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Correlation between field dependent electrical conduction and dielectric breakdown in a SiCOH based low-k (k = 2.0) dielectric

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The electrical conduction of a SiCOH based ultralow-k (k = 2.0) dielectric is investigated over an electric field range from 1.0 MV/cm to breakdown. Below 4.0 MV/cm, space-charge-limited current dominates the leakage. Above 5.0 MV/cm, a transition is found from trap-assisted Fowler-Nordheim (F-N) tunneling to F-N tunneling. It is hypothesized that under F-N tunneling stress, intrinsic material degradation causes positively charged defects generated in the dielectric. Moreover, this change of the dominant conduction path has a significant impact on the time dependent dielectric breakdown lifetime behavior. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4816019]

One of the most critical concerns for the semiconductor industry moving towards more advanced technology nodes is the electrical reliability of low-k dielectrics, as the dielectric spacing and the porosity have to keep scaling. The time dependent dielectric breakdown (TDDB) lifetime at use condition is a widely used reliability criterion. This is normally extrapolated from TDDB results collected at higher electric fields. Several TDDB lifetime extrapolation models have been proposed by different research groups.[1] However, none of these models can be applied to a wide range of low-k materials and most importantly the underlying physical mechanism is still not well understood. Moreover, it has been recently reported by Croes *et al.* that for an ultralow-k (k = 2.0) material, the extrapolation trend of TDDB lifetimes shows different acceleration factors over different field ranges, which is not consistent with any of the suggested models.[2] As the conduction mechanism is an integral part of the extrapolation model construction,[3] a fundamental understanding of leakage behavior over a wide electric field range is necessary.

In this letter, we characterize the electrical conduction of a SiCOH based ultralow-k (k = 2.0) material and establish a direct connection between the leakage mechanism and the TDDB lifetime extrapolation. Experiments were conducted on a dedicated metal-insulator-semiconductor (MIS) planar capacitor test structure, which enables the investigation of pristine properties of low-k/barrier systems.[4,5] For this study, a 90 nm thick organosilicate glass (OSG, k = 2.0) with 46% porosity and 1.5 nm pore radius was deposited using a plasma enhanced chemical vapor deposition method.[6] Then a physical vapor deposited Ta(N)Ta layer was used as the barrier followed by copper seed, plating, CMP, and passivation formation processes.

Using a Semiconductor Device Analyzer Agilent B1500A and a probe station with a thermal chuck, the current-voltage (I-V) characteristics within a temperature range between 233 K and 373 K were measured. TDDB experiments were carried out using a HP4142B Modular DC Source. The capacitance-voltage (C-V) measurements were performed using a HP4284A Precision LCR Meter. During all the experiments, the silicon substrate was grounded.

The relation between current density and electric field (J-E) at different temperatures is shown in Fig. 1. Between 1.0 MV/cm and 4.0 MV/cm, the J-E data show a power law dependence. The slope of log(J) vs. log(E) is greater than two at all measured temperature levels, which agrees well with the theory of trap limited space-charge-limited current (SCLC).[7] The high exponent value is attributed to the filling of exponentially distributed trap states with the maximum density at the band edge. The gradients of the slopes decrease with increasing the temperature. It suggests that at higher temperatures, the extra carriers generated by thermal emission tend to fill up all trap levels which results in a shallower gradient described by the trap free SCLC (Child's law).[8]

Beyond 5.0 MV/cm, the current increase is strongly field dependent. The rapid rise of the current leads to a too low estimate of the dielectric constant as extracted by plotting log(J) as a function of $E^{1/2}$ in accordance with Schottky emission (SE) or Frenkel-Poole (FP) emission.[9] Moreover, the extracted dielectric constant decreases with increasing the temperature, e.g., 1.67 at 233 K and 0.39 at 373 K in the field range between 5.0 MV/cm and 6.2 MV/cm for the FP fitting. For the SE case, the calculated k-value is even lower. Therefore, the SE and FP types of conduction mechanisms are not applicable in the high field region. The J-E characteristic is also found to be less sensitive to temperature, might indicating that tunneling mechanisms become dominant. One such mechanism is Fowler-Nordheim (F-N) tunneling,[10] described by

$$J_{FN} = \frac{q^3 m E^2}{8\pi h \varphi_B m^*} \exp\left(-\frac{8\pi\sqrt{2m^*}\,\varphi_B^{\frac{3}{2}}}{3hqE}\right), \tag{1}$$

where φ_B is the barrier height at the emitting interface, h is Planck's constant, m is the electron mass, and m* is the

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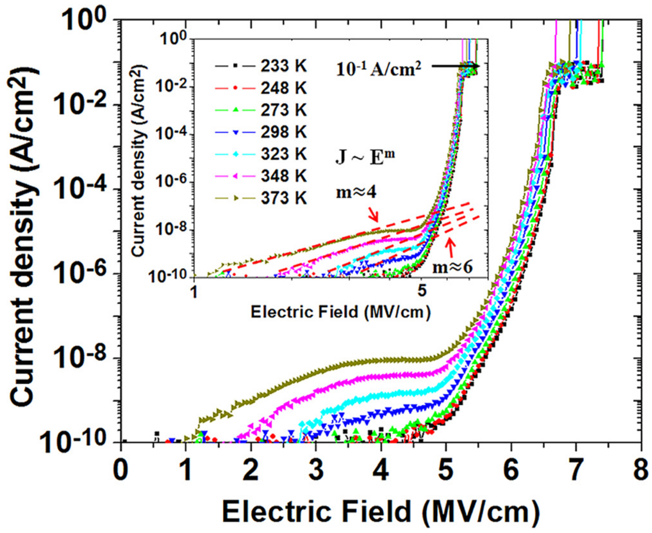

FIG. 1. Leakage current density as a function of applied electric fields in the temperature range from 233 K to 373 K. Inset: Plot of log(J) vs. log(E) shows a linear relationship, suggesting space charge limited current in the low field range (<5.0 MV/cm).

effective electron mass which is assumed similar to that of SiO_2 ($m^* = 0.5\,m$).[11] The other possible conduction mechanism is trap assisted F-N tunneling which describes the tunneling current through the traps in the bulk insulator instead of the cathode interface,[12] described by

$$J_{TAT} \propto J_{FN}. \tag{2}$$

By re-plotting ln(J/E^2) as a function of 1/E, two linear regions are observed, as shown in Fig. 2. The slope of the curve in the linear region is used to calculate the potential barrier height. Within the field range of 5.0 MV/cm to 6.2 MV/cm, the energy level of 2.4 eV is derived, suggesting that the dominant leakage mechanism in this region is trap assisted F-N tunneling.[11,13] Whereas in the high field region (>6.2 MV/cm), the calculated energy level is around 4.2 eV which is the same as the reported barrier height of the low-k/Si interface.[14] It suggests that the F-N tunneling current through the thinned triangular barrier of the insulator starts to dominate.

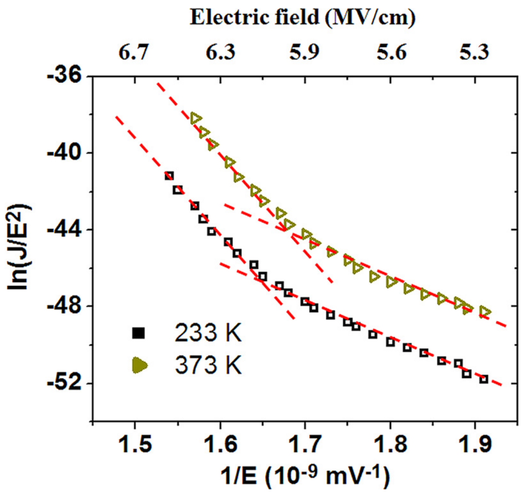

FIG. 2. Plot of ln(J/E^2) vs. 1/E showing a transition of the dominant conduction mechanism from trap assisted F-N tunneling to F-N tunneling.

Before the dielectric breakdown, a sharp increase in current followed by a shoulder-like plateau region is observed. This current rise is a feedback of the field enhancement at the cathode caused by positive charges build up inside the dielectric. The accumulation of positive charges is suggested by the large negative flat band voltage shift measured after the current increase (Fig. 3). The flattening off is due to electron trapping after the abovementioned positive charge generation saturates.[15,16] Finally, a catastrophic thermal runaway takes place and causes dielectric breakdown.

A further investigation of the influence of the positive charges generated at high fields is done by performing a double voltage ramp stress at 298 K, where the voltage approaches but does not reach the breakdown voltage (Fig. 3). The second J-E characteristic deviates largely from the first one within the field range of 1.0 MV/cm to 6.2 MV/cm, which suggests that after the high field stress, the generated positively charged defects create new leakage paths.[17,18] However, the current behavior in this field range cannot be modeled by simply assuming a fixed trap depth with only one conduction mechanism. This complexity may link to the complicated nature of the degradation mechanisms of the low-k dielectrics. Direct diffusion of Cu and the penetration of TaN barrier are the two main extrinsic explanations for the negative flat band voltage shift and the conduction mechanism change.[9,19,20] To exclude these options, the double voltage ramp stress measurements are performed with a negative bias as well. Similar changes to the J-E characteristics and the negative direction flat band voltage shift are observed. Therefore, intrinsic material degradation instead of extrinsic factors is suggested to be the source of the positively charged defects. The formation of these localized states could be related to the bond breakage in the disrupted low-k network driven by the high field stress or by hole trapping, such as the breakage of weak Si-H or distorted Si-O bonds.[21–23]

Typical TDDB J-t curves collected between 5.7 MV/cm and 6.8 MV/cm at 373 K are summarized in Fig. 4. For stress fields >6.2 MV/cm, transient current peaks are observed. As depicted in Fig. 4, extrapolating the peak current to time

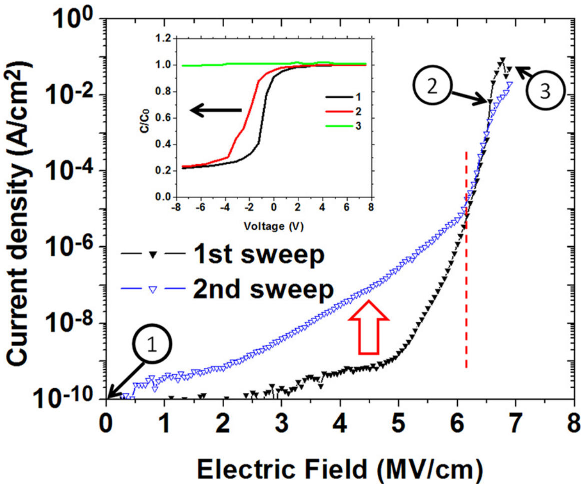

FIG. 3. Double voltage ramp stress (approaching breakdown) at 298 K shows high discrepancies between the two J-E characteristics below 6.2 MV/cm. Inset: A large negative flat band voltage shift is observed after the sharp current increase at high fields.

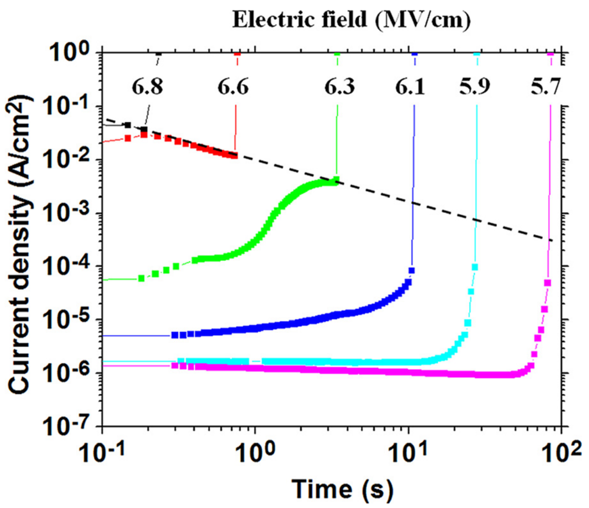

FIG. 4. Typical J-t curves for TDDB measurements ranging from 5.7 MV/cm to 6.8 MV/cm at 373 K.

zero gives almost the same current density as that of the plateau region under the voltage ramp stress indicated in Fig. 1. This suggests the same process of positive charge generation and saturation.[24,25] Furthermore, after reaching the peak current, the current density decay follows a power law relationship with time. However, all devices stressed at fields ≤6.2 MV/cm break before the formation of current peaks. This strongly suggests that the time to fail (TTF) is driven by the dominant leakage mechanism migrating from F-N tunneling to the trap assisted F-N tunneling. Similar trends of TTF dependence on field are observed by Croes *et al.*,[2] where a relatively low transition field around 4.5 MV/cm was reported. This value is in the transition field range (4.0 MV/cm–5.0 MV/cm) in this work where the dominant conduction mechanism starts to change from trap assisted F-N tunneling to SCLC. Therefore, it is believed that the lifetime trend in the low field range is also influenced by the dominant leakage mechanism in this low-k dielectric.

In summary, for a SiCOH based ultralow-k ($k = 2.0$) material, the conduction mechanism changes with electric field. The leakage is dominated by trap limited SCLC in the low electric field range from 1.0 MV/cm to 4.0 MV/cm. Above 5.0 MV/cm, the transition from trap-assisted tunneling with a trap depth of 2.4 eV to F-N tunneling (over the low-k/Si barrier) is found. Breakdown events under voltage ramp stress or during high field TDDB are impacted by the generation of positively charged defects. For this ultralow-k material, a universal model for the lifetime estimation at use condition (≤1.0 MV/cm) is not appropriate, as the transition between different conduction paths is proved to have a significant impact on the TTF. As a result, for the ultralow-k material reliability investigation and modeling, it is highly recommended to examine TDDB lifetimes in the lower electric field range.

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