-type

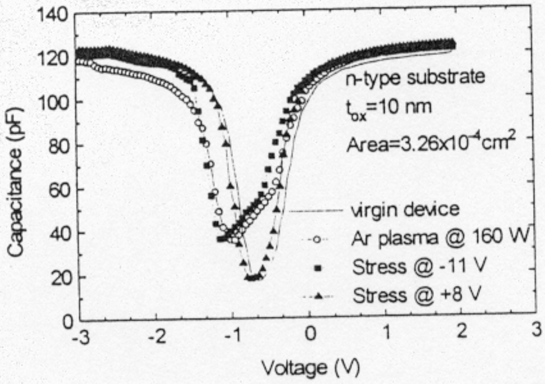

Fig. 6. Comparison of QS C-V curves of devices exposed to plasma and DC bias stressed.

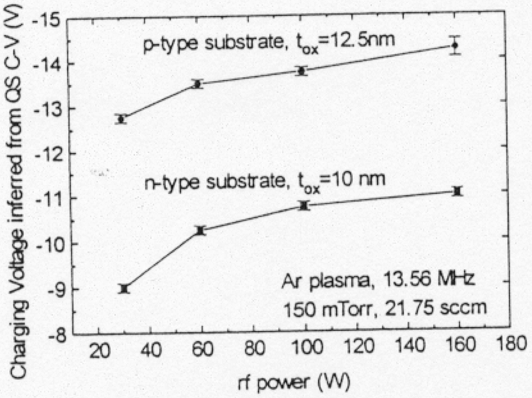

Fig. 7. Charging voltage inferred from DC bias stressing and matching the QS C-V curves for n & p type substrate MOS capacitors.

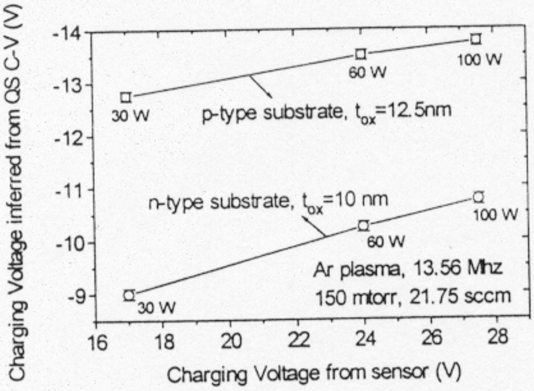

Fig. 8. Comparison of charging voltage as measured by sensor and inferred from QS C-V degradation at different rf power .

substrates, and the plasma-induced voltage increased with oxide thickness [6] (Fig. 7). A comparison of the charging voltage as measured by the sensors at different plasma rf power and that inferred from the MOS capacitors is shown in fig. 8. There is a direct one-to-one relation between the two measurements.

CONCLUSION

We have demonstrated a noninvasive method for quickly measuring plasma-induced charging in-situ and in real time in a plasma reactor. The method can also be used to map charging across large areas. We have shown that the sensor can be used to predict damage to gate oxides resulting from plasma process.

This work was supported by ARPA under contract no. USAF-TPSU-CCT-1464-966 and by the Plasma Science and Technology Program at Princeton University.

REFERENCES

[1] S. Fang and J.P. McVittie, J. Appl. Phys., 72, 4865 (1992).

[2] S. J. Fonash, J. Electrochem. Soc., 137, 3885 (1990).

[3] K.Pangal, S.L. Firebaugh and J.C. Sturm, Appl. Phys. Lett., 69 (10), 1471 (1996).

[4] K.E. Petersen, IEEE Trans. Electron Devices, 25, 1241 (1978).

[5] H. Shin and C. Hu, IEEE/SEMI Advanced Semicond. Manufacturing Conference, 79-83 (1992).

[6] H. Shin, N. Jha, X.Y. Qian, G. W. Hills and C. Hu, Solid State Technol., vol. 36, no. 8, 29-36 (1993).