Letters to the Editor

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Measurement and Interpretation of Conductance of *P*-Type Inversion Layers on Germanium*

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INVERSION layers in both *n*- and *p*-type germanium have previously been observed,[1–5] but quantitative measurements reported only for the *n*-type inversion layers.[1,2] Results of similar measurements on *p*-type inversion layers are described here and explained in terms of a constant Fermi level at the surface (a high density of surface states).

It is believed that the theory of oxidation,[6] as developed for metals, describes correctly the situation of oxidized germanium surfaces. In this theory, a strong electric field at the germanium-germanium oxide interface is expected, arising from the negative surface charge. On *n*-type germanium this field does not end at the surface but it can penetrate a considerable distance into the germanium, thus producing a space charge layer or even an inversion layer (Fig. 1). For a quantitative interpretation, the surface states which lie at the germanium-germanium oxide interface[7] have to be taken into account. These same states are considered to be responsible for surface recombination.

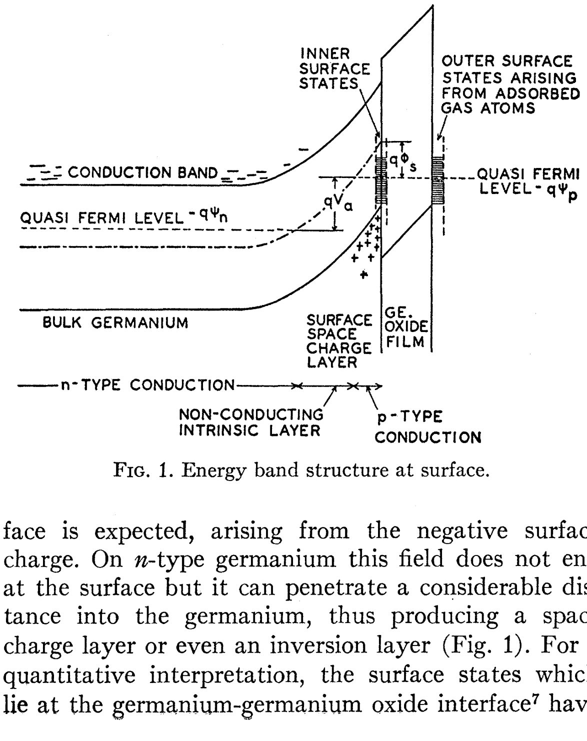

FIG. 1. Energy band structure at surface.

P-type inversion layers can be produced in many ways.[4] In this laboratory, the germanium was etched in CP4, washed, and dried. Exposure of the sample to a mixture of wet O_2 and O_3, followed by a dry mixture of O_2 and O_3 created a stable *p*-type inversion layer. Dry N_2 was also used, but the inversion layer so produced decayed gradually over a period of several hours. Active oxygen seemed to be essential in obtaining an inversion layer.

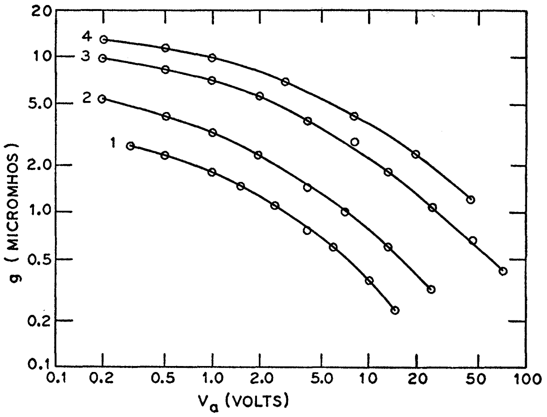

FIG. 2. Steady-state channel conductance *versus* bias voltage.

In Fig. 2, the measured conductance values $g(V_a)$ of four different inversion layers on 8 ohm-cm *n*-type material are given. $p-n-p$ grown junction germanium bars, with 0.4-cm *n*-type regions, were used. The four runs were made for surfaces which had been exposed for different times to wet oxygen and ozone. The longer the exposure, the higher the conductance of the inversion layer. All conductance readings are normalized and the numbers given represent the conductance of a unit square of *p*-type skin. All values are steady state. For each bias voltage, it was found that it took a time ranging from a few seconds for the lowest curve to a few minutes for the highest curve of Fig. 2 to establish equilibrium. The explanation for the slow adjustment will be given in a following letter.[8] For the interpretation of the conductivity values of the channel, the position of the quasi-Fermi level is calculated with respect to the middle of the band at the surface, i.e., ϕ_s (Fig. 1). The total positive space charge Q inside the semiconductor, which results from ionized donor atoms and holes is also computed. This space charge must be compensated by electrons in surface states which lie at the germanium-germanium oxide interface and at the germanium oxide surface. The same quasi-Fermi level ψ_p which describes the occupancy of the states in the valence band just inside the germanium will also describe the occupancy of the two types of surface states. Thus, the relation between ϕ_s and Q will give

TABLE I. Position of the quasi-Fermi level at the surface and the total charge in the surface states for various bias voltages.x (Steady-state case.)

V_a	Run 1		Run 2		Run 3		Run 4	
	ϕ_s (volts)	No. electronic charges/cm^2 $\times 10^{-10}$	ϕ_s (volts)	No. electronic charges/cm^2 $\times 10^{-10}$	ϕ_s (volts)	No. electronic charges/cm^2 $\times 10^{-10}$	ϕ_s (volts)	No. electronic charges/cm^2 $\times 10^{-10}$
0.2	0.110	4.97	0.134	6.50	0.158	9.42	0.169	11.4
0.5	0.117	6.26	0.135	7.37	0.160	10.2	0.171	12.3
1	0.119	7.75	0.137	8.70	0.162	11.5	0.173	13.6
3	0.121	11.7	0.138	12.4	0.164	14.8	0.178	16.9
5	0.122	14.7	0.138	15.2	0.165	17.2	0.180	19.4
7	0.122	17.1	0.138	17.5	0.167	19.5	0.182	21.8
10	0.120	20.2	0.138	20.4	0.167	22.3	0.183	24.3
12	0.120	21.9	0.137	22.3	0.167	24.1	0.183	25.9
14	0.118	23.6	0.137	23.9	0.167	25.5	0.183	27.3
15	0.117	24.4	0.137	24.7	0.167	26.3	0.183	28.0
16			0.137	25.5	0.167	27.0	0.183	28.7
18			0.137	26.9	0.168	28.4	0.185	30.2
20			0.137	28.4	0.168	29.8	0.184	31.4
25			0.136	31.6	0.168	32.7	0.184	34.3
45					0.167	42.9	0.183	44.0
70					0.167	52.9		

information about the total density of surface states (i.e., the sum of the densities of the two states).

The computation of ϕ_s and Q has been carried out by using the mobility for holes in inversion layers as calculated by Schrieffer.[9] This analysis does not make use of the approximations described by Brown[1] or Kingston.[10] The results for the four runs are given in Table I.

It is seen that ϕ_s is essentially constant for each run. It is uncertain whether any significance can be attributed to the deviation of ϕ_s from a constant. The total charge in the surface traps continues to increase with increasing bias voltage. If the slight increase of ϕ_s for voltages approximately below 10 volts is real, then this represents a serious difficulty. From Fig. 1, it may be seen that an increase in ϕ_s means a decrease in the occupancy of the surface states. On the other hand, the requirement of total neutrality gives an increasing charge in the surface states. This difficulty can be avoided by assuming some specular reflection of holes at the surface in Schrieffer's calculation.[9] Another possible source of error is Schrieffer's simplifying but incorrect assumption of spherical energy surfaces. In addition, the base resistivity used in the calculation may have been incorrect by as much as 20 percent.

In every case, it may be said that the Fermi level is essentially constant and the change in charge very considerable, so that the total density of surface states will be high. It is not possible to give a numerical result for the density of states, because the Fermi level shifts by an amount that is smaller than the probable error of this determination. However, from the measurements described in the accompanying letter,[8] it may be concluded that this high total density of states is due only to surface states outside the germanium oxide. The charge in the states at the germanium-germanium oxide surface does not change by such a large amount for so little change in the Fermi level.

Kingston[10] has reported that the data for channels on p-type germanium can also be understood by assuming a constant value of ϕ_s. It is interesting to note that our curves, which deviate greatly from the $1/V_a$ relationship measured by Kingston, still give approximately a constant ϕ_s value, indicating that Kingston's approximations are not applicable in our case.

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[9] J. R. Schrieffer, Phys. Rev. **97**, 641 (1955). The authors thank Mr. Schrieffer for a preprint of this article.

[10] R. H. Kingston (to be published). The authors are grateful for the privilege of seeing a preprint of Dr. Kingston's paper.

Structure of Surface States at the Germanium-Germanium Oxide Interface*

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IN the accompanying Letter,[1] the conductance of p-type inversion layers on 8 ohm-cm n-type germanium under steady-state conditions has been discussed. In this Letter, investigations of the nonsteady-state conductance and its interpretation in terms of surface states at the germanium-germanium oxide interface are reported.