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Hall Measurements on Silicon Field Effect Transistor Structures*

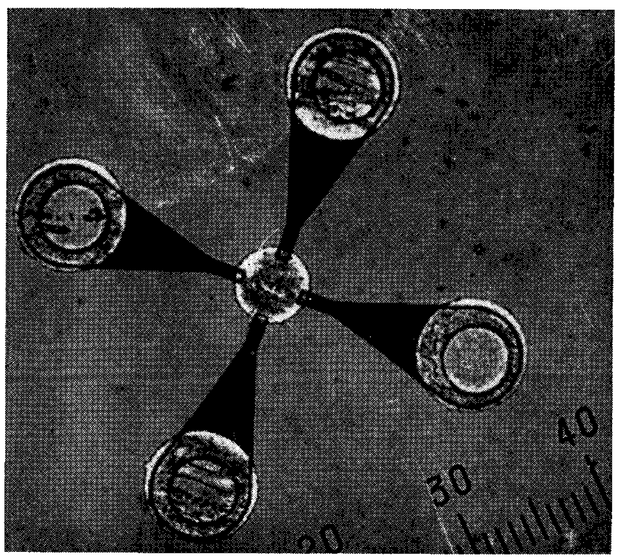
Introduction

The primary purpose of the work reported in this paper was to determine whether surface trapping plays any significant role in altering the transconductance of metal-oxide-silicon field-effect transistors. Fang and Triebwasser[1,2] have reported that the effective mobility of carriers in the surface region of these devices followed a modified Schrieffer formula[3] for diffuse scattering. However, since the mobility values were derived from transconductance measurements, effects of surface trapping could not be directly measured. We have measured the Hall constant, and hence the surface free-charge density, over a large enough range of gate voltage to show that trapping does not play a significant role in the region of interest and that a modified Schrieffer expression does fit the experimental data.

The theory of Hall measurements on surface layers has been discussed by many workers starting with Petritz.[4,5,6] In general, experiments[7,8,9,10] have tended to demonstrate a decrease in mobility as the surface charge density is increased, and thus to confirm the existence of the effects of diffuse scattering. Most of the uncertainty in the results of such experiments relates to the confinement of the measuring current to the carriers on the surface; for instance, if the current is divided between a surface inversion region and the bulk, the measured Hall signal represents a sort of averaging of effects produced by the properties of the two regions.[4,10] In the samples we have used this difficulty is avoided in large measure in the case of *n-p-n* devices by making contact to the inversion layer with diffused *n*-type contacts. The resulting *p-n* junctions isolate the contacts from the high resistivity *p*-type bulk so that the current is confined to the surface except when the gate voltage is such that there is no or little inversion. Thus it is the properties of the surface region itself that are studied.

The samples were made by standard fabrication techniques employed by Cheroff et al.[11] A plan view of the devices is shown in Fig. 1. In the *n-p-n* devices the *n*-regions were diffused into 100 ohm-cm *p*-type silicon in the form of peripheral pointed regions. An aluminum gate was evaporated in the central circular region over the SiO_2 layer so that the gate region just overlapped the four contacts. Since in most cases there was no inversion except under the gate, the contacts and the inversion layer under the circular gate constituted a Van der Pauw[12] Hall sample. In general, leakage currents in regions not under the gate were much smaller than currents in the sample area; this could be checked by biasing the device off.

Figure 1 **Plan view of the Hall field-effect transistor device.** *(One division is equivalent to 10 μ.)*



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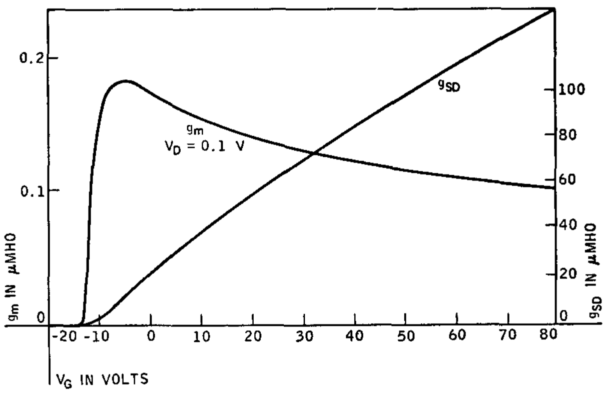
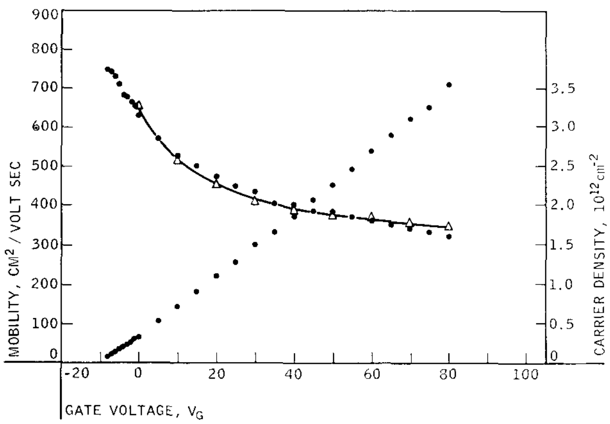


Figure 2 **Transconductance, g_m, and conductance, g_{SD}, as functions of gate voltage, V_G.**

Figure 3 **Carrier density and mobility of n-p-n device as functions of gate voltage, V_G.** *Points derived as experimental data are indicated by heavy dots; triangles indicate least square fit to $\mu = 273 + 1500\ [\ln (V - 8.25)/(V - 8.25)]$.*



Experimental results

All significant measurements reported here were made when the current through the inverted region under the gate was several orders of magnitude greater than the leakage currents. The measurements were made at constant current, usually at 1.8×10^{-6} amperes, from a 10^8 ohm source in a field of 12 000 oersteds. A Keithley 610 voltmeter with an input impedance of 10^{14} ohms was used to measure the voltage. The data were either recorded as the gate voltage V_G was swept in about five minutes or were taken point by point. There was no significant hysteresis over most of the range of measurement. The devices showed transconductances which varied in a manner similar to those for normal FET devices; however, because of the geometry of the sample their magnitudes were quite low, as may be seen in Fig. 2.

Figure 3 shows typical results for an *n-p-n* sample at about 15°C. The surface density of charge was calculated in the usual manner for Van der Pauw geometries[12] by substituting in the equation

$$N = \frac{HI \times 10^{-8}}{q\Delta V_{13,24}}, \tag{1}$$

where N is the surface charge density/cm^2, and $\Delta V_{13,24}$ is the change, for a field H, in the voltage across contacts 2 and 4 when current I is through 1 and 3 and the contacts are numbered in order around the gate. The density of charge is seen to vary linearly with gate voltage and $dN/dV = 3.97 \times 10^{10}/\text{cm}^2\text{-}V$. The total charge induced per unit area may be calculated from

$$N_t = \frac{k_{SiO_2}}{4\pi qd}(V + V_0), \tag{2}$$

where $k_{Si\,O_2}$ is the dielectric constant of SiO_2, V_0 is the built-in voltage in the oxide, and d is its thickness, 5600 Å. Then $dN_t/dV = 3.95 \times 10^{10}/\text{cm}^2\text{-V}$. Thus the agreement between variation of free and total charge is well within the margin of experimental error, which is estimated to be less than 5%. Consequently, since there was no significant trapping in the range of measurements from 0 to 85 volts, the transconductance measurements give a valid measure of the mobility. In the voltage range —10 to 0 volts there was a departure from a straight line. This may have been an experimental artifact due to leakage currents but more investigation of this point is needed. Calculation of the free charge densities in this range indicate that the deviation is too large to be caused by charging the depletion region. This is experimentally verified by the fact that the capacitance is constant in this region.

The mobility could also be determined from the measurements by substituting into

$$\mu = \frac{2 \ln 2}{\pi H} \frac{\Delta V_{13,24}}{V_{12,34} + V_{23,41}}. \tag{3}$$

No variation of Hall mobility was observed from 2500 to 15 000 gauss. The data, shown in Fig. 3, could be fitted with an equation of the form

$$\mu = \mu_0 + \frac{A \ln (V + V_0)}{(V + V_0)}. \tag{4}$$

Least square fits were made for several values of V_0. The quality of the fit was not very dependent on the choice of V_0. For the curve shown in Fig. 3, the following sets of values are applicable: $V_0 = 8.25\text{V}$, $\mu_0 = 273$, and $A = 1500$; $V_0 = 9\text{V}$, $\mu_0 = 326$, and $A = 1129$; and $V_0 = 12\text{V}$, $\mu_0 = 265$ and $A = 1700$. All of the fits were good to 5%. This result is different from those reported by Fang and Triebwasser in their earlier paper[1]; their results, on different surfaces, indicate that μ_0 is zero.

Results from our work were fitted to a simple model assuming that μ_0 is a specular scattering term and that the second term is due to diffuse scattering. (This procedure is certainly theoretically questionable although Fuchs' arguments[13] support it.) On these assumptions,

$$\mu = p\mu_B + (1 - p)\mu_D, \tag{5}$$

where p is the probability for specular scattering, μ_B is the bulk mobility, and μ_0 is the surface scattering term given by Fang and Triebwasser,

$$\mu_D = \sqrt{\frac{2kT}{\pi m}} \frac{dk_{SiO_2}}{k_{Si}} \frac{\ln (V - V_0)}{(V - V_0)}, \tag{6}$$

where $m = 0.27\ m_0$. Thus, if we allow the addition of specular and diffuse terms linearly, these samples exhibit about 20% specular scattering. This was not the case for the samples studied by Fang and Triebwasser in an earlier paper.[1] These samples were not prepared in a similar way, however. Since many other causes[14,15] for variation of mobility with field have been suggested that may also fit these data, there is need for more extensive measurements and especially for measurements as to the function of orientation and temperature.

Conclusions

In the range of fields used, it seems well established that trapping does not play a major role in these *n-p-n* field effect devices. This range was extensive enough to indicate that there was no high density of states in the gap from 0.3 eV below the conduction band edge to 0.125 eV below the conduction band edge. Hence, in this range for samples so prepared, the transconductance may be used to study the mobility.

Acknowledgments

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