Direct Observation of the Threshold for Electron Heating in Silicon Dioxide

D. J. DiMaria, M. V. Fischetti, and E. Tierney
IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598

and

S. D. Brorson
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
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Vacuum-emission and carrier-separation techniques, together with novel metal-oxide-semiconductor structures, have been used to observe the threshold field for the onset of electron heating in silicon dioxide. The magnitude of this electric field is ≈ 1.5–2.0 MV/cm, independent of oxide thickness and composition. This value is consistent with all of the current theoretical calculations. A minimum average electronic energy of ≈ 1.0 eV is shown to be necessary to observe emission of the electrons into vacuum.

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The electron heating problem in silicon dioxide (SiO_2) is currently of great interest from both a fundamental and technological point of view. In the middle 1970's, Hughes had shown that at *low* fields ($\lesssim 1$ MV/cm) the electron energy distribution was stabilized by longitudinal-optical (LO) phonon scattering at an average energy less than that of the dominant LO-phonon mode at 0.15 eV.[1,2] Recent work has shown both experimentally[3–5] and theoretically[6–11] that significant heating occurs above this energy at electric field magnitudes greater than 1 MV/cm where the energy distribution can no longer be stabilized by LO-phonon scattering. However, at higher energies the electrons are increasingly scattered by acoustic phonons (in particular, in umklapp processes) and become stabilized after gaining about 2 eV of kinetic energy with respect to the bottom of the oxide conduction band.[7,9,10] The important physical aspect of the acoustic phonon interaction is large-angle scattering (momentum reversal) which gives the electrons much larger path lengths than the actual length of material traversed. LO-phonon scattering still accounts for most of the energy loss. The results of several theoretical calculations which predict the average energy as a function of the electric field are plotted in Fig. 1. Electron energy measurements which will be discussed in this Letter are also shown. Previous experiment results were limited to fields greater than 3 MV/cm for amorphous SiO_2 thicknesses in the range from 37 to 1500 Å (Refs. 3–5), or were limited to fields less than 1 MV/cm for fused-quartz thicknesses greater than 0.02 cm (Refs. 1 and 2). Thus, the threshold for runaway from the dominant LO-phonon modes was never observed. Observation of this threshold for electron heating above the LO-phonon energy is an important test of the high-field transport theories. The purpose of this Letter is to describe a series of experiments where this threshold has been obtained and studied as a function of oxide thickness. Vacuum-emission and carrier-separation techniques have been used to accomplish this. Vacuum emission directly measures the distribution of hot electrons ejected into vacuum.[4,5] Carrier separation measures the average electron energy of the distribution by counting the number of electron-hole pairs produced in single-crystal silicon (Si) by incoming hot SiO_2 electrons.[3,4]

To measure the vacuum-emission threshold, special metal-oxide-semiconductor (MOS) capacitors using

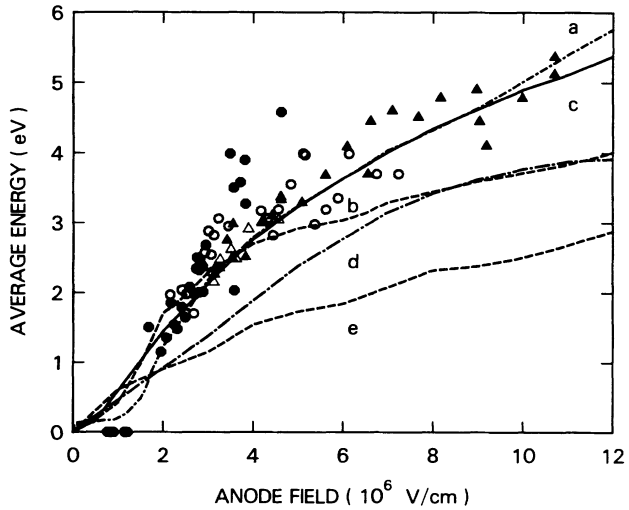

FIG. 1. Comparison of experiment and theory for average hot-electron energy in SiO_2 as a function of electric field. Electron energy is defined with respect to the bottom of the SiO_2 conduction band. Vacuum-emission experiments on 1500-Å-thick SiO_2 layers with 250-Å-thick Al and 250-Å-thick Au/250-Å-thick Al metal electrodes are indicated by open and closed triangles, and open and closed circles, respectively. Theoretical calculations, as described in text, are represented by curves labeled *a*–*e*.

Si-rich SiO_2 electron injectors were required. The principal differences between these structures and those used in previous experiments were the metal gate-electrode size and composition.[4,5] Increased sensitivity was gained in the vacuum-emission experiment by use of areas up to a factor of 100 larger than previously used (1.27 cm^2 maximum). The use of Si-rich SiO_2 injectors for cathodic field enhancement and breakdown reduction make these experiments possible.[4,12] In previous attempts without injectors, destructive breakdown of the oxide layer limited all observations.[13] Since the energy relaxation length for electrons in SiO_2 is ≈ 30 Å, the cathodic injection mode is not important in determining the electronic energy.[3-5,7,9,10] The oxide field near the anode (SiO_2/metal interface) determines the average energy of the electron distribution. Also, a thin double metallization scheme employing Au(250 Å)/Al(250 Å) on top of the SiO_2 layer was used to "cesiate" the oxide and recover the portion of the hot-electron distribution in approximately the first electron volt.[5] This fraction of electrons cannot escape into vacuum with single metallizations because of the 0.9-eV electron affinity of the SiO_2.

Figure 1 shows average energy data for these large-area capacitors with double metallizations and compares them to other structures with single metallizations and/or smaller areas. The data in this figure were obtained from a count of the total number of hot electrons ejected into vacuum as a function of the analyzer potential for different anode fields.[4,5] These data for the average energy of the distribution (with respect to the bottom of the SiO_2 conduction band) as a function of anode field clearly show an abrupt increase near 1.5 MV/cm. No dependence on the area, thickness, or type of metallization used for the top gate electrode was seen, except for the additional points at lower energies and fields with the large-area double metallizations. Previous studies have shown that the effect of the metal is not important for the average energy versus anode field characteristics, but it does have an effect on the details of the electron distribution and the total number of emitted electrons.[5] This is consistent with the observation, at least on thin (200 Å) Al films, that $\approx 1\%$ of the gate electrode area area has missing Al grains (≈ 500 Å in size) and cracks along grain boundaries.[14] Electrons escaping into vacuum are therefore believed to be emitted through metal areas near the edges of these voids or through other locally thin areas in the gate metal.[5] The data in Fig. 1 are for a 1500-Å-thick SiO_2 layer; however, similar heating curves were observed for other oxide thicknesses in the range from 150 to 3000 Å.

In Fig. 1, the vacuum-emission data are compared to the results of various theoretical simulations. Curve *a* is the result of a conventional Monte Carlo simulation which includes both polar (Fröhlich) scattering with the LO phonons and nonpolar scattering with acoustic and band-edge phonons. Both normal and umklapp scattering are considered.[7] Curve *b* is the result of a similar simulation which partially accounts for the broadening of the electron energy[15] at very high scattering rates.[9] A single parabolic conduction band with unit effective mass is considered in both simulations. Curve *c* results from a quantum Monte Carlo simulation which accounts for a nonparabolic conduction band and treats high-field electron transport beyond the Boltzmann-equation scheme.[10] A conventional Monte Carlo simulation for a multivalley conduction band, without and with the inclusion of quantum effects (collision broadening and intracollisional fields[16]), yields the results corresponding to curves *d* (Ref. 8) and *e* (Ref. 11), respectively. Earlier Monte Carlo simulations which included only the polar-electron–LO-phonon scattering[6] also correctly predicted a value of about 1.5 to 2.0 MV/cm for the critical field above which the LO-phonon scattering alone could not maintain a steady-state electron transport regime and *velocity runaway* would occur. All the theoretical calculations shown give reasonable agreement with the experimental data. The conventional Monte Carlo approach of Fischetti,[7] curve *a* in Fig. 1, which is the simplest, appears to give the best agreement, particularly at low fields near the threshold. However, more recent calculations using a quantum Monte Carlo approach, curve *c* in Fig. 1, give better agreement with the measured energy distributions at high fields.[10]

The experimental data at low fields in Fig. 1 show the effect on the electron emission at constant current as the anode field is swept through threshold. The points at an average energy equal to 0 eV are for cases where no observable electrons were emitted into vacuum. Permanent bulk electron trapping in the SiO_2 on water-related impurities is used to increase the anode field.[4,5] There is a dramatic increase in the number of counts at threshold and distributions with average energies $\lesssim 1.0$ eV were not observed. The reason for this is not entirely clear at the present time, since quantum reflections, scattering at the oxide/metal interface, scattering at the metal/vacuum interface, and/or scattering in the metal layers could have an effect. This 1.0-eV limit is not believed to be due to the electron affinity of the SiO_2 since the double metallization clearly shows the recovery of the missing 0.9 eV of the distribution, at least at higher fields.[5] For "uncesiated" surfaces, raw data for the number of electrons ejected into vacuum as a function of analyzer voltage obtained on single-layer Al (250 Å) metallizations show shifts of the characteristics to more positive voltages by ≈ 1.0 eV as compared to Au/Al charac-

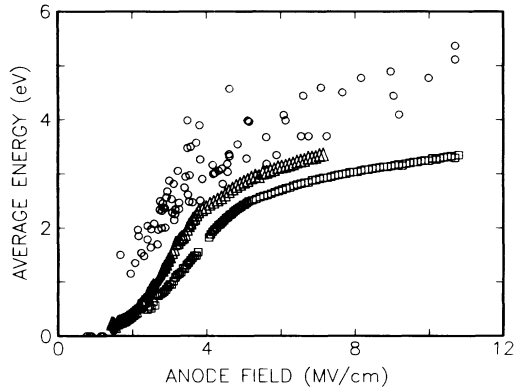

FIG. 2. Comparison of vacuum-emission data (open circle) from Fig. 1 and carrier-separation data (open triangle, closed circle, and open square) for average hot-electron energy in SiO_2 as a function of electric field at room temperature. Silicon dioxide thickness variation is indicated by open square for 1000 Å, open circle and open triangle for 1500 Å, and closed circle for 3400 Å.

teristics at similar electric fields. To obtain average energies for this Al-electrode data, extrapolations were performed to recover the missing 0.9 eV of the distribution near the band edge. This has been discussed at length in a previous publication.[5]

Since the total number of electrons emitted into vacuum is attenuated strongly near the threshold for runaway from LO phonons in the vacuum-emission experiments, carrier-separation measurements were used to confirm the data in Fig. 1. Specially designed large-area (4.6×10^{-3} to 2.5×10^{-2} cm^2) p-channel field-effect transistors (FET's) were fabricated for these measurements. As discussed in other work,[3,4] this technique measures the electron-hole pair-generation rate produced by the hot electrons entering the Si substrate on which the oxide is grown or deposited. The number of pairs produced is then related to the average energy of the incoming hot-electron distribution by the theory of Alig, Bloom, and Struck.[17] The principal difference between these devices and previously used structures, besides the factor of ≈ 100 increase in area, is the larger electron injection capability at lower average fields. This increase is achieved by higher local field enhancement near the oxide/cathode interface as a result of the device design and processing. Figure 2 shows carrier-separation data for three different oxide thicknesses and compares it to the vacuum-emission data from Fig. 1. The agreement is good given the differences in the experimental techniques and the sample preparation. Thermally grown SiO_2 layers were used for the carrier-separation devices, while chemically vapor-deposited oxides were used for the vacuum-emission structures. Similar to the vacuum-emission results, the carrier-separation data also show no strong dependence on oxide thickness.

In summary, we have measured the threshold field for electronic heating and runaway from scattering by the LO phonon modes in SiO_2 which previously had not been observed experimentally. Anode fields of 1.5–2.0 MV/cm, consistent with all the recent theoretical calculations, have been measured by both vacuum-emission and carrier-separation techniques. A *smooth* transition from stabilization by the LO-phonon modes at low fields to stabilization by the acoustic-phonon modes at higher fields was seen from the carrier-separation results. However, a minimum energy of 1 eV is necessary to see detectable vacuum emission of hot electrons. This threshold field was independent of the oxide thickness and composition, consistent with theoretical predictions.

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