

Noninvasive measurement of charging in plasmas using microelectromechanical charge sensing devices

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The plasma induced charging of surfaces in a plasma during semiconductor processing has been measured noninvasively using microelectromechanical devices. We have designed, modeled, and fabricated microcantilevers to act as charge sensing probes. The devices exhibit a mechanical deformation when charged, which is probed *in situ* by optical techniques, or measured by optical inspection after removal from plasma. Charging voltage measurements in a parallel-plate reactive-ion-etching reactor show that more charging is evident at the electrode edge, and that the charging is a strong function of input rf power, chamber pressure, and flow rate of gases. © 1996 American Institute of Physics. [S0003-6951(96)04536-6]

Plasmas are being widely used in the semiconductor industry for delineation of fine line pattern and deposition at low temperature. In recent years, it has been reported that plasma nonuniformity across the wafer due to nonuniformities in radio frequency (rf) current flow, electron current flow, and ion current flow can cause significant charging of surfaces, which can severely degrade or destroy devices, especially metal oxide semiconductor (MOS) gate dielectrics.^{1,2} This particular problem is becoming more important as gate oxides become thinner and, hence, more vulnerable to this surface charging.

In this work we report for the first time, a device that can noninvasively measure this charging *in situ* in real time in the plasma reactor, as opposed to the conventional method of inferring the charge from the later measurement of device degradation or using wires and probes or other elements that may perturb the plasma.³⁻⁶ Our method can also be used to quickly map charging across the electrode. The charging is measured *in situ* by measuring the deflection of microcantilevers.

A microscopic cantilever made from a conducting material, suspended above, and electrically isolated from a conducting surface, can act as a charge-sensing structure. If an interaction with plasma or fluid were to add electrons or ions to the cantilever surface, the cantilever would become charged. The substrate would mirror that charge, resulting in an electric field between the cantilever and the surface below and, hence, causing deflection of the beam as shown in Fig. 1. The beam would deflect towards the substrate for either positive or negative charge. The deflection may be measured by the shift in the reflected spot of a laser probe caused by the charge in the angle of reflection of the laser beam, and the charge on the cantilever can be calculated from the deflection.

Experimentally, the use of cantilevers might be difficult 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. Therefore, we modified the cantilever concept to fabricate paddles, where a large area is connected to the support by thin arms (Fig. 2). In these structures, the sensitivity was enhanced compared to cantilevers, the angle of deflection was nearly constant over most of the reflecting area, and the laser beam covered several adjacent identical paddles. Various sizes of these structures were made so that each paddle detects a particular range of voltage.

The paddle structures and the cantilevers are fabricated by standard surface micromachining technique. N^+ -type silicon wafers ($0.5\text{--}2.0\ \Omega\ \text{cm}$) are used as substrate. First a layer of silicon nitride of thickness 150 nm is deposited by chemical vapor deposition (CVD). This serves to alleviate “stiction” problems during processing. Stiction occurs when the cantilever deflects all the way and sticks to the substrate. The second step involves creating the sacrificial layer that will be isotropically etched to realize free standing structures. In this case a $2\ \mu\text{m}$ thick silicon dioxide (SiO_2) layer is deposited by atmospheric pressure CVD. A $1\text{-}\mu\text{m}$ -thick polycrystalline silicon layer is then deposited by low-pressure CVD and is doped heavily with phosphorus

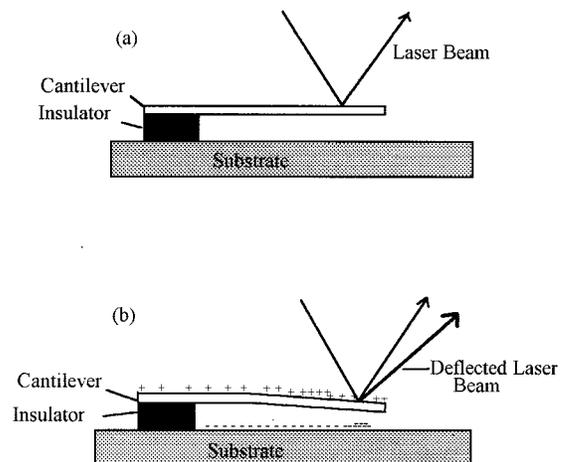


FIG. 1. Microscopic charge-sensing structure for (a) uncharged and (b) charged surfaces.

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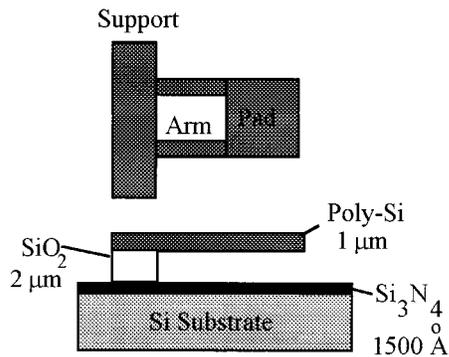


FIG. 2. Top and side views of the paddle structure.

($\sim 10^{20} \text{ cm}^{-3}$) to have high conductivity, and annealed to reduce the internal stress^{7,8} in the polysilicon cantilevers.

The polysilicon is first dry etched in SF_6 plasma (rf power 30 W, pressure 150 mTorr and flow rate 15 sccm). Next, photoresist (AZ1518) is spin coated on the support structure to prevent the silicon dioxide underneath the support from being etched during the release step. The final processing step to create free-standing micromechanical structures is sacrificial layer etching of SiO_2 by buffered hydrofluoric (HF) acid. The wafers are then rinsed in deionized water and later in acetone to remove the photoresist. Drying the wafers under atmospheric conditions leads to stiction.⁹ Hence, various drying methods were attempted, like vacuum drying⁸ and drying the wafer on a hot plate.¹⁰ The second method gave better results. It involved soaking the wafer in pure isopropyl alcohol for 10 min until the alcohol displaced the water underneath the paddles and then evaporating the alcohol by placing the wafer on a hot plate at 200°C . The reflecting pad areas of the paddles range from $60 \times 50 \mu\text{m}$ to $30 \times 50 \mu\text{m}$ with arm lengths from 40 to $30 \mu\text{m}$, but all structures had an arm width of $10 \mu\text{m}$. The dimensions of all the paddle structures are designed for a sacrificial layer etch of about 4 hrs.

Prior to exposure to plasma, the devices are externally calibrated by observing the deflection in response to an applied electrical voltage, using a needle probe to apply voltage to the polysilicon on top of the support. Figure 3 shows the tip deflection angle of the paddle as a function of voltage. Simulations of deflection vs voltage were performed by finite difference modeling. The results are in good agreement with measured data.

The schematic of the experimental setup used to detect charging *in situ* in the parallel-plate reactor is shown in Fig. 4. A He-Ne laser is directed into the reactor chamber through a quartz window after passing through a beam splitter. The laser beam covers several identical paddles so no focusing is necessary. The reflected light is projected onto a screen. When charging occurs, the paddles deflect leading to a shift in the reflected laser spot on the screen. From the tip deflection angle, which can be easily computed from this shift, the charging voltage in the plasma can be determined. The advantage of this technique is that it is direct and gives fairly accurate results ($<5\%$ error). But the disadvantage is that it requires an optical port and one cannot measure charge-

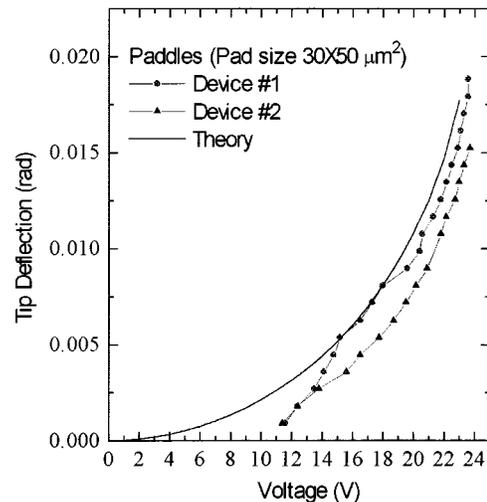


FIG. 3. External calibration of paddles of pad size $30 \times 50 \mu\text{m}^2$ showing the tip deflection angle versus applied voltage.

ing voltage at different parts of the electrode.

During plasma exposure, cantilevers that deflect far enough suffer “pull in”¹¹ and touch the substrate. When this occurs, they often suffer from “stiction,” i.e., they remain stuck after the removal of the charge. This can be quickly detected by external inspection under an optical microscope after the plasma exposure. The charging voltage can be estimated by having a range of paddle sizes with different pull in voltages on the wafer, and observing which ones have pulled in. Charging voltages inferred by this approach agree well with those measured directly *in situ*. The main advantage of this method is that no optical ports are required and one can quickly map charging nonuniformities across the electrode.

The charging voltage in a parallel-plate reactive-ion-etching reactor has been measured by both techniques. The electrode diameter is 24 cm and spacing between the electrodes is 5 cm. The gases are injected into the chamber through a shower head in the top electrode. All experiments were done in oxygen plasma with rf frequency 13.56 MHz.

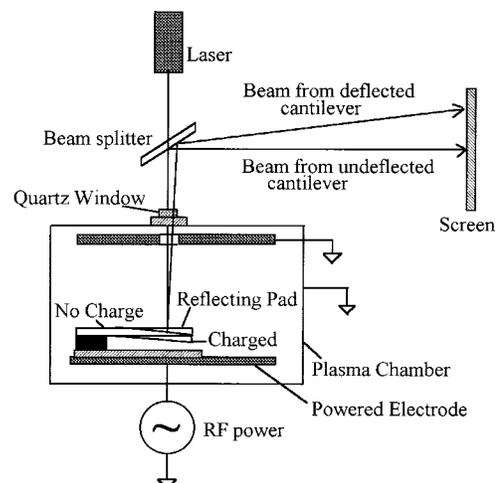


FIG. 4. Experimental setup used to detect charge in plasma, showing reflected beam from charged and uncharged sensor.

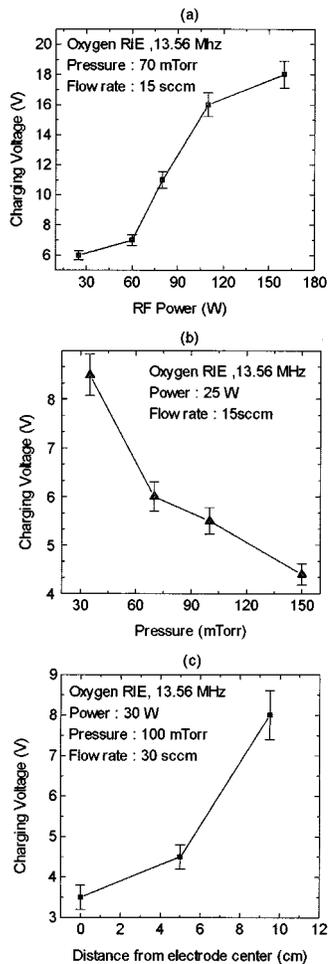


FIG. 5. (a) charging voltage as a function of input rf power at constant flow rate and chamber pressure, (b) charging voltage as a function of chamber pressure at constant flow rate and rf power, and (c) charging voltage as a function of position across the electrode at constant rf power, chamber pressure, and flow rate.

The charging voltage near the electrode edge (9.5 cm from the center) is measured by the *in situ* technique. The charging voltage was found to increase as rf input power increased [Fig. 5(a)], and a charging voltage as large as 20 V

was seen. The charging voltage decreased as the chamber pressure was reduced [Fig. 5(b)], as has been seen by others using electrical probes inside the plasma⁶ at the electrode edge, albeit for a different gas. These results clearly demonstrate the utility and versatility of the technique. Note that the voltages measured are sufficient to damage thin gate dielectrics (e.g., 5 nm oxide has a breakdown voltage of ~ 10 V). We also measured charging voltages at the 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. 5(c)].

In summary, we have demonstrated a noninvasive method for quickly measuring charging effects that occur in plasma-based semiconductor processing. The method also allows *in situ* measurement of the charge or mapping charging effects over large areas. The method should prove valuable for the development of advanced etch processes, and the structure may prove useful for general charge sensing problems.

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