Strong Electric Field Heating of Conduction-Band Electrons in SiO_2

T. N. Theis, D. J. DiMaria, J. R. Kirtley, and D. W. Dong[(a)]
IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598
(Received 29 December 1983)

We demonstrate that average conduction-band electrons in a wide-band-gap insulator, SiO_2, are heated several electronvolts above the conduction-band edge at fields of 5 to 12 MV/cm. The electronic energy distribution appears to be stabilized at these high fields by energy-loss mechanisms other than LO-phonon scattering.

PACS numbers: 72.20.Ht, 73.40.Qv, 73.40.Ty, 73.60.Hy

Theoretical studies of polar insulators in general[1] and SiO_2 in particular[2-5] have emphasized longitudinal-optical (LO) phonon scattering as the dominant energy-loss mechanism for conduction-band electrons. Experimentally this has been demonstrated in SiO_2 for fields up to 1.0 MV/cm,[6] but we show here that this is not the case at fields an order of magnitude larger. Because the rate of energy loss to the lattice is peaked near the dominant LO-phonon energy, $\hbar\omega_{LO}$, there exists a threshold electric field, F_{th}, above which the electronic energy distribution is unstable.[7] Below F_{th} the average electronic energy should be $\lesssim \hbar\omega_{LO} = 0.15$ eV,[3-5] while above F_{th} it has often been assumed that electrons are freely accelerated to impact ionization energies.[1-5] However, acoustic-phonon scattering must become dominant at higher energies,[8,9] and Ridley[8] has suggested that this loss mechanism may stabilize the electronic energy distribution at fields greater than F_{th} and at energies where impact ionization is not important. We present evidence that at fields between 5 and 12 MV/cm, average conduction-band energies are $\gg \hbar\omega_{LO}$, and thus F_{th} is less than 5 MV/cm, lower than nearly all theoretical estimates (Ref. 5 is the exception). Above F_{th} the conduction-band electronic energy distribution appears to be stabilized by additional scattering mechanisms.

We have obtained these results by two different experimental techniques, which we shall refer to as luminescence[10] and carrier separation.[11-14] Both techniques monitor the energy of electrons injected from the conduction band of SiO_2 into another material. After discussing separately the experimental results obtained by the two techniques, we will show that the combined results give a consistent picture of high-field conduction in SiO_2.

Luminescence.—These experiments were conducted on metal-oxide-semiconductor capacitors called electron injector structures.[15,16] As shown in Fig. 1(a), a layer of SiO_2 is separated from the degenerately doped n-type Si substrate by a layer of silicon-rich (Si-rich) SiO_2. The Si-rich material is two phase, containing many small (~ 5 nm) inclusions or islands of Si in an SiO_2 matrix.[17] As illustrated in the energy-band diagram of Fig. 1(b), electrons tunnel from Si island to Si island, and then enter the SiO_2 conduction band *at thermal energies* by Fowler-Nordheim tunneling. The tunnel-

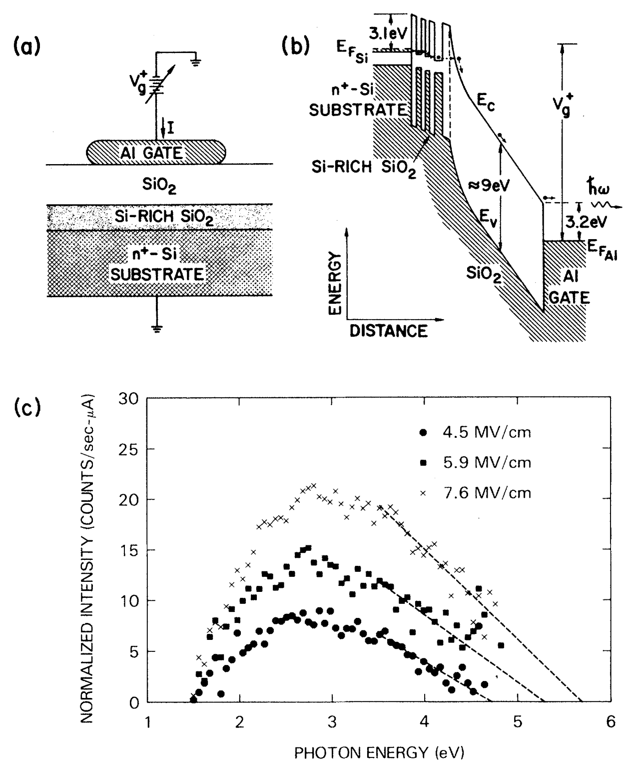

FIG. 1. (a) Electron injector structure. (b) Energy-band diagram of the structure under positive bias. (c) Surface-plasmon–mediated emission spectra for various electric fields F_{im} near the SiO_2-Al interface. The SiO_2 and Al layers were, respectively, 65 and 25 nm thick. The data have been normalized to the relative throughput of the spectrometer and detection system, with the throughput at 3.5 eV set arbitrarily to 1. The spectral cutoff (dashed lines) increases in energy as electrons enter the metal with increasing energy.

ing occurs at comparatively low bias voltages because of the local enhancement of the electric field near each island. Electrons in the SiO_2 conduction band are quickly swept to the opposite interface and injected into the Al electrode. Some small fraction of these electrons lose energy to surface plasmons, which may in turn radiate.[10] Electrons injected from the SiO_2 conduction-band edge, E_c, can generate a surface plasmon of maximum energy $E_c - E_F$, where E_F is the metal Fermi energy [see Fig. 1(b)]. Luminescence at higher energies is therefore evidence for electronic heating in the SiO_2.

The surface-plasmon–mediated luminescence is greatly enhanced by fabricating the samples on a rough substrate. It can therefore be distinguished from electroluminescence of the bulk SiO_2[18] by comparing the spectra of samples fabricated on smooth and on roughened substrates. Sample fabrication and experimental techniques have been described in Refs. 10. During the luminescence measurements, special attention was paid to the permanent charge trapping which occurred as current was passed through the devices. Since the current, controlled by the field near the Si-rich SiO_2–SiO_2 interface, was held constant, the gate voltage had to be gradually increased to compensate the internal field associated with the trapped charge. Since the trapping occurs uniformly throughout the bulk of the oxide,[19] the field at the SiO_2-Al interface is given in terms of the time-dependent gate voltage $V_g(t)$ as

$$F_{im}(t) = [2V_g(t) - V_g(0)]/l, \quad (1)$$

where l is the oxide thickness. Small terms involving the work-function difference between the Al electrode and the Si substrate, the Si surface potential, and the potential drop across the Si-rich SiO_2 have been neglected. By monitoring $V_g(t)$ at constant current, both the average field, $F_{av}(t) = V_g(t)/l$, and $F_{im}(t)$ were known at all times. The field was also varied by abruptly changing V_g. Regardless of how the field was varied, the current-normalized luminescence intensity was well correlated with F_{im}, but more poorly correlated with F_{av}. We shall return to this important point in our concluding discussion.

Figure 1(c) shows surface-plasmon–mediated luminescence spectra at various field values determined with the aid of Eq. (1). A roughly linear decrease in intensity at high energy is indicated by a dashed-line least-squares fit to the data points above 3.6 eV for each field. Our optical system limits the observations to photon energies less than 5 eV, but the spectral cutoff clearly moves to higher energies with increasing field. Even at the lowest field the 4.7-eV cutoff is well above the energy, $E_c - E_F = 3.2$ eV,[20] contributed by the potential step between the SiO_2 conduction band and the Al Fermi level. In the absence of a detailed model, electronic energy distributions cannot be extracted from the luminescence spectra, but an important conclusion can be drawn. If the majority of electrons were near the bottom of the conduction band, then the spectra would show a dramatic reduction in intensity above 3.2 eV, with perhaps some tailing to higher energies. Instead, the observed spectra indicate that the *average* electronic energy is well above E_c and increasing with electric field.

Carrier separation.— As shown in Fig. 2(a), these experiments were performed on field-effect transistors based on the electron injector structure. The deposition sequence of the SiO_2 and Si-rich SiO_2 layers was the reverse of that for the luminescence devices, the gate electrode was n^+ polycrystalline Si, and the n-type Si substrate had p^+ source and

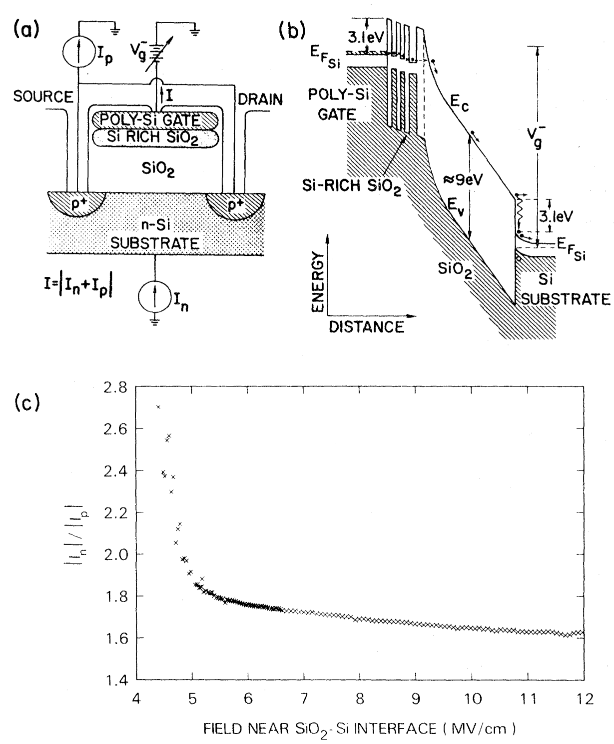

FIG. 2. (a) Field-effect transistor and circuit for carrier separation. (b) Energy-band diagram showing impact ionization as electrons enter the Si from the SiO_2 conduction band. (c) α, the absolute ratio of electron to hole current, as a function of field F_{is} in the SiO_2 near the SiO_2-Si interface. α decreases as electrons enter the Si with increasing energy.

drain diffusions. As shown in Fig. 2(b), the Si-rich layer alowed enhanced current flow from the gate, through the SiO_2 and into the Si substrate. Energy loss in the Si is by the competing mechanisms of phonon generation and impact ionization. The ionization rate is monitored by using the simple circuit of Fig. 2(a) to separate the electron and hole components of the substrate current. Under negative gate bias a hole inversion layer is formed in the Si at the Si-SiO_2 interface. The internal field sweeps holes to the inversion layer while electrons are swept into the substrate. The p^+ source and drain regions collect the hole current, while the electron current is collected by the substrate contact. A decrease in $\alpha = |I_n|/|I_p|$, the absolute ratio of electron to hole current, with increasing oxide electric field is evidence that more charge pairs are being created and the average energy of electrons entering the Si is increasing.

I_n and I_p were measured at constant time intervals while the bias voltage was ramped. Figure 2(c) shows α as a function of F_{is}, the field in the SiO_2 near the SiO_2-Si interface. Charge trapping caused F_{is} to deviate from F_{av}, and the field values in the figure were calculated from a relationship similar to Eq. (1), as discussed in Ref. 15. Electrons entering the Si substrate from the SiO_2 have a minimum energy of 3.1 eV with respect ot the Si conduction-band edge. The average energy required to generate one electron-hole pair ($\alpha = 2.0$) in the Si by impact ionization is 4.3 eV according to a recent calculation.[21] Thus we find $\alpha > 2.0$ at the lowest fields and dropping well below this value as the field is increased and the electronic energy distribution heats up. The electrons are already hot when $\alpha \sim 2.0$, contrary to the conclusions of those authors who have inferred the absence of heating from such a result.[12-14]

Alig, Bloom, and Struck[21] have calculated the probability $p_n(E)$ that an electron entering the Si with energy E above the Si conduction-band edge will cause n impact-ionization events. We write

$$\alpha(E) = \frac{|I_n(E)|}{|I_p(E)|} = \frac{\sum_{n=0}^{\infty} p_n(E)(n+1)}{\sum_{n=0}^{\infty} p_n(E) n}. \qquad (2)$$

For energies of interest here, $\alpha(E)$ is a nearly linear function of E. In this case, Eq. (2) is still valid if E is the *average* energy of an arbitrary energy distribution. Using Eq. (2), we then obtain from the data of Fig. 2(c) the average electronic energy with respect to the SiO_2 conduction band. This is plotted as a function of F_{is} in Fig. 3. This procedure is not reliable near the threshold for impact ionization, so that the abrupt increase in average energy between

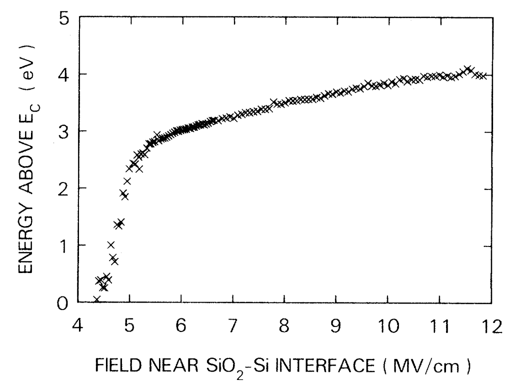

FIG. 3. The average energy of electrons with respect to the SiO_2 conduction-band edge as a function of electric field F_{is}.

4.5 and 5 MV/cm may be an artifact. As in the luminescence experiment, we find that *average* electrons are heated several electronvolts above the bottom of the SiO_2 conduction band. The average energy increases gradually and linearly with increasing field over the range from 5 to 12 MV/cm. We interpret this result as indicating the stabilization of the electronic energy distribution at high energies, perhaps by acoustic phonon scattering.[8] Under this interpretation, the slope of the energy versus field curve yields a characteristic energy-loss length, $d \sim 2.3$ nm. This is also roughly the distance through which an electron is accelerated before its rate of energy loss equals the rate of energy gain from the field. Thus, the electronic energy distribution must be a local (within a few nanometers) function of the electric field in the SiO_2. This is consistent with our observation above that the luminescence intensity is best correlated with F_{im}, the local field near the SiO_2-Al interface, and not F_{av}. Furthermore, if the oxide thickness is decreased toward d, the electronic heating at constant field should dramatically decrease. This has also been observed.[22]

We thank J. A. Tornello and J. Calise for help in sample fabrication. We enjoyed many fruitful discussions with Z. A. Weinberg, P. M. Solomon, and D. L. Mills.

[a]Deceased.

[1]K. K. Thornber and Richard P. Feynman, Phys. Rev. B **1**, 4099 (1970).

[2]W. T. Lynch, J. Appl. Phys. **43**, 3274 (1972).

[3]D. K. Ferry, Appl. Phys. Lett. **27**, 689 (1975).

[4]D. K. Ferry, J. Appl. Phys. **50**, 1422 (1979).

[5]H.-J. Fitting and J.-U. Frieman, Phys. Status. Solidi

(a) **69**, 349 (1982).

[6]R. C. Hughes, Phys. Rev. Lett. **35**, 449 (1975).

[7]F_{th} can be estimated from the condition that the *average* rate of energy gain from the field not exceed the *average* rate of energy loss to the lattice (Refs. 1 and 3). A proper calculation must, however, include fluctuations in the energy-loss rate (Refs. 4 and 5).

[8]B. K. Ridley, J. Appl. Phys. **46**, 998 (1975).

[9]M. Sparks, D. L. Mills, R. Warren, T. Holstein, A. A. Maradudin, L. J. Sham, E. Loh, Jr., and D. F. King, Phys. Rev. B **24**, 3519 (1981).

[10]T. N. Theis, J. R. Kirtley, D. J. DiMaria, and D. W. Dong, Phys. Rev. Lett. **50**, 750 (1983). T. N. Theis, J. R. Kirtley, D. J. DiMaria, and D. W. Dong, in *Insulating Films on Semiconductors,* edited by J. F. Verweij and D. R. Wolters (North-Holland, Amsterdam, 1983), pp. 134–140.

[11]A. S. Ginovker, V. A. Gritsenko, and S. P. Sinitsa, Phys. Status Solidi (a) **26**, 489 (1974).

[12]Z. A. Weinberg, W. C. Johnson, and M. A. Lampert, Appl. Phys. Lett. **25**, 42 (1974).

[13]Dieter K. Schroeder and Marvin H. White, IEEE Trans. Elec. Devices **26**, 899 (1979).

[14]Eiichi Suzuki, Yutaka Hayashi, and Hisayoshi Yanai, J. Appl. Phys. **50**, 7001 (1979).

[15]D. J. DiMaria, R. Ghez, and D. W. Dong, J. Appl. Phys. **51**, 4830 (1980).

[16]D. J. DiMaria, K. M. DeMeyer, C. M. Serrano, and D. W. Dong, J. Appl. Phys. **52**, 4825 (1981).

[17]D. J. DiMaria, in *The Physics of MOS Insulators,* edited by G. Lucovsky, S. T. Pantelides, and F. L. Galeener (Pergamon, New York, 1980), pp. 1–18.

[18]P. Solomon and N. Klein, J. Appl. Phys. **47**, 1023 (1976); C. Falcony, Doctoral dissertation, Lehigh University, 1980 (unpublished).

[19]Z. A. Weinberg, D. R. Young, D. J. DiMaria, and G. W. Rubloff, J. Appl. Phys. **50**, 5759 (1974).

[20]The value may actually be as high as 3.5 eV. See P. M. Solomon and D. J. DiMaria, J. Appl. Phys. **52**, 5867 (1981).

[21]R. C. Alig, S. Bloom, and C. W. Struck, Phys. Rev. B **22**, 5565 (1980); see also, Jon Geist and Warren K. Gladden, Phys. Rev. B **27**, 4833 (1983).

[22]C. Chang, M. S. Liang, C. Hu, and R. W. Broderson, in *IEDM Technical Digest 1983* (IEEE, New York, 1983), pp. 194–197; D. J. DiMaria, T. N. Theis, J. R. Kirtley, F. A. Pesavento, D. W. Wong, and S. D. Brorson, to be published.