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SURFACE MOBILITY OF SILICON MOS DEVICES

by

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Recent investigations conducted in this laboratory and elsewhere[1] have considered the electron mobility in the n-type inversion layers of metal-oxide-semiconductor (MOS) devices (Fig. 1). By comparing experimentally determined values of mobility in typical devices to the theory developed by Schrieffer,[2] it was observed that too small a value of mobility is predicted by Schrieffer's assumption of constant field throughout the channel width [Case (a)]. In applying Schrieffer's second case, which employs a solution of Poisson's equation, a difficulty was encountered since the Schrieffer theory produces a relation between μ_{eff}, the effective mobility, and ψ_S, the amount of band bending at the semiconductor-oxide interface (Fig. 2). A relation between μ_{eff} and V_G, the applied gate voltage, is needed to compare Schrieffer's theory with experimental data on MOS performance. A derivation of the relation between V_G and ψ_S has been made in this laboratory. The substance of the derivation is outlined in the following.

From the Kingston-Neustadter theory[3] which was extended by Young,[4] we know that the electric field at the semiconductor-oxide interface is given by

$$\mathcal{E}_S = - \frac{\partial\psi}{\partial z}\Big|_{\psi = \psi_S} = \frac{kT}{qL_D} F(U_S, U_B), \qquad (1)$$

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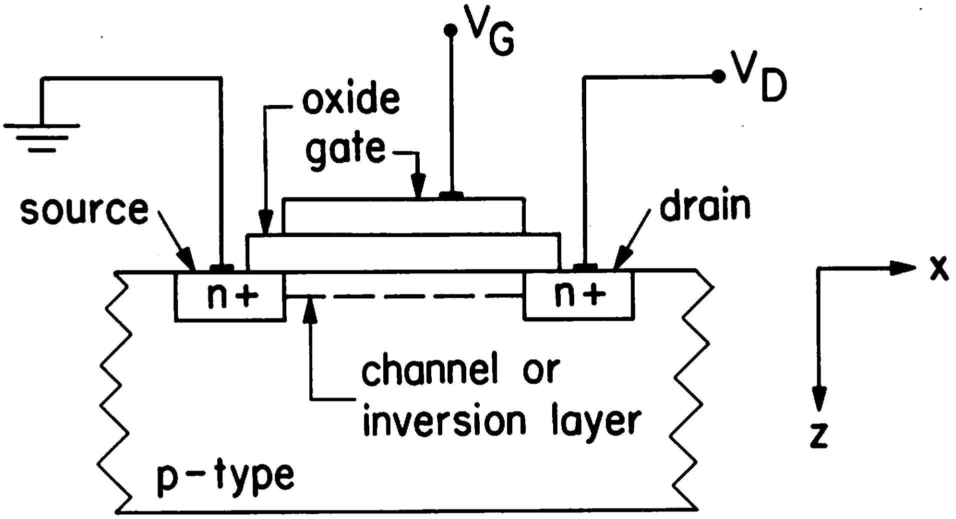

Fig. 1. Typical metal-oxide-semiconductor (MOS) device.

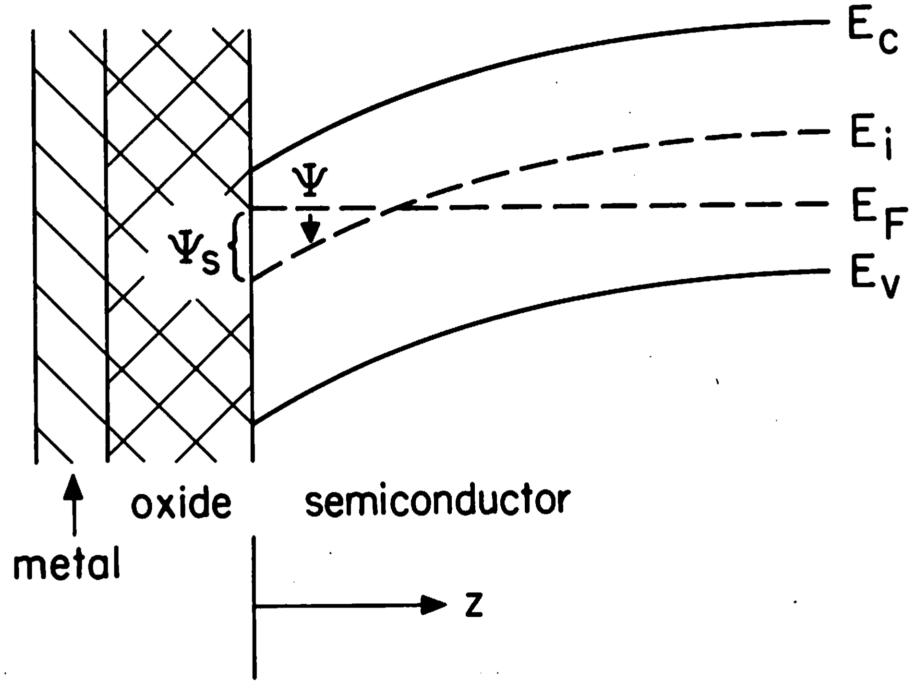

Fig. 2. Energy-level diagram for an n-type inversion layer.

where

$$U = \frac{q\psi}{kT}, \qquad L_D = \left(\frac{\epsilon_s kT}{2q^2 n_i} \right) \tag{2}$$

$$F(U_S, U_B) = \sqrt{2}\,[\sinh U_B(U_B - U_S) - (\cosh U_B - \cosh U_S)]^{1/2} \tag{3}$$

and the subscripts s, ox, S, and B denote the semiconductor, the oxide, the semiconductor-oxide interface, and the bulk semiconductor properties, respectively.

The electric displacement $\epsilon\mathcal{E}$ is continuous across the semiconductor-oxide interface under the assumption of no surface charge. If surface charge is present, it can be considered by a shift in the zero value of the gate voltage at the end of the derivation.[5] Thus,

$$\epsilon_s \mathcal{E}_S = \epsilon_{ox} \mathcal{E}_{ox}. \tag{4}$$

Assuming that there is no charge storage in the oxide, the oxide field, $\mathcal{E}_{ox}$, can be written as

$$\mathcal{E}_{ox} = \frac{V_G - \frac{kT}{q} U_S}{t_{ox}}, \tag{5}$$

where t_{ox} is the oxide thickness. Combining expressions (1), (4), and (5), one obtains

$$V_G = \frac{kT}{q} U_S - \frac{\epsilon_s t_{ox}}{\epsilon_{ox} L_D} \frac{kT}{q} F(U_S, U_B). \tag{6}$$

The function $F(U_S, U_B)$ has been calculated[3, 4] for positive values of U_B. For p-type bulk material, however, $UB < 0$, and we must relate $F(U_S, U_B)$ to a function of $-U_B$. Kingston and Neustadter have shown that $F(U_S, U_B) = -F(-U_S, -U_B)$[3], so that we can write

$$V_G = \frac{kT}{q} U_S + \frac{\epsilon_s t_{ox}}{\epsilon_{ox} L_D} \frac{kT}{q} F(-U_S, -U_B). \qquad (7)$$

Thus, we have seen that if we know the relative dielectric constant and the intrinsic carrier concentration of the semiconductor, the oxide thickness, and the temperature, we can relate the gate voltage to the band bending at the surface. Figure 3 is a plot of Eq. (7) for intrinsic silicon at room temperature where an oxide thickness of 0.2 micron has been assumed. By using both the relation connecting the effective mobility to U_S for Schrieffer's Case (b) and Eq. (7) derived here, it is possible to relate the effective channel mobility μ_{eff} directly to the applied gate voltage. The relationship is illustrated for intrinsic silicon in Fig. 4. The dependence of μ_{eff} on V_G for Schrieffer's Case (a) (constant field in the channel) is also plotted in Fig. 4 so that a comparison between the two models can be made. It is seen that the curve for Case (b) predicts somewhat higher values of mobility than are predicted for Case (a). If Schrieffer's model includes the major cause of lower surface mobility, Case (b) should provide a more accurate value for μ_{eff} since this case accounts for the presence of space charge in the channel.

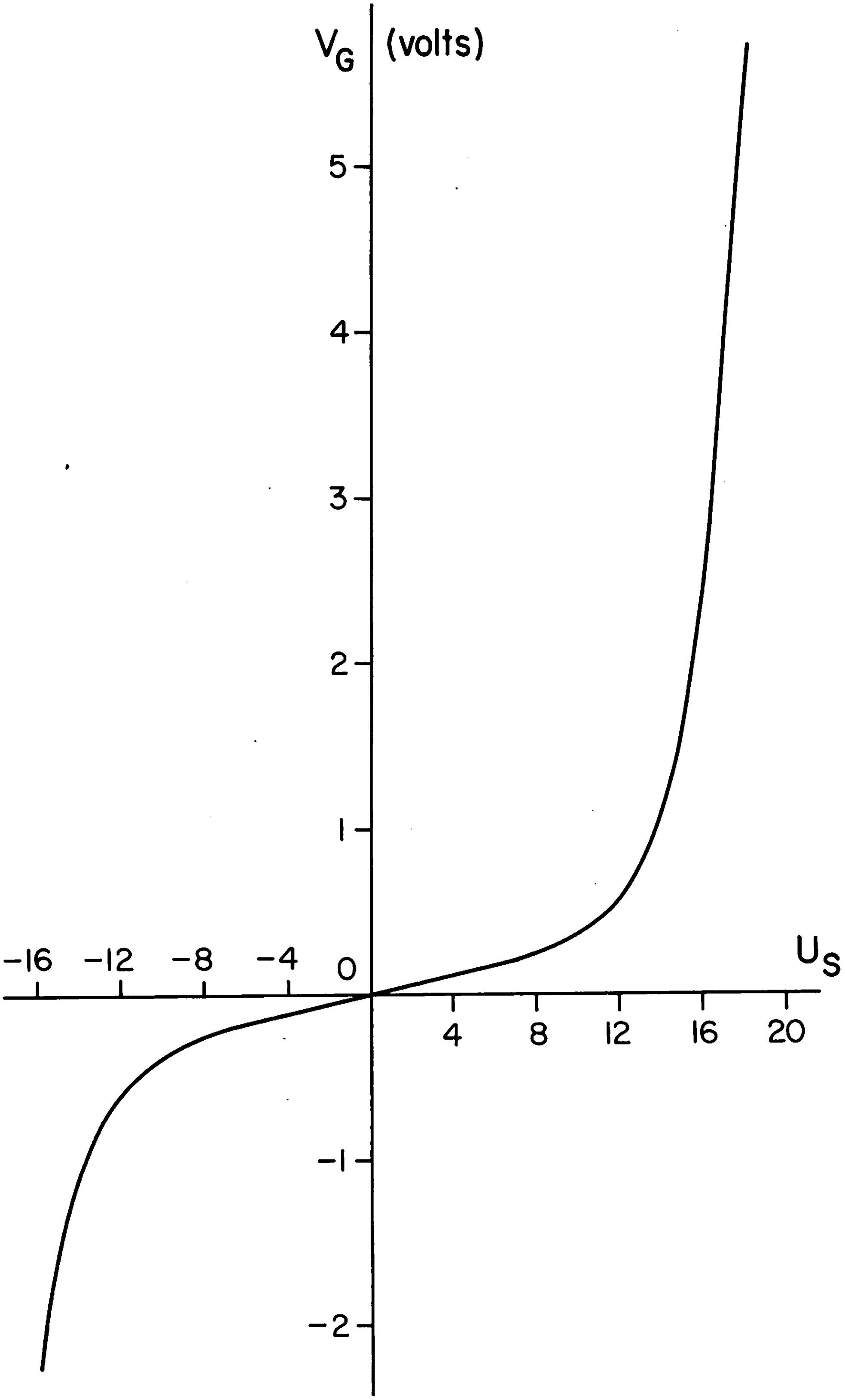

Fig. 3. Normalized band bending as a function of the applied gate voltage for intrinsic silicon.

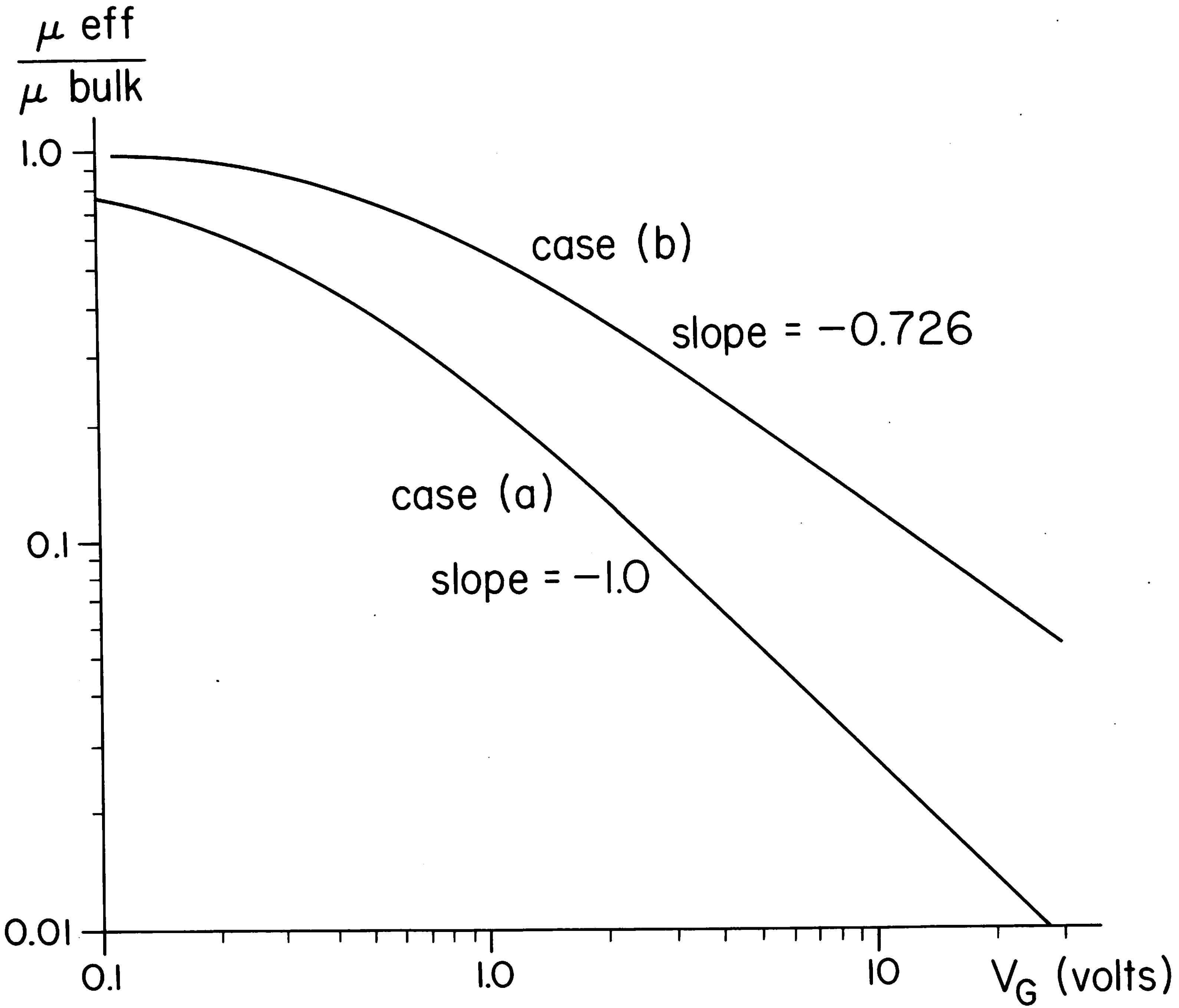

Fig. 4. Effective mobility as a function of the applied gate voltage for intrinsic silicon for the two cases considered by Schrieffer.

Most studies of surface mobility in silicon MOS devices[1, 5] have attempted to relate experimental results to Schrieffer's formula for Case (a), which is a greatly simplified picture of the actual physical situation. The calculated theoretical values were, consequently, much lower than the actual experimental values. The experimental values found elsewhere[1, 6] and the preliminary results obtained in this laboratory appear to agree more closely with the values predicted by the treatment in Case (b).

Since Schrieffer's analysis is limited to a classical treatment of the Boltzmann transport equation, it is possible that even the more representative solution will not be adequate to fit the experimental data, and quantum effects will have to be considered.

Addendum: The derivation contained in this report closely parallels that of Waxman, et. al.,[7] but was carried out independently. Waxman derives an expression similar to Eq. (7), relating the band bending at the semiconductor surface to the applied gate voltage for the accumulation layer of a vapor-deposited CdS film.

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