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MECHANISM OF SUBSTRATE CHARGING AFTER PLASMA PROCESSING

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Abstract

An electrostatic charge can be left on an insulating substrate after RF plasma processing, even though the plasma and surfaces are globally neutral. High voltages and breakdown can then occur when the substrate is manipulated. If the substrate is not a perfect insulator, charge appears on its back face where there is no contact with the plasma. In this case, the substrate sticks electrostatically to the electrode, and partial discharging can occur when it is lifted. Analysis of *in situ* charge measurements reveals the mechanism responsible for the charging, which is analogous to electrostatic chucking of the glass to the electrode when exposed to plasma.

1. Introduction

Electrostatic charging of an insulating substrate when exposed to plasma is a concern for electronic device fabrication where several plasma processing steps (deposition, etching and ashing) are involved. In particular, for thin film transistors (TFT's) on glass substrates in active-matrix liquid crystal displays (AM-LCD's), the residual charge left on the substrate at the end of the process can induce high voltages on the glass and large electric fields along its surface when manipulating it afterwards. Via the interconnecting circuitry within the matrix, this field can induce high local voltages across thin dielectrics resulting in breakdown and irreversible damage. In this paper, we describe a mechanism of back face charging of the glass substrate during plasma processing. The predictions of the model are shown to be consistent with measurements of substrate charge in a large area industrial parallel plate rf reactor.

2. Mechanism of backface charging; description of the gap between glass and electrode

We will first consider a simple model to describe the charging mechanism of the plasma-glass-electrode system and then show how it can account for experimental measurements of the substrate charge in section 4. The model involves a small gap h (several microns) between the glass and the electrode where electrical contact is poor due to surface roughness. A schematic and equivalent circuit of the plasma-glass-electrode system is shown in Fig. 1, where it is assumed that the plasma maintains a small dc voltage V_{glass} on the upper glass surface during the plasma processing time. The amount of charge accumulated and its location on the glass substrate during the plasma processing time is then determined by the resistances R_{glass}, R_{gap} and capacitances C_{glass}, C_{gap} of the glass and the gap, and by the plasma-induced voltage V_{glass}. These parameters are estimated below.

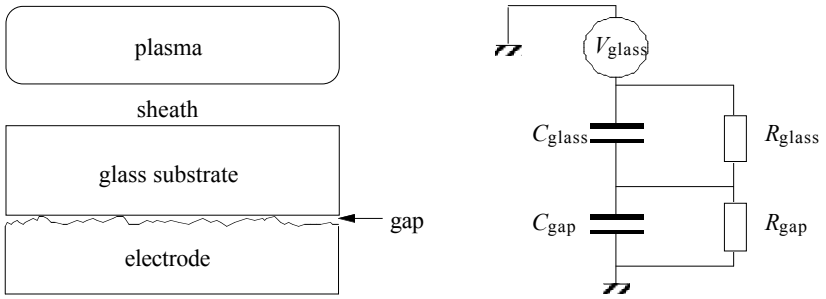

Fig. 1: *Schematic of the plasma-glass-electrode system and its equivalent circuit*

The electrical resistivity of glass varies strongly with temperature, approximately obeying an Arrhenius law. At room temperature, the resistivity of Corning display-quality glass is 10^{21} Ωm, but at a plasma processing temperature of 280°C the resistivity falls to 10^{11} Ωm and the hot glass is slightly conductive. In a homogeneous resistive dielectric, with relative permittivity ε_r, charge moves to cancel time-averaged electric fields on the timescale of the dielectric relaxation time $\rho\varepsilon_0\varepsilon_r$. This is 10^3 years for room temperature glass (ε_r=6), and therefore any charge placed on cold glass is immobile. For the hot glass the dielectric relaxation time is only several seconds, and we have the important result that charge can be displaced in a hot glass substrate to cancel dc electric fields during the timescale of plasma processing.

To estimate the mechanical and electrical properties of the glass-electrode interface, we use the model of Greenwood and Williamson [1] for the contact of nominally flat, rough surfaces. The glass substrate and aluminium electrode touch at N contact points which are the highest asperities. The results for unit substrate area are summarised in equations 1) to 4), where N_0 is the number of asperities per unit area, h is the gap height, L is a scaling length describing the distribution of the highest asperities, A is the cumulated area of full contact, r is the average radius of curvature of the asperity summits, E^* is the combined plane stress modulus of both materials, P is the mechanical pressure between the glass and electrode causing elastic deformation of the asperities, and R_{gap} is the glass-aluminium contact resistance:

Number of contact points	$N=N_0\exp(-h/L)$	1)
Area of full contact	$A=\pi LrN$	2)
Pressure	$P=E^*LN\sqrt{\pi Lr}$	3)
Contact resistance	$R_{gap}=E^*L\rho/P$	4)

In the specific case of glass lying on an aluminium electrode we can estimate the parameters as follows:

L	1-2 μm	defined principally by the machining of the aluminium electrode;
r	4-6 μm	estimated average radius of curvature of the asperity summits;
E^*	30 GPa	approximate combined stress modulus for aluminium and glass;
P	27 Pa	pressure due to the weight of 1.1 mm thick glass, density 2540 kgm^{-3}.

By setting the contact pressure P equal to the weight of a 1m^2 glass substrate in Eq. 3), we estimate the number of contact points N~10^2, the contact resistance of the gap R_{gap}~10^{14} Ω at 280°C from Eq. 4), and the fractional area of full contact ~10^{-8} at the glass-electrode interface from Eq. 2). On the other hand, the plasma has electrical contact over the full area of the glass, and the resistance between the plasma-glass surface and the glass back face is $R_{glass}=t\rho$ ~10^8 Ω at 280°C, where t = 1.1 mm is the glass thickness. Therefore we have the

result $R_{gap} >> R_{glass}$, principally because the glass-electrode contact area is far smaller than the plasma-glass contact area. Moreover, for an estimated surface-averaged gap height $h \sim 20\mu m$, the $1m^2$ glass-electrode capacitance $C_{gap} = \varepsilon_0/h \sim 0.44$ μF, whereas $C_{glass} = \varepsilon_0\varepsilon_r/t \sim 0.048$ μF and therefore $C_{gap} \sim 10^1 C_{glass}$.

The implication of the model equivalent circuit in Fig. 1 is that the voltage V_{glass} applied by the plasma to the glass surface at 280°C will charge up the glass back face via a leakage current through the glass to the plasma in a plasma processing 1/e time given by:

Back face charging time (independent of substrate area): $\tau_{charge} \sim R_{glass}C_{gap} \sim 10^2$ s 5)

and the voltage V_{glass} will appear across the glass-electrode gap. The asymptotic value of the back face charge, $Q_{max}=V_{glass}C_{gap}$, is then larger than the charge which would appear on the top surface of perfectly-insulating glass by a factor C_{gap}/C_{glass}, i.e. by an order of magnitude.

After plasma extinction, the current leakage path via the plasma is cut, and the back face charge can only discharge to the electrode via the contact point resistance, with a 1/e discharge time $\tau_{discharge} >> \tau_{charge}$. If, on the other hand, the glass back face were charged up during the plasma by leakage currents via contact with the electrode, the glass would discharge in a comparable time after plasma extinction. Furthermore, a more complete treatment to be presented in a future paper shows that the back face charge is accumulated and trapped in localised potential wells between the points of contact. Nevertheless, the simple model presented here serves to illustrate that:

i) *The back face of the hot glass substrate can be charged up during a plasma processing step lasting several minutes;* and
ii) *At the end of the plasma processing step, the charge can remain trapped on the back face of the glass substrate.*

3. Origin and polarity of the plasma-induced voltage on the glass surface

The polarity and magnitude of the glass charge depend on the glass surface dc potential V_{glass} in the presence of plasma. Accounting for the equilibration of ion and electron currents in the complex situation of a large asymmetric reactor with the ground electrode partially covered by a substrate, it can be shown that the glass surface potential is ~ 0.7 of the self-bias. The rf electrode area is smaller than the ground electrode resulting in a negative dc self-bias, and therefore the substrate is predicted to charge negatively during exposure to the plasma.

Finally, when the plasma is extinguished, the charges in the afterglow will move to cancel electric fields in the plasma volume. But even if the glass top surface potential is reduced completely to zero during the afterglow, a majority negative charge will remain on the back face of the glass.

4. Experimental method, results and evidence for back face charging of glass substrates

Experiments were performed in a KAI "plasma-box" reactor [2] devoted to PECVD of amorphous silicon, silicon nitride and silicon oxide films on glass substrates for mass production of AM-LCD's. The substrate size for these experiments was 350 mm x 450 mm x 1.1 mm thick. The rf (13.56 MHz) discharge was capacitively coupled with a 24 mm inter-electrode distance *d*. The Corning glass substrate was placed on the ground electrode and could be moved up and down for loading and unloading by four ceramic pins. For substrate charge measurements, an electrometer was inserted between the ground and rf electrodes after

plasma extinction [3]. The displacement current J, measured when the charged substrate is moved, is given by:

$$J = uQ/d \qquad 6)$$

which is constant during the movement if the substrate speed u is constant and the total residual charge Q on the substrate remains unchanged. The voltage V on the substrate, area A, is given by:

$$V = \frac{Qd_1(d-d_1)}{\varepsilon_0 Ad} \qquad 7)$$

which reaches its largest value at mid-height between the electrodes. This voltage arises from the work done by lifting the charged substrate against the electrostatic attraction of the induced image charges on the electrodes. If the charge is distributed non-uniformly on the substrate in localised potential traps, the values of charge density and potential will locally be higher.

Up to this point, the substrate charge diagnostic provides no information on the origin of the charge, nor where the charge resides on the glass plate. Experiments 1 to 5 presented below were designed to test the predictions of the back face charging model.

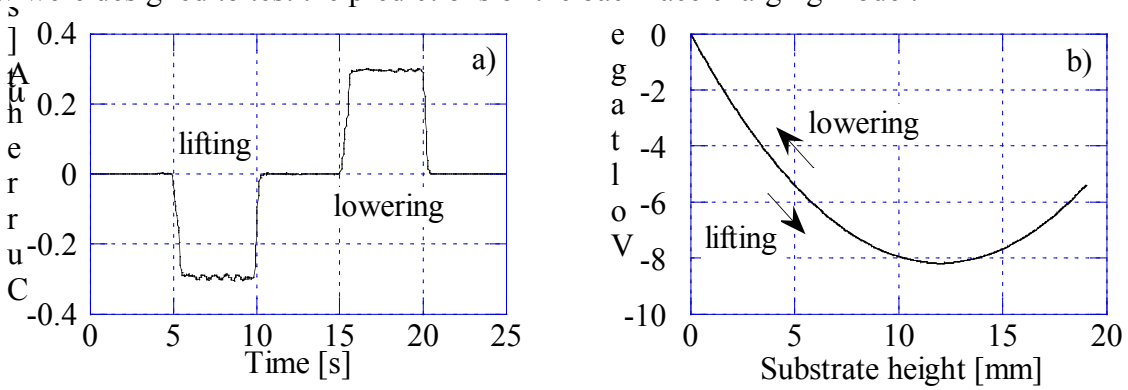

Fig. 2a: *Displacement current measurement;* **b:** *Deduced substrate voltage during lift cycle*

Expt. 1: For the measurement in Fig. 2a, the substrate was exposed to a nitrogen plasma (200 W, 1 mbar) for 15 minutes with the reactor and glass substrate heated to 280°C; the reactor was then evacuated to below 10^{-5} mbar and the displacement current was measured during lifting through 19 mm and back. The measured charge was negative, as predicted, and the magnitude of the charge remained constant even after leaving the glass on the electrode overnight. The charge was therefore trapped on the glass substrate after plasma processing, consistent with the description of very slow discharging through the glass-electrode interface. Quantitatively, the current plateau -0.3 μA in Fig. 2a induced by the substrate lifting speed u = 3.8 mm/s indicates a substrate charge Q = -1.9 μC, using Eq. 6. If Q is taken to be on the back face, then $Q = V_{glass}\varepsilon_0 A/h$, and with a 20 μm gap this corresponds to a plasma-induced substrate voltage $V_{glass} \sim$ -27 V. The measured self-bias was -47 V, in good agreement with the estimation in Section 3 that $V_{glass} \sim 0.7$ of the self-bias. Conversely, if Q were taken to be on the glass *top* surface, this would imply an unrealistic substrate voltage of $V_{glass} \sim$ -250 V.

In Fig. 2b, the corresponding substrate voltage V calculated using Eq. 7 reaches -8.2 kV at mid-gap: clearly a serious electrostatic hazard. The strong voltage magnification by lifting the charged substrate several mm above the electrode is only possible because the charge is initially in such close proximity to the electrode. To summarise, the large values of substrate charge and voltage can only be explained in terms of back face charging.

Expt. 2: When the back face of the same glass substrate was coated with a metallic layer to ensure good electrical contact between the glass and the aluminium ground electrode, the measured charge was reduced by orders of magnitude, presumably because the charge was efficiently conducted to ground ($R_{gap} \sim 0$). When the *top* face was metallised, the observations of Expt. 1 were unchanged. Furthermore, if the uncoated glass was supported on several thin glass shims (0.5mm thick) to prevent close contact between the back face and the ground electrode during the plasma, the gap capacitance was then too small to build up a significant charge for the plasma-induced voltage V_{glass}. These experimental observations are consistent with back face charging of the glass substrate in the presence of plasma.

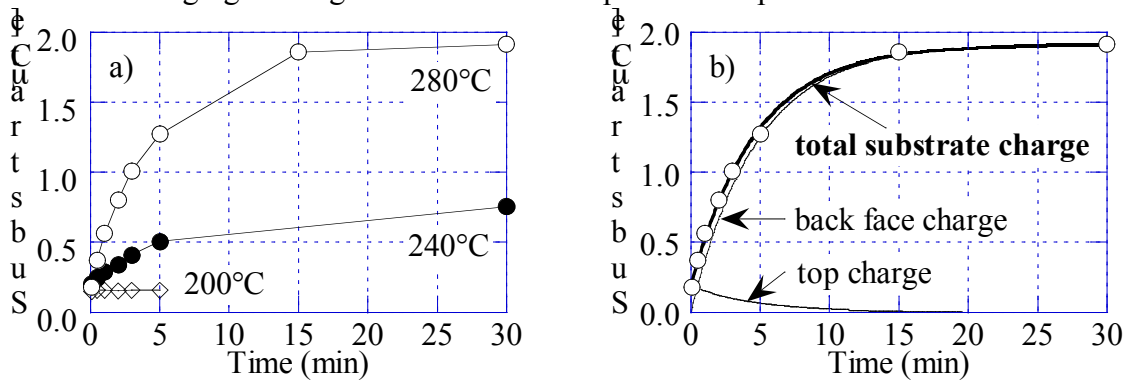

Fig. 3a: *Substrate charge vs plasma duration;* **b:** *Curve fitting to the data points for 280°C.*

Expt. 3: The plasma-induced substrate charge is predicted to increase with time as the back face gradually charges up via leakage currents through the hot glass to the plasma. Fig. 3a shows the substrate charge, measured using the displacement technique above, for different plasma exposure times and three substrate temperatures. The plasma parameters were identical to those in Expt. 1. On the basis of the simple equivalent circuit of Fig. 1, with $R_{gap} >> R_{glass}$, the charge on the top of the glass is:

$$q_{top} = q_0 \exp\left(-t/\tau_{charge}\right), \text{ with } q_0 = VC_{gap}C_{glass}A/\left(C_{gap}+C_{glass}\right), \qquad 8)$$

and the charge on the back face of the glass is:

$$q_{back} = VC_{gap}A\left(1-\exp\left(-t/\tau_{charge}\right)\right), \text{ where } \tau_{charge} = R_{glass}\left(C_{gap}+C_{glass}\right) \qquad 9)$$

and R_{glass}, C_{glass} and C_{gap} are the values per unit area. The expression for the total substrate charge, $Q = q_{top} + q_{back}$, is fitted to the data at 280°C in Fig. 3b for a charging time τ_{charge} = 282 s. The initial charge is all on the top face, whereas the final charge, for plasma duration of at least $3\tau_{charge}$ = 14 minutes, is almost entirely on the back face and the voltage V_{glass} exists across the glass-electrode gap. The ratio of these limiting charges is $\left(1+C_{gap}/C_{glass}\right) \sim 10$, from which we estimate the gap width $h = t/9\varepsilon_r = 20\mu m$, as used retrospectively throughout this paper. The glass resistivity, estimated from the charging time, is 5.10^{11} Ωm, and the plasma-induced glass voltage is $V_{glass} \sim$ -27 V (the data point at 15 minutes corresponds to the measurement discussed in Expt. 1). For the lower temperatures, the glass is much more resistive and so the charging time is much longer: the substrate charge is predicted to be confined to the top of the glass at 200°C in Fig. 3a, and the measured substrate charge corresponds only to the initial value. Substrate charge and voltage levels are consequently an order of magnitude smaller at lower processing temperatures.

Expt. 4: The sudden collapse of the current signal in Fig. 4a indicates non-contact, partial discharging of the substrate while it is rising a few mm above the ground electrode. The slow

discharging in Fig. 4b occurs while the pressure is gradually increased with the substrate fixed at 4 mm above the ground electrode. Townsend and/or Paschen discharging is not observed when the substrate is lifted *in vacuo*, as in Fig. 2a. Such discharging demonstrates that the substrate reaches high voltages during lifting.

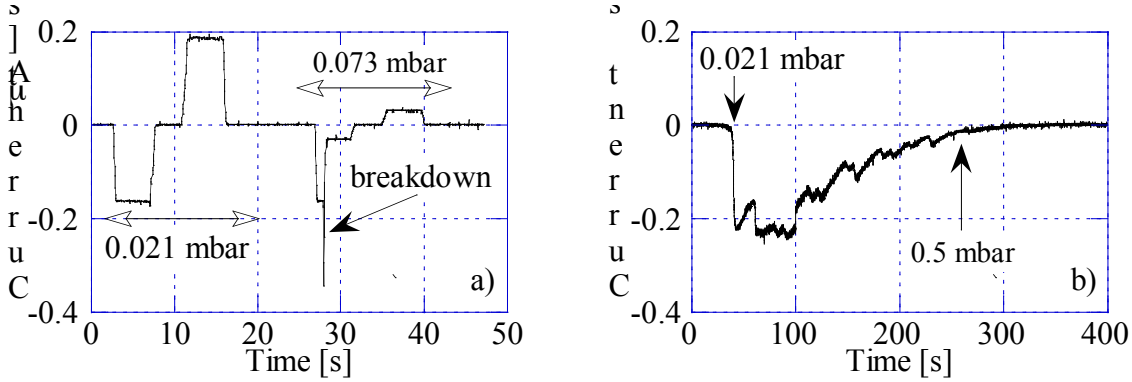

Fig. 4a: *Discharge during lifting;* **b:** *Slow discharge with the substrate fixed at 4 mm height.*

Expt. 5: Glass substrates can stick electrostatically to the electrode after high power plasma processing. The electrostatic pressure across the glass-electrode gap is given by $P_e=\varepsilon_0 V_{glass}^2/2h^2$. At 400 W rf power, for example, the voltage V_{glass} ~ -50 V across the 20 μm gap gives an electrostatic force equal to the unit area glass weight (27 Pa for 1.1 mm thickness). However, if the same V_{glass} were applied to the glass top surface, the electrostatic force of 0.05 Pa would be trivial. Electrostatic sticking of the glass substrate to the electrode is the same as electrostatic adhesion of a resistive dielectric to a metal plate by application of a dc potential which appears across the small gap between them; this is the basis of the Johnsen-Rahbek effect [4] used nowadays in electrostatic chucks. In this context, the charging and discharging times, τ_{charge} and $\tau_{discharge}$, correspond to the chucking and de-chucking times.

5. Conclusions

After several minutes plasma processing of a hot glass substrate on the ground electrode in an asymmetric rf reactor, the back face of the substrate will be left with a negative charge which remains trapped after plasma extinction. When raised for removal, the substrate voltage can reach several kV. A simple model successfully accounts for the measurements of substrate charge in a wide variety of experimental conditions. The mechanism is analogous to electrostatic chucking of the glass dielectric to the electrode by the plasma-induced potential. An understanding of the phenomena involved helps to find ways of eliminating and/or avoiding electrostatic problems due to substrate charging in plasma processing.

References

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