Time-dependent dielectric breakdown of plasma-exposed porous organosilicate glass

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Time-dependent dielectric breakdown (TDDB) is a major concern for low-*k* organosilicate dielectrics. To examine the effect of plasma exposure on TDDB degradation, time-to-breakdown measurements were made on porous SiCOH before and after exposure to plasma. A capillary-array window was used to separate charged particle and vacuum ultraviolet (VUV) photon bombardment. Samples exposed to VUV photons, and a combination of VUV photons and ion bombardment exhibited significant degradation in breakdown time. The samples exposed to VUV photons and ion bombardment showed more degradation in breakdown time in comparison to samples exposed to VUV photons alone. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.3693526]

Porous low-*k* organosilicate dielectrics are replacing SiO_2 as the preferred intermetal layer dielectric to reduce signal propagation delay and power dissipation in ULSI circuits.[1] It is of considerable importance to characterize the chemical and physical stability of these films in order to determine the lifetime and potential applications of these materials.[2] One of the most critical issues is the time-dependent dielectric breakdown (TDDB) of low-*k* dielectrics. TDDB failure, defined as spontaneous dielectric breakdown due to the long-term application of relatively low electric fields, can be exacerbated by several effects including electric field stress (resulting in damage-inducing leakage currents), and thermal stress, as well as plasma-processing induced degradation of the electrical, chemical, and mechanical properties of the dielectric.[3,4] However, under normal operating electric field stress, the dielectric lifetime must be in years. Thus, an accelerated failure analysis technique must be used.[5]

During plasma processing, both ion bombardment and vacuum ultraviolet (VUV) irradiation can occur.[6–9] Defect states (and subsequent trapped charge) generated by both VUV irradiation and charged-particle bombardment of low-*k* dielectrics have been shown to adversely affect the capacitance,[10–12] breakdown voltage,[13] and leakage currents[14,15] in addition to causing chemical and structural changes[16] in organosilicate dielectrics. In this letter, it is shown that *both* photons and charged particles emitted during plasma processing have a deleterious effect on the time to dielectric breakdown, i.e., the dielectric lifetime.

TDDB measurements are based on the hypothesis that stress produced by external electric fields eventually leads to a breakdown of the dielectric.[17] Under influence of an external electric field, a leakage current exists because of Schottky emission or Poole-Frenkel conduction.[18] If the electrons are energetic enough to damage the dielectric material, they can create additional defect states. Over time, the cumulative damage to the dielectric material can lead to catastrophic failure (i.e., dielectric breakdown). To determine the time to breakdown, the leakage current under a fixed electrostatic potential stress is measured as a function of time.[19] Similarly, the total charge-to-breakdown calculated from the leakage current measurements will be used to examine the role of electron fluence in TDDB failure.

TDDB lifetime measurements on silica-based dielectrics have been made using several methods including constant voltage, constant current, ramping voltage, and ramping current.[20] In this work, constant-voltage TDDB measurements will be utilized. This technique applies a constant voltage bias across the dielectric. The resulting electric field generates leakage currents that can be measured as function of time.[21] Under the influence of the electric field, a small, time-dependent leakage current persists until the breakdown point. It is expected that the leakage current will show a small decrease on the onset of stress, followed by a gradual small increase and finally an abrupt increase at breakdown point.[22] At the breakdown point, the current increases rapidly over several orders of magnitude. The time taken to reach this point is the time to dielectric breakdown. Each breakdown measurement is repeated many times under the same electric field stress and exposure conditions, and Weibull statistics[23] are then used to analyze the failure data and determine the characteristic lifetimes for each set of samples.

Although in typical device operation, the intermetal dielectric layer electric field stress is less than 0.5 MV/cm, higher electric fields are used in testing to simulate the breakdown process over a condensed time scale.[24] By fitting the measurement results at elevated stress levels to a physical model, it is possible to estimate the reliability of the dielectric under typical (low-field) operating conditions.[19] Several competing field breakdown-acceleration models have been proposed to describe the TDDB behavior of low-k dielectrics, with the most prominent showing the log of the time to breakdown (t_{BD}) proportional either to E (thermochemical

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model)[25] or to the square root of E ($\sqrt{E}$ model).[26] In this work, we use an electron-fluence driven, Schottky emission based $\sqrt{E}$ breakdown model[27] which predicts the TDDB lifetime as a function of electric field to be

$$t_{BD} \propto \exp\left[\frac{-\beta_s\sqrt{E}}{k_B T}\right], \qquad (1)$$

where $\beta_s = (q^3/4\pi\kappa\varepsilon_0)$, E is the electric field, k_B is Boltzmann's constant, T is the temperature, q is the charge of the electron, κ is the relative permittivity of the dielectric, and ε_0 is the permittivity of free space.[28] As discussed below, this model was found to provide the best empirical fit to unexposed SiCOH using the experimentally verified dielectric permittivity of $\kappa = 2.55$.

To elucidate the differences between photon and ion effects, charged-particle bombardment and VUV irradiation are separated using a capillary-array window.[29] The capillary-array window shields the dielectric layer from charged-particle bombardment without disrupting VUV irradiation. After simultaneous plasma exposure to both window-covered and uncovered dielectrics, the changes in TDDB properties can be examined.

The dielectric films were prepared as follows: 640 nm of low-k porous SiCOH was deposited with plasma-enhanced chemical vapor deposition (PECVD) on ⟨100⟩ Si wafers.[30] The deposition took place in a capacitively coupled PECVD reactor utilizing a 13.56 MHz RF source in the presence of several inert and reactive gases with an organosilane precursor. It should be pointed out that neither structure-forming techniques nor the introduction of porogen molecules were used in the deposition process. After deposition, the sample was UV cured with a Novellus Systems SOLA® ultraviolet thermal-processing system. Photons with energies between 3.1 and 6.2 eV were used in the UV curing process. The UV fluence was approximately 1×10^{16} photons/cm^2. After UV curing, the dielectric thickness was measured to be 500 nm. The dielectric constant (k) of the cured material was measured to be 2.55 using capacitance-voltage (C-V) characteristics. A film density of 1.24 g/cm^3 was determined using x-ray reflectivity and Rutherford backscattering (RBS) measurements. Ellipsometric porosimetry (EP) measurements showed a porosity fraction of 15%-20%.[31]

After the films were produced, an electron cyclotron resonance (ECR) plasma system was used to investigate plasma-induced damage to the dielectric films.[32] A mapping mercury probe (MDC 862) was used to make electrical contact with the dielectric. A computer-controlled DC power supply was used to apply voltage bias, and a picoammeter (Keithley 485) was used to measure leakage currents as a function of time. For each measurement, a constant positive bias voltage was applied across the dielectric sample with the substrate grounded, and the current was measured as a function of time until breakdown occurred. A range of biases was chosen so that each set of measurements corresponded to an applied electric field between 2.5-5.5 MV/cm.

As stated earlier, a capillary-array window over the sample was used to separate charged particle and photon bombardments.[33] The argon plasma conditions used for these exposures were previously found to emit radiation primarily

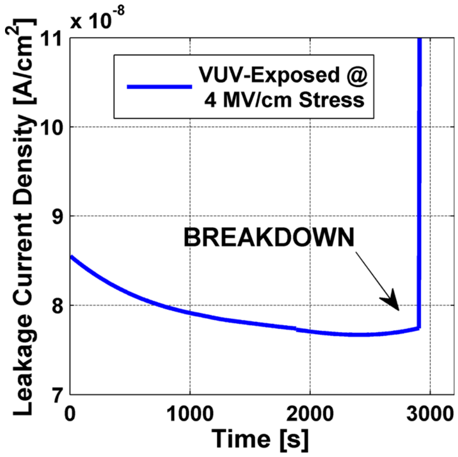

FIG. 1. (Color online) Typical leakage current profile of VUV irradiated SiCOH with an electric field stress of 4 MV/cm.

in the VUV range, with dominant emission peaks at 11.6 and 11.8 eV.[34] Each of the VUV-exposed samples was exposed to a photon fluence of approximately 5×10^{15} photons/cm^2. Figure 1 shows a typical leakage-current profile under stress voltage as a function of time on a VUV-irradiated (i.e., capillary-array window covered) sample.

To estimate the dielectric reliability, several TDDB measurements were made at each combination of plasma/VUV exposure condition and electric field. Figure 2 shows a plot of the Weibull distribution for the pristine SiCOH samples for two different electric field stresses. Weibull statistical distributions are the preferred tools for TDDB lifetime projections due to the fact that they project a "worst-case" scenario,[35] which can more accurately predict failure due to less probable breakdown events. When plotted as shown in Figure 2, several significant details of the cumulative distribution function, and thus of the reliability of the dielectric material, can be ascertained. First, the slope of the Weibull plot is equal to the shape factor, which is an indicator of how the failure rate changes with increasing electric field. Shape factors greater than one indicate an increasing failure rate or "wear-out," whereas shape factors less than one indicate premature failure or "infant mortality." Second, the characteristic lifetime of the material, defined as the time at which

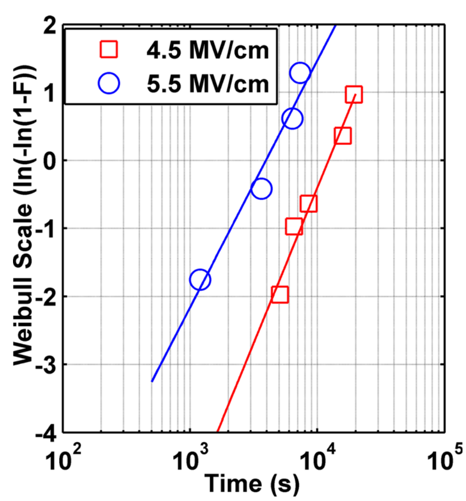

FIG. 2. (Color online) Field acceleration data for pristine SiCOH samples between 4.5 MV/cm and 5.5 MV/cm electric field.

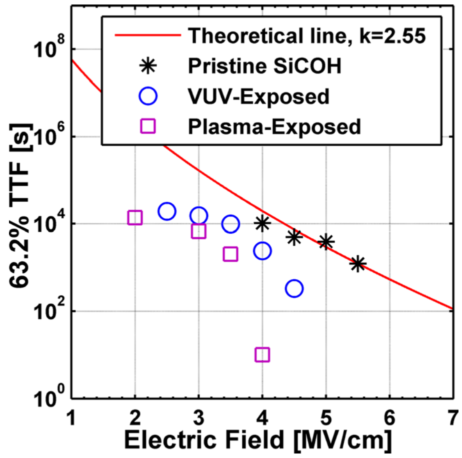

FIG. 3. (Color online) 63.2% TTF versus electric field for pristine, VUV-exposed, and plasma-exposed samples. The solid line indicates a $\sqrt{E}$-based analytical equation for $k = 2.55$.

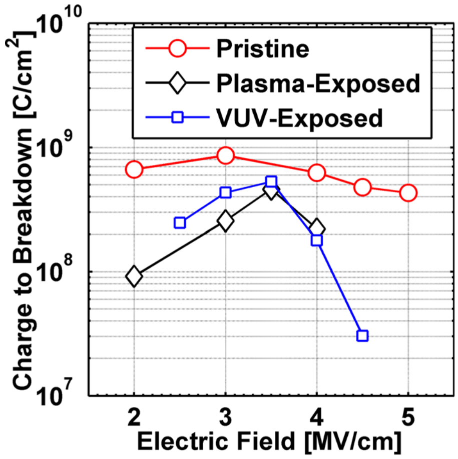

FIG. 4. (Color online) Calculated charge-to-breakdown versus applied electric field.

63.2% of the samples have failed, can be obtained by noting the time at which the straight line fit crosses the x-axis.

For pristine samples, the shape factor was found to be relatively independent of field, approximately 1.51 for 4.5 MV/cm field and 1.64 for 5.5 MV/cm. For both exposure conditions, a steeper shape factor was observed, indicating an increased failure rate. However, VUV-exposed and plasma-exposed samples were both found to have a poor fit to the Weibull distribution compared with the pristine samples. This indicates the existence of multiple breakdown mechanisms or failure modes.

Figure 3 shows the comparison of Weibull characteristic failure percentages as a function of applied electric field for pristine, VUV irradiated and plasma-exposed samples. Although the range of fields used here is necessarily limited, the lifetime of the pristine samples was found to fit well with the $\sqrt{E}$ model, as confirmed by good correlation with the calculated Schottky emission-based breakdown model (Eq. (1)) for $k = 2.55$. However, both VUV and plasma exposure resulted in reduced characteristic lifetimes relative to the pristine case. Reduced time-to-failure (TTF) may simply indicate an accumulation of defects due to exposure-induced damage. However, both plasma-exposed and VUV-exposed samples were also found to deviate significantly from the $\sqrt{E}$ model. This confirms the possibility that in the case of plasma and VUV irradiated samples, an additional failure mechanism exists beyond the electron-fluence driven model.

VUV exposure has been previously found to break chemical bonds and encourage the formation of a weakened SiO_2-like structure within the photon penetrated layer,[36] which could potentially result in lower-energy conduction pathways through the material. Similarly, energetic Ar ion bombardment in the presence of oxygen can result in selective sputtering of carbon groups from the surface of organosilicate dielectrics;[37] this may further enhance TDDB degradation by reducing the energy barrier at the dielectric surface, resulting in increased electron injection by Fowler-Nordheim tunneling.

Figure 4 shows the charge-to-breakdown (Q_{bd}) as a function of applied field for each of the three exposure conditions. Q_{bd} data were obtained by integrating the leakage current as a function of time from the application of the electric-field stress until breakdown. Leakage-current data corresponding as close as possible to the characteristic lifetimes were used. As might be expected, the pristine samples exhibit the largest Q_{bd} values across the full range of fields analyzed here, indicating a higher degree of tolerance of Schottky emission type conduction currents. As the applied field is increased, the total Q_{bd} is observed to decrease, which is consistent with the electron fluence-driven breakdown model used in this work.

For both VUV-exposed and plasma-exposed samples, there is an order-of-magnitude reduction in Q_{bd}. Furthermore, at electric fields of about 3.5MV/cm, there is a noticeable inflection point as shown in Figure 4, beyond which there is a marked further decrease in $Q_{bd.}$ This also agrees with the likelihood of an additional failure mechanism for both exposure conditions.

In summary, plasma exposure has been found to degrade the TDDB characteristics of low-*k* dielectric films. It was found that both VUV photon and charged particle bombardment contribute to TDDB degradation. Although the experimental data for pristine samples is consistent with the $\sqrt{E}$ model over the range of fields analyzed, this model does not adequately describe VUV-exposed and plasma-exposed sample lifetimes. It is thus very likely that both VUV and charged particle bombardment introduce additional breakdown mechanisms.

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