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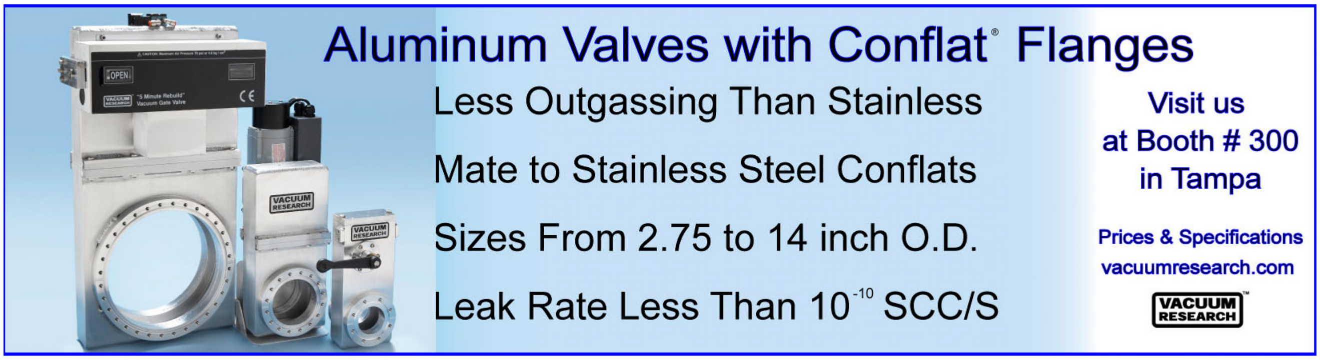

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Equivalent-circuit model for vacuum ultraviolet irradiation of dielectric films

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Vacuum ultraviolet (VUV) irradiation, which occurs during plasma processing, causes photoemission of electrons from the dielectrics. Photoemission primarily occurs from defect states in the band gap of the dielectric and results in trapped positive charges. The trapped positive charges are negated by photoinjection of electrons from the underlying substrate into the dielectric. The authors propose an equivalent-circuit model using with which, once the circuit parameters are determined, charging of dielectric materials under VUV irradiation can be predicted. The circuit includes a dielectric capacitor, the intrinsic and photo conductivities of the dielectric and substrate, and the processes of photoemission and photoinjection. © *2012 American Vacuum Society*. [http://dx.doi.org/10.1116/1.3693602]

I. INTRODUCTION

The trapped positive charge generated in dielectrics from vacuum ultraviolet (VUV) irradiation present in processing plasmas often results in a positive surface potential. Monitoring the surface potential is one of the ways to analyze the effect of irradiation on the dielectrics. To separate VUV irradiation from charged particle flux, a synchrotron can be used instead of a processing plasma. However, the entire procedure to determine the response of dielectrics to VUV can be experimentally cumbersome. Through the equivalent-circuit model presented here, once the circuit parameters are determined, the model can be used to analytically compute charging of dielectric films under VUV irradiation. In this work, we describe the model and explain how the circuit parameters can be found from experimental data of VUV irradiation of organosilicate glass (SiCOH). To validate the circuit model, we show the experimental correlation with the calculated photoemission current for a number of dielectric thicknesses.

II. BACKGROUND

VUV irradiation of dielectrics can cause electron-hole pair generation, photoconduction, photoemission, and photoinjection of electrons from the substrate into the dielectric.[1–4] These processes depend on the incident photon energy and the dielectric thickness and composition. Electron-hole pairs will be formed if electrons are excited into the conduction band from the valence band or from defect states within the dielectric. Depending on their energy, the electrons and holes can travel in the dielectric with a number of them being photoemitted.[5] Electrons dominate photoconduction, photoemission, and photoinjection, since the mobility of electrons is larger than the mobility of holes.[6]

Photoemission can occur from the dielectric when the energy supplied by irradiation is greater than the sum of the bandgap energy and the electron affinity.[5] In addition, photoemission can also occur from defect states in the dielectric. These lead to depopulation of electrons within the dielectric. Thus, after photoemission, a dielectric develops a net positive charge.

Conversely, photoinjection reduces the number of trapped positive charges in the dielectric. This is the case because electrons injected from the substrate into the dielectric can repopulate the defect states.[2] It should be noted that photoinjection is a function of the thickness of the dielectric because VUV photons must penetrate through the dielectric to generate electron-hole pairs in the substrate. These electrons are then photoinjected into the dielectric.

It is plausible that photoinjected electrons drift from the substrate-dielectric interface to the dielectric-vacuum interface and are photoemitted.[5] Thus, at any given time during VUV irradiation, the photoemitted electrons will consist of (1) depopulated electrons from the defect states and (2) photoinjected electrons. Trapped positive charge resulting from the depopulation of the defect states will continue to build up until a steady state is achieved. In steady state, the net number of trapped charges in the dielectric reaches a constant and the photoemitted electron flux matches the flux of photoinjected electrons. In order to have a complete circuit, charge conservation dictates that when the substrate is connected to ground, the photoemitted electrons are returned to the substrate. Thus, in steady state, the photoinjection current is equal to the substrate/photoemission current.[7]

The processes of photoemission, photoinjection, and photoconduction can be seen visually in Fig. 1, which represents a dielectric film exposed to synchrotron radiation.

Equivalent circuit models for such VUV irradiation have been proposed earlier.[8,9] The model in Ref. 9 has value in that it predicts the photoemission current, although it has two disadvantages. First, the model does not physically differentiate between the dielectric and substrate layers. This means that all the circuit-parameter values would change even if only the dielectric or substrate properties are altered. Second, the model utilizes current sources in series with other passive circuit elements. Thus, the current flowing through the circuit is independent of the values of the passive circuit elements. The model described in this work eliminates these drawbacks.

III. EQUIVALENT-CIRCUIT MODEL

The equivalent-circuit model for the experimental configuration shown in Fig. 1 is shown in Fig. 2. The back of the substrate is grounded through an ammeter to the vacuum chamber. The ammeter reads the substrate current (I_{subs}).

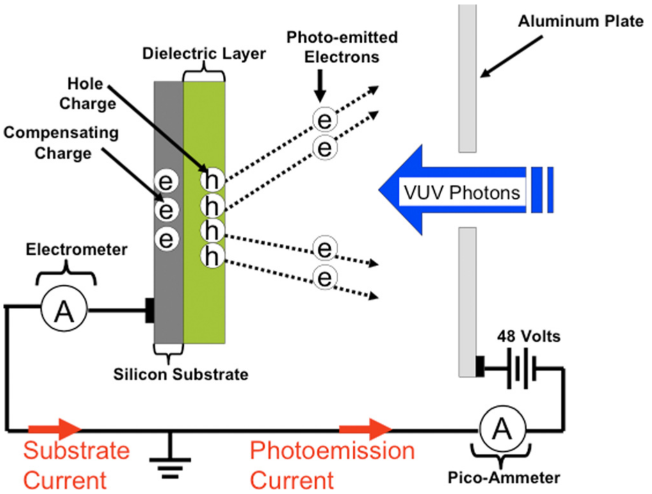

FIG. 1. (Color online) Substrate/photoemission currents during VUV irradiation of dielectrics.

However, to model the circuit between the dielectric sample and the vacuum chamber, which collects photoemitted electrons, we use a photodiode (D). When the radiation is off, no electrons can travel from the dielectric to the vacuum chamber so it is equivalent to an open circuit. Electrons can only be photoemitted, i.e., a current can flow, from the dielectric sample to the vacuum chamber when the VUV radiation is on. The surface potential (V_{sp}) is the potential measured at the dielectric-vacuum surface of the dielectric with respect to ground and is marked on the circuit diagram in Fig. 2.

The sample itself, i.e., the dielectric deposited on a Si substrate, is represented by a combination of capacitors, resistors and dependent voltage sources as follows. First, we know that an ideal dielectric can be modeled as a parallel-plate capacitor (which is represented by C_d) if fringing fields are neglected. The capacitance can be approximated as

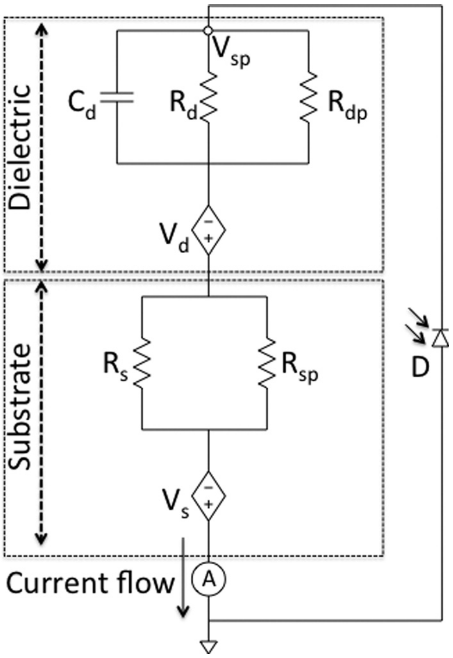

FIG. 2. Circuit model for the dielectric and the substrate.

$$C_d = \frac{\varepsilon_r \varepsilon_o A}{d}, \tag{1}$$

where ε_r is the dielectric constant, ε_o is the vacuum permittivity, A is the area of the dielectric, and d is the dielectric thickness. However, in case of a real dielectric, both bulk and interfacial defect states are present. These defect states can cause Fowler–Nordheim tunneling currents.[10,11] Thus, we include a resistor (R_d) in parallel to the capacitor to represent the intrinsic conductivity of the dielectric. In addition to intrinsic conductivity, photoconductivity is introduced in the dielectric during VUV radiation. This is shown by a resistor (R_{dp}) also in parallel with the capacitance. R_{dp} will be inversely proportional to photon flux, becoming infinite when the VUV photon flux is zero. Both resistors R_d and R_{dp} will be directly proportional to the thickness of the dielectric.

In addition to C_d, R_d, and R_{dp}, electron depopulation from the defect states due to VUV irradiation also needs to be included. This means that the dielectric acts as a source of electrons and results in a flow of current. A source of electrons can be shown by a dependent voltage source (V_d). The rate of depopulation of electrons at a given photon energy is proportional to the photon flux (f) of VUV irradiation and the number of populated defect states remaining. The rate of change of the surface potential is thus proportional to the rate of change of the populated defect-state density. Hence the value of the dependent voltage source is given in both the time domain and the Laplace-transform frequency domain by

$$V_d = Kf\,\frac{dV_{SP}}{dt} = Kf\,sV_{sp} = K_s V_{sp}, \tag{2}$$

where K is a constant that depends on the material property, f is the VUV photon flux, and V_{sp} is the dielectric surface potential. Since the flux is constant at a given time for a given energy, K times flux can be replaced by a new constant K_1.

The substrate also needs to be included to have a complete model. We represent the substrate, which is a semiconductor, by a resistor (R_s). This resistor signifies the intrinsic resistance of the substrate. In addition, as VUV photons cause electron-hole pair generation in substrate, a photoresistance component is added in parallel to the intrinsic resistance. This is shown as a resistor (R_{sp}). Again, R_{sp} will be inversely proportional to the VUV photon flux and will be infinite when flux is zero. As stated earlier, electron-hole-pair generation can occur in the substrate. This results in photoinjection of electrons across the substrate-dielectric energy barrier. The photoinjection can be represented by a dependent voltage (V_s) source. This dependent voltage source will be a function of photon flux and is written as

$$V_s = K_2 f, \tag{3}$$

where K_2 is also a constant that depends on the material property and f is the VUV photon flux.

Thus, the circuit in Fig. 2 is a set of two Thevenin-equivalent circuits in series. By use of an appropriate source transformation, the circuit can be transformed into two Norton-equivalent sources, in which current sources are in parallel with the same equivalent impedances shown in Fig. 3. The Norton-equivalent current sources in the Laplace-transform frequency domain are I_{dN} for the dielectric and I_{sN} for the substrate and can be found to be

$$I_{dN} = \frac{V_d}{\left[(R_d||R_{dp})||\left(\frac{1}{sC}\right)\right]}, \tag{4}$$

$$I_{sN} = \frac{V_s}{(R_d\,||\,R_{dp})}, \tag{5}$$

where the symbol || represents the parallel combination of the resistors on each side of the symbol. The circuit can be simplified to three separate circuits for the following cases: (1) before steady state is achieved, (2) during VUV irradiation after steady state is achieved, and (3) after the VUV is turned off.

Just after VUV irradiation begins, the capacitance C_d is equivalent to a short circuit. This is because the capacitor has no charge and hence all the current will flow directly into the capacitor. In addition, the diode can be represented by a short circuit while VUV irradiation is on.

In Fig. 4, the circuit during steady state is shown. Since no further depopulation will occur in steady state, the derivative of the surface potential (V_{SP}) with time is zero. Hence, the dependent voltage source V_d becomes zero and is represented by a short circuit. Also, the capacitor C_d is completely charged and thus acts as an open circuit. In addition to these conditions, the diode remains a short circuit while the VUV irradiation is on.

Figure 5 shows the equivalent circuit when the VUV is turned off after reaching steady state. Because no radiation is present, the resistances linked to photoconduction become infinite. Hence, R_{sp} and R_{dp} are shown as open circuits. Also, the zero photon flux causes the diode to be an open circuit. For zero photon flux the two dependent voltage sources V_d and V_s are zero, i.e., short circuits.

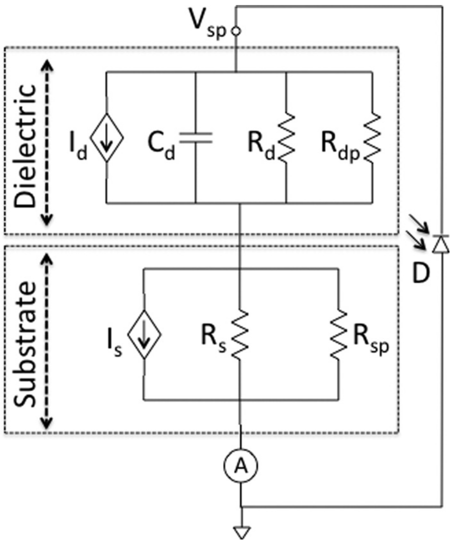

FIG. 3. Norton-equivalent circuit of the model.

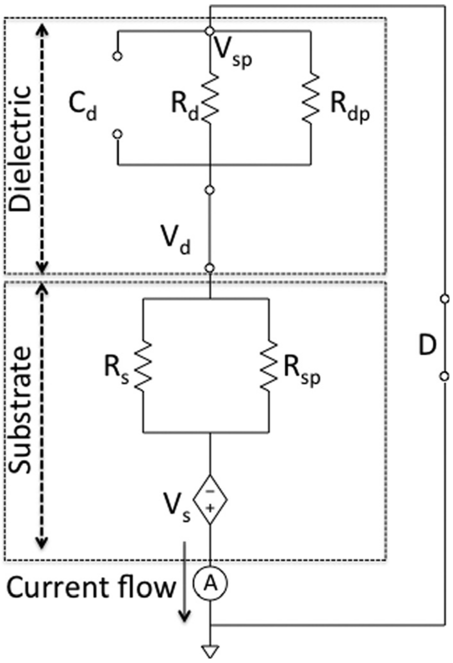

FIG. 4. Reduced-circuit for the dielectric-substrate layer when steady state is achieved during VUV irradiation.

IV. DETERMINATION OF CIRCUIT MODEL PARAMETERS AND EXPERIMENTAL CORRELATION

The circuit parameters are found as follows. The capacitance C_d can be approximated as a parallel plate capacitor since the dielectric constant and thickness are known. As a first example, a 500 nm thick UV-cured SiCOH dielectric with a dielectric constant of 2.65 was used. For a 1 cm × 1 cm area, the capacitance is

$$C_d = \frac{\varepsilon_r \varepsilon_o A}{d} = \frac{2.65 \times 8.85 \times 10^{-12} \times (10^{-2})^2}{500 \times 10^{-9}} = 4.69 \times 10^{-9}[F]. \tag{6}$$

To determine the intrinsic conductivity, we use the circuit shown in Fig. 5 that models the case after irradiation from the moment the VUV radiation has been turned off. Based on this circuit, the intrinsic resistance of the dielectric can determined from the time constant (τ) for trapped charge decay. The trapped charge decay when VUV is turned off (post irradiation) can be modeled with an exponential.[12] The surface-potential decay rate was found experimentally to be[13]

$$V_{decay} = 9.24 e^{-3.22 \times 10^{-5} t}[V]. \tag{7}$$

Hence, the intrinsic dielectric resistance can then be computed to be

$$R_d = \frac{\tau}{C_d} = \frac{3.1 \times 10^4}{4.69 \times 10^{-9}} = 6.6 \times 10^{12}[\Omega]. \tag{8}$$

Now, we move to the case when VUV irradiation is just turned on. When VUV irradiation begins (Fig. 2), we can write

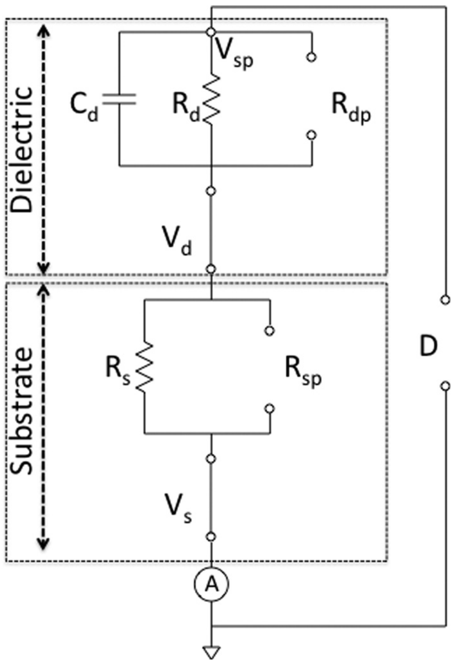

FIG. 5. Reduced-circuit for the dielectric-substrate layer after VUV irradiation is turned off.

$$I_{\max}(t=0^+) = \frac{V_s + K_1 \frac{dV_{sp}}{dt}|_{t=0^+}}{R_{sp}}. \tag{9}$$

This is based on the assumption that $R_{sp} \ll R_s$, therefore $R_{sp} \approx R_{sp} \| R_s$ when VUV irradiation is on. By data substitution and simplification

$$I_{\max} = \frac{V_s + K_1 \times 1.33 \times 10^{-2}}{R_{sp}}.$$

Now $I_{\max}$ is known experimentally from the synchrotron exposure measurements. Hence,

$$8.54 \times 10^{-10} = \frac{V_s + K_1 \times 1.33 \times 10^{-2}}{R_{sp}}. \tag{10}$$

Looking back at Fig. 2, the photoemission current at any time while the VUV is on can be written as

$$I_{pe}(t) = \frac{V_s + V_d(t)}{R_{sp} + R_{dp}}.$$

The above equation can also be rewritten as

$$I_{pe}(t=t') = \frac{V_s + K_1 \frac{dV_{sp}}{dt}|_{t=t'}}{R_{sp} + R_{dp}}.$$

Using the current value at $t = 100$ s, from the experimental measurement shown in Fig. 6,

$$1.38 \times 10^{-10} = \frac{V_s + K_1 \times 1.152 \times 10^{-2}}{R_{sp} + R_{dp}}. \tag{11}$$

Now, we use the condition when VUV irradiation is on and the substrate current has reached steady state. The expression for current at steady state can be derived from the circuit shown in Fig. 4:

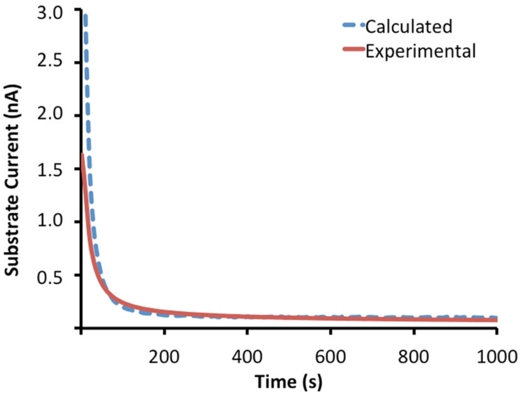

FIG. 6. (Color online) Calculated and experimental substrate/photoemission currents for 500 nm of UV-cured SiCOH deposited on Si during VUV irradiation.

$$I_{pi} = I_{pe}(t=\infty) = \frac{V_s}{R_{sp} + R_{dp}}.$$

Based on experimental measurements, I_{pi} was found to be

$$I_{pi} = 5.614 \times 10^{-11} = \frac{V_s}{R_{sp} + R_{dp}}. \tag{12}$$

Using Eqs. (10), (11), and (12), we determine

$$V_s = 1.107 \times 10^{-9} R_{sp},$$

$$K_1 = 6.431 \times 10^{-8} R_{sp},$$

$$R_{dp} = 18.71 R_{sp}.$$

Based on these values the photoemission current is calculated and is shown in Fig. 6 along with the experimentally measured current. The results show a good correlation between calculated and experimental data.

To further verify the model, the same model and calculation technique was used for 640 nm thick as-deposited SiCOH. The results are shown in Fig. 7.

The model can be extended to predict photoemission/substrate currents flowing during VUV irradiation of dielectrics. The constants K_1 and K_2 are dependent on material

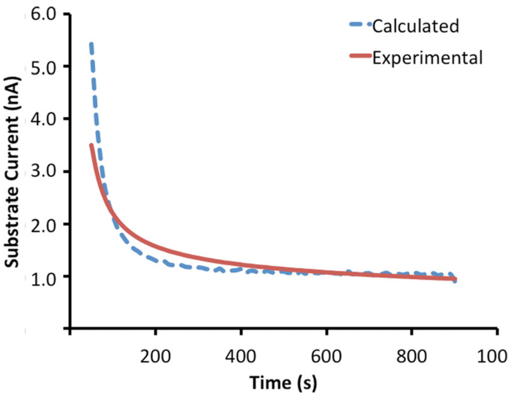

FIG. 7. (Color online) Calculated and experimental substrate/photoemission current for 640 nm of as-deposited SiCOH deposited on Si during VUV irradiation.

properties, and the dielectric/substrate resistances (R_d, R_{dp}, R_s, and R_{sp}) are function of thickness. By determining the correlations the circuit model will become a predictive model.

V. CONCLUSIONS

The effect of VUV radiation on charging and currents in dielectrics can be modeled with an equivalent circuit. The circuit has been shown to effectively model the photoemission/substrate current flowing during VUV irradiation.

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