

Two components of tunneling current in metal-oxide-semiconductor structures

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Two distinct components of tunneling current in silicon metal-oxide-semiconductor structures are identified. In addition to the electron tunneling from the conduction band of the semiconductor, there is a second component interpreted as electron tunneling from the valence band. This is manifested as hole current in the silicon substrate. The ratio of valence-band to conduction-band tunneling currents is about 10^{-3} , and increases slightly with the oxide field. This ratio is independent of oxide thickness, temperature, and gate-electrode material.

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Tunneling in metal-oxide-semiconductor (MOS) structures has been thoroughly covered in the literature.^{1,2} Most of the authors have used MOS capacitors to measure the oxide current.^{1,3,4} In this work, tunnel current was measured in the gate oxide of silicon MOS transistors at positive gate voltage, using an experimental technique which separates electrons and holes in the semiconductor.^{5,6} It is shown in this work that in addition to the electron current there is a second current component which appears in the silicon as hole current.⁷ It is suggested that this second tunnel-current component is due to tunneling of electrons from the silicon valence band.

The experimental setup is shown schematically in Fig. 1. Electron current is measured at the drain, which is connected to a shallow n^+ -implanted layer (or an inversion layer) beneath the gate. Hole current is measured at the reversed-biased p -type substrate. Simultaneously, the oxide current is measured at the gate. This experimental technique has been used by Weinberg *et al.*^{6,8} and by Ginovker *et al.*⁵ to investigate high field conduction in MNOS^{5,8,9} and SiO₂.⁶

Typical results for both the gate and substrate currents as a function of gate voltage are shown in Fig. 2. The gate current is due to electrons tunneling from the n^+ side of the junction to the gate. However, there is a hole substrate current, which tracks the familiar Fowler-Nordheim characteristic, and is smaller than the electron component by approximately three orders of magnitude. It was verified, using current measurement techniques which eliminated offset and calibration errors, that the gate current is always larger than the electron current from the n^+ side of the junction. The two currents I_G and I_{SUB} are independent of the substrate bias and hence they depend only on the oxide electric field. This verifies that the origin of the substrate hole current is not direct band-to-band tunneling in the Si, nor any junction leakage mechanism, but a true source of excess holes under the tunnel oxide.

The ratio of the substrate current to the gate current as a function of the gate current is shown in Fig. 3 for two different oxide thicknesses. As can be seen, the ratio increases with the gate current, which means that the substrate current rises faster than the gate current as V_G is increased. While

the gate current I_G is increased by 3.5 orders of magnitude (see Fig. 2), the ratio I_{SUB}/I_G is changing by less than one order of magnitude. The sensitivity of I_{SUB}/I_G to device and injection parameters is summarized below.

(a) Oxide thickness. A typical example of the oxide thickness effect is shown in Fig. 3, where the ratio I_{SUB}/I_G as a function of the gate current is drawn. The gate current is used in order to have the comparison at the same field across the Si-SiO₂ interface for different oxide thickness. The ratio I_{SUB}/I_G is equivalent for the 85-Å and the 365-Å oxide. Measurements for oxide thickness up to 1000 Å show that the ratio I_{SUB}/I_G is relatively independent of the oxide thickness for a given gate current.

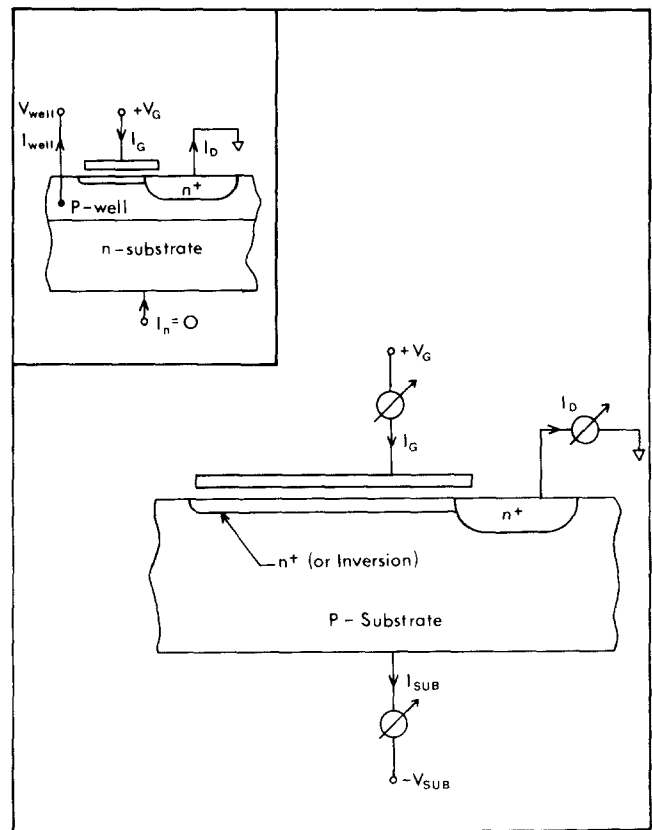


FIG. 1. Schematic picture of the experimental structure. Electron currents are measured at the drain and gate terminals, and hole current is detected at the p -type substrate or p well (see insert).

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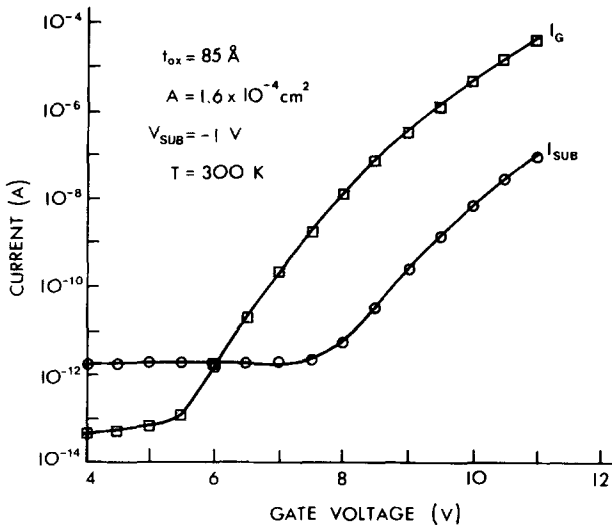


FIG. 2. Typical gate current and substrate current vs gate voltage. At low voltage the substrate current is dominated by junction leakage.

(b) Oxide growth conditions. Oxides grown in the temperature range 850–1100 °C, HCL or dry, show the same ratio of I_{SUB}/I_G .

(c) Gate material. Both Al and Si gate devices were measured, and the ratio I_{SUB}/I_G was found to be independent of the gate material and doping.

(d) Temperature. The ratio I_{SUB}/I_G is independent of the temperature in the range 100–300 K.

(e) Substrate doping. Experiments were done using shallow n^+ arsenic implant in the range 10^{11} – 10^{13} cm^{-2} with no effect on I_{SUB}/I_G . The same results were obtained using inversion layers on p -type substrates with boron implants in the same range.

(f) Trapping in the oxide. For a constant gate voltage, both the gate and the substrate currents decay as a function of time due to electron trapping in the SiO_2 .¹⁰ For cases where both currents were reduced by more than a factor of 10, the ratio I_{SUB}/I_G still remained constant around 10^{-3} .

(g) Interface-state density. The I_{SUB}/I_G ratio is sensitive to interface-state density. The ratio increased by factor ~ 10

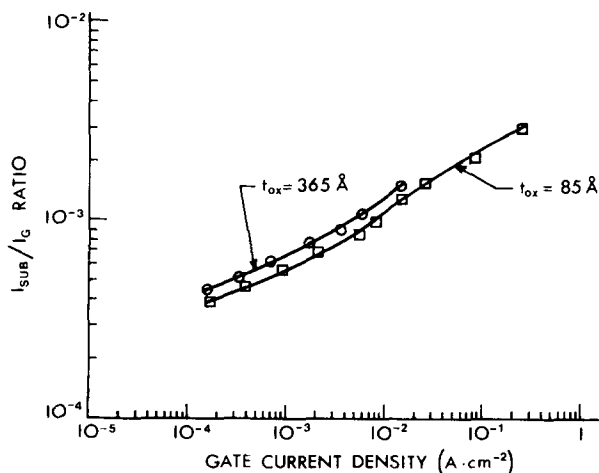


FIG. 3. Ratio of hole current to the total gate current vs the gate current, for two oxide thicknesses: 85 Å (same data as in Fig. 2) and 365 Å.

in some samples after a high-field current stress. C - V analysis of these samples showed that about 10^{12} cm^{-2} interface states have been generated by the stress.

Three possible mechanisms that can explain the hole substrate current have been considered (see Fig. 4): (1) electron tunneling from the Si valence band¹¹; (2) hole transport through the oxide^{6,12}; (3) photogeneration of hole-electron pairs in the silicon. The following discussion presents experimental evidence that eliminates the two latter mechanisms and supports electron tunneling from the silicon valence band as the origin of the hole current.

Optical pair generation in the silicon could occur if the tunneling process involves photon emission; e.g., tunnel electrons can cause photon emission while losing their energy in the oxide or in the gate electrode.^{13,14} Although this mechanism is expected to have a low quantum yield, which can hardly explain the relatively high current ratio, an experiment has been conducted to check this possibility. The experimental n -channel device depicted in the insert of Fig. 1 was fabricated in a p well on an n -type substrate. If photogeneration were occurring in the silicon bulk, part of the photons would be detected as photocurrent in the underlying reverse-biased junction of the p well and the n substrate. The results of such measurements show no photoelectrons in the n substrate, while electron and hole currents in the drain and the p well exhibit the same behavior as in Fig. 2. Thus, photogeneration cannot explain the observed hole current.

The appearance of holes at the Si/SiO₂ interface could be due to hole transport through the oxide. Holes can be either introduced into the oxide from the gate,⁶ or generated by impact ionization within the oxide.^{12,15,16} Impact ionization in the SiO₂ is ruled out since the hole current in Fig. 2 is already detected for a gate voltage of 8.5 V; considering the Si/SiO₂ energy barrier of about 3 eV, electrons drifting in the oxide conduction band can gain a maximum energy of about 5.5 eV, which is much below the energy necessary for impact ionization in SiO₂ with a 9-eV band gap. In addition to this, impact ionization is expected to increase with increasing oxide thickness and reduced temperatures for a given electric field in the oxide, but the observed hole current was found to be independent of oxide thickness and temperature for any given gate current. Hole tunneling from the gate is unlikely, because of the high-energy barrier for holes.¹¹ In principle, tunnel electrons could create hot holes in the gate electrode while they lose the 3-eV drop from the oxide conduction band to the gate,⁶ and those hot holes could have a higher tunneling probability. However, the fact that there was no difference in the hole current between samples with metal and polysilicon gate rules out the possibility of hole tunneling from the gate, since a major difference is expected between hole generation in metal and semiconductor.

The mechanism of electron tunneling from the Si valence band is shown schematically in Fig. 4. While electrons are tunneling from the valence band to the gate, they create holes which are collected by the p -type substrate. Electron tunneling from the Si valence band can explain all the experimental results presented in this work. It is expected that the ratio of electron tunneling from the conduction and valence bands will depend only on the energy difference between

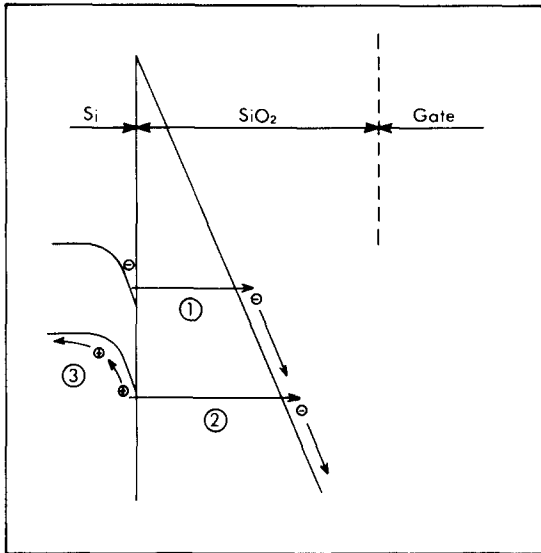


FIG. 4. Energy-band diagram for MOS tunneling at positive gate voltage: (1) electron tunneling from the Si conduction band; (2) electron tunneling from the Si valence band; (3) hole current into the substrate.

these two bands and the SiO₂ bands. The Si-SiO₂ interface is invariant for all of the experiments in this work, except for the case of interface-state generation. This explains why the ratio of I_{SUB} to I_G is unchanged, while both the SiO₂ and gate electrode parameters are varied. The observed correlation between the hole current and interface-state density also supports this hypothesis, since tunneling from the valence band is expected to be enhanced¹¹ through intermediate states in the forbidden gap, localized at the surface. It is interesting to note that a simple extension of the Fowler-Nordheim calculation to tunneling of electrons from the Si valence band, by adding 1.1 eV to the 3.2 eV Si/SiO₂ potential barrier, gives a ratio of about 10^{-6} for I_{SUB}/I_G . By adjusting the effective mass from $0.5 m_e$ (Ref. 2) to 0.35 of the free-electron mass, the above ratio becomes 10^{-3} and its de-

pendence on the field is close to the observed experimental results. Reduction in effective mass near the middle of SiO₂ forbidden gap has been suggested previously.¹⁷ However, it is not implied here that this simple fit is either a confirmation of the theory or a direct method to measure the effective electron mass in the SiO₂ forbidden gap.

In conclusion, an extra tunnel current component in MOS structure has been identified. This component, which is measured as a hole current in the semiconductor, is explained as electron tunneling from the silicon valence band.

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¹M. Lenzlinger and E. H. Snow, *J. Appl. Phys.* **40**, 278 (1969).

²Z. A. Weinberg, *J. Appl. Phys.* **53**, 5052 (1982).

³G. Krieger and R. M. Swanson, *J. Appl. Phys.* **52**, 5710 (1981).

⁴M. Av-Ron, M. Shatzkes, T. H. Distefano, and R. A. Odula, *J. Appl. Phys.* **52**, 2897 (1981).

⁵A. S. Ginovker, V. A. Gritsenko, and S. P. Sinitza, *Phys. Status Solidi A* **26**, 489 (1974).

⁶Z. A. Weinberg, W. C. Johnson, and M. A. Lampert, *J. Appl. Phys.* **47**, 248 (1976).

⁷This same observation was made by L. Yau, C. Ha, and F. T. Liou (private communication).

⁸P. C. Arnett and Z. A. Weinberg, *IEEE Trans. Electron Devices* **ED-25**, 1014 (1978).

⁹O. K. Schroder and M. H. White, *IEEE Trans. Electron Devices* **ED-26**, 899 (1979).

¹⁰E. Harari, *J. Appl. Phys.* **49**, 2478 (1978).

¹¹H. C. Card, *Inst. Phys. Conf. Ser.* **50**, 140 (1980).

¹²N. Klein, *Adv. Phys.* **21**, 605 (1972).

¹³P. Solomon and N. Klein, *J. Appl. Phys.* **47**, 1023 (1976).

¹⁴A. G. Chynoweth and K. G. McKay, *Phys. Rev.* **102**, 369 (1956).

¹⁵J. J. O'Dwyer, *J. Appl. Phys.* **40**, 3887 (1969).

¹⁶T. H. Distefano and M. Shatzkes, *Appl. Phys. Lett.* **25**, 685 (1974).

¹⁷C. A. Mead, *Tunneling Phenomena in Solids* (Plenum, New York, 1969).