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Degradation and Breakdown of Silicon Dioxide Films on Silicon

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Degradation and breakdown of silicon dioxide films is shown to be correlated to hot-electron-induced defect production near the interfaces. Two mechanisms are shown to account for most of this defect production and the effective "interface softening".

For many years, there has been a controversy over the mechanism responsible for destructive breakdown in silicon dioxide films. Although many previous models for "intrinsic" breakdown exist,[1-3] only recently has the importance of hot electron kinetics in the oxide conduction band and the defects they create been directly shown to be correlated to oxide destruction. This work will review these recent results and show that the "interface softening" caused by the continuous defect generation due to the hot carriers eventually triggers breakdown.

The oxide degradation caused by hot electrons is primarily due to the two defect-producing mechanisms[4-6] shown schematically in Fig.1. For historical reasons, these will be referred to as "trap creation" (Fig. 1a) and "impact ionization"(Fig. 1b). Trap creation occurs for electrons with energies greater than 2 eV,[5] where all energies discussed here are with respect to the bottom of the oxide conduction band. It is believed that these hot electrons release hydrogen from defect sites near the anode/oxide interface. This mobile species can then move to the cathode/oxide interface where it produces interface states and a distribution of oxide electron-traps near the cathode.[5] This process is thermally activated, not dependent on oxide thickness (for films over 10 nm), increases moderately with average field above 1.5 MV/cm, and is measurable after injection of about 0.001 Coul/cm^2 on polycrystalline-silicon (poly-Si) gated structures.[6] Figure 1b shows degradation produced by the impact ionization process which generates holes in the oxide valence band for electron energies greater than 9 eV.[6] These mobile holes produced in the oxide bulk closer to the anode move under the applied field to the cathode/oxide interface where some are trapped in as-fabricated energetically-deep sites. Some of the injected electrons from the cathode recombine with these trapped holes producing interface states and traps near the cathode. This process has a strong oxide thickness dependence up to 50.0 nm, occurs only at fields exceeding 7 MV/cm, is measurable at injected fluencies as low as 1×10^{-6} Coul/cm^2, and has a weak temperature dependence.[6] Holes can also be injected from the anode at energies less than 9 eV (but greater than 6 eV), however this process is less probable and only observable on thin oxide layers at moderate electric fields.[6] Similar interfacial defect generation can also occur near the anode from both of these mechanisms. However, the discussion will be limited here to the sites created near the cathode (the substrate-Si/SiO_2 interface for these studies).

Figure 2 shows the quantities of interest in device degradation: trapped positive/negative charge (Fig. 2a) and interface state (Fig. 2b) buildup as a function of injected electron fluence. These ex-

perimental data were obtained using capacitance-voltage (C-V) and current-voltage (I-V) characterization on n-channel poly-Si-gated field-effect-transistors (FETs).[5] Figure 2 shows typical data at an average field of 9 MV/cm where both generation mechanisms can occur and their variation with oxide thickness and charge fluence are well resolved. At low injected-electron fluencies in Fig. 2a, there is a build-up of positive charge due to impact ionization.[6] The observed saturation of this charging is due to a steady-state condition caused by free-electron/trapped-hole recombination.[6] The decrease from this steady-state positive charge level at fluencies of $\geq$ .001 Coul/cm^2 with an eventual reversal in the sign of the net trapped-charge is due to the charge compensation caused by trap creation and background electron trapping.[6] This negative charging continues to increase until destructive breakdown occurs. As the oxide layer is made thinner, the impact-ionization probability decreases, and only negative charging can be observed, as shown in Fig. 2a for 5.5 and 9.3-nm-thick oxide films. The two distinct charging regions can also be identified in the interface-state generation data of Fig. 2b which continuously increases with injected-charge fluence.

All these observable trends for defect production in Fig. 2 can be summarized in terms of an "initial" generation rate, P_{gen}. This rate is extracted from data like those in Fig. 2 over a wide range of electric field and oxide thickness. In Fig. 3, the *inverse* of this generation rate determined from the interface-state buildup is shown. The inverse of P_{gen} is plotted so that a comparison with the charge-to-breakdown data in Fig. 4 can be made. These data in Fig. 4 were taken from two recent studies of charge-to-breakdown verses constant current-density.[3,7] Electric field values used in Fig. 4 were calculated from these reported current-densities assuming Fowler-Nordheim tunneling with minimal changes in the applied field due to net charge build-up.

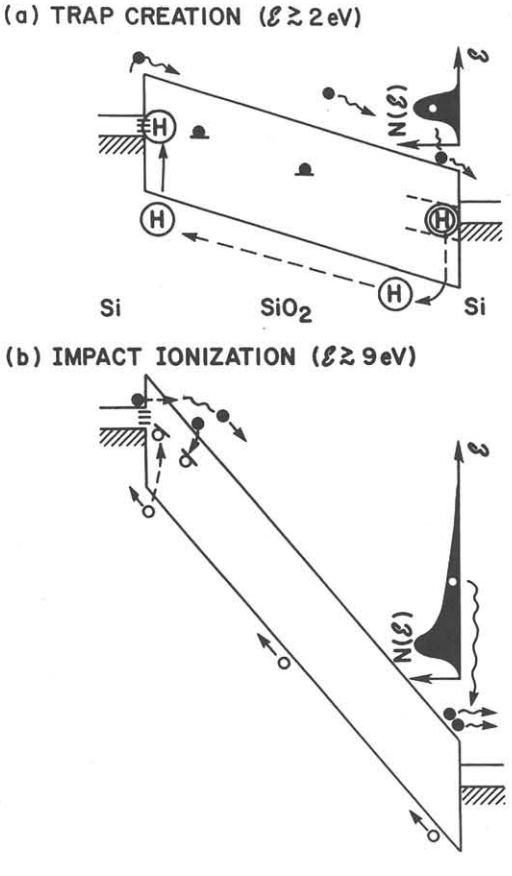

Fig. 1: Schematic energy-band diagram showing (a) trap creation near the cathode caused by mobile hydrogen release from decorated sites near the anode and (b) defect generation near the cathode caused by free-electron/trapped-hole recombination where holes were generated in the oxide bulk by impact ionization.

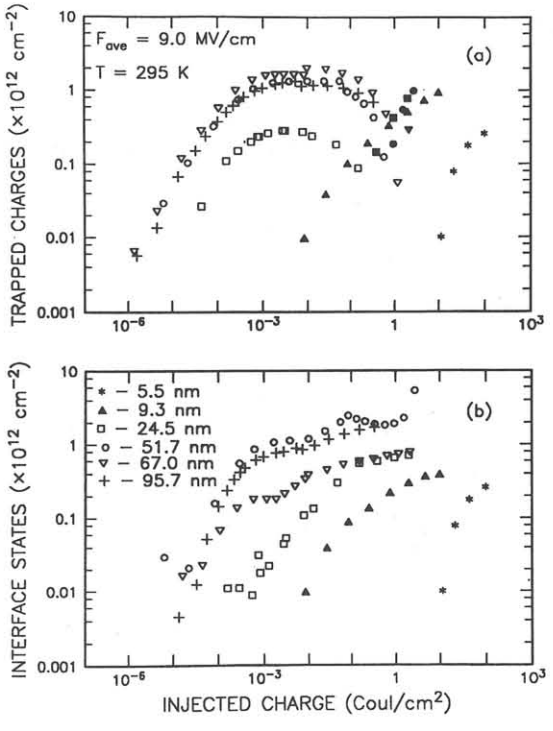

Fig. 2: Magnitude of the number of trapped charges, positive and negative, (a) and interface-states (b) as a function of injected electron-fluence at room temperature for various oxide-thickness from 5.5 to 95.7 nm under a field of 9.0 MV/cm. Open and solid symbols indicated net positive and negative charging, respectively, in Fig. 1a.

The two transition regions observed in both Figs. 3 and 4 are due to defect production from the trap creation and impact ionization. On the thinnest oxides in Fig. 4, a large decrease in charge-to-breakdown is observed as the electric field increases above the value necessary to give a condition of near-ballistic carriers attaining a kinetic energy of 2 eV.[5] This transition occurs on the 4.5 and 5.5 nm films near 11 and 9 MV/cm, respectively. At higher fields for oxides with thickness from 4.5 to 7.0 nm, a change from ballistic to quasi-steady-state transport is observed[5] with trap creation by non-steady-state carriers with kinetic energies exceeding 2 eV controlling the charge-to-breakdown. From 7 to 13 nm, the charge-to-breakdown magnitude is relatively insensitive to oxide thickness and slowly decreasing with increasing field. This type of behavior would be expected if only trap creation by steady-state hot-electrons was participating in the interface deterioration.[5] The added defect generation due to the electron-hole recombination process (triggered by mostly bandgap impact-ionization) leads to the second transition region.[4,6] Here, the charge-to-breakdown rapidly decreases with increasing field for oxides thicker than 13 nm.

Additionally, the temperature and processing dependence of defect generation near the interfaces will be reviewed and compared to charge-to-breakdown studies. This comparison will be shown to also support the idea of interface softening by one or both of these hot-electron induced mechanisms until destructive breakdown of the oxide layer occurs.

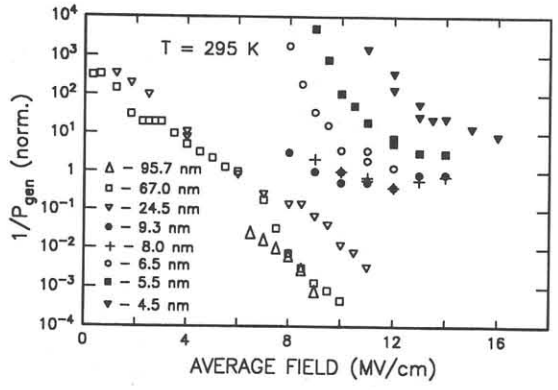

Fig. 3: Normalized reciprocal of the initial rate of interface-state generation per injected electronic-carrier as a function of the average electric field for an oxide thickness range from 4.5 to 95.7 nm at room temperature.

References

1) P. Solomon, J. Vac. Sci. Technol. ***14*** (1977) 1122, and references contained therein.
2) E. Harari, Appl. Phys. Lett. ***30*** (1977) 601.
3) I.C. Chen, S. Holland, K.K. Young, Appl. Phys. Lett. ***49*** (1986) 669.
4) D.J. DiMaria, D. Arnold, and E. Cartier, Appl. Phys. Lett. ***61*** (1992) 2329.
5) D.J. DiMaria and J.W. Stasiak, J. Appl. Phys. ***65*** (1989) 2342.
6) D.J. DiMaria, E. Cartier, and D. Arnold, J. Appl. Phys. ***73*** (1993) 3367, and references contained therein.
7) Y. Ozawa and K. Yamabe, from Ext. Abstr. 1991 Inter. Conf. Solid-State Dev. and Mat., Yokohama (1991), pp. 240-242.

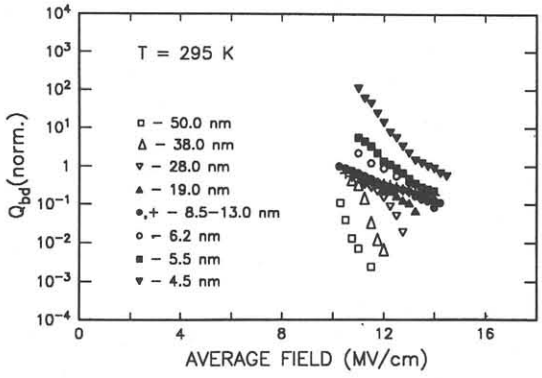

Fig. 4: Normalized charge-to-breakdown as a function of average electric-field for an oxide thickness-range from 4.5 to 50.0 nm at room temperature.