Conductivity of inversion layers in InSb MIS structures below the "mobility threshold"

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The temperature and field dependences of the conductivity of inversion layers in InSb MIS structures are studied. The experimental results are interpreted using the fluctuation theory of surface states and the conductivity of MIS structures [Zh. Eksp. Teor. Fiz. **84**, 719 (1983)].

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In recent years, the study of the surface conductivity of inversion channels in MIS structures elicits, in addition to applied interest, purely scientific interest related to the problem of two-dimensional quantum transport.[2] Experimental results available here have been obtained primarily in silicon MOS structures.[3] We believe that the results of experimental studies of the temperature and field dependences of the conductivity of inversion layers in MIS structures based on InSb material, distinguished by the small effective mass of the electrons, and their theoretical interpretation presented below will be of interest.

The structures investigated were formed by anodic oxidation of *n*- and *p*-type InSb with impurity concentration $N \sim 10^{14}$ cm^{-3}. The large area of the gate ($\sim 10^{-4}$ cm^2) permitted measuring, together with the current characteristics, the voltage-capacitive dependences. In order to avoid nonlinearities, the conductivity measurements were performed with low drawing fields ~ 1 V cm^{-1}.

The temperature dependences of the conductivity Σ of *n*- and *p*-type inversion channels in the range 40–110 K are shown in Fig. 1. As in silicon MOS structures,[3] they have an activation nature $\Sigma = \Sigma_0 e^{-\epsilon_a/kT}$ over a rather broad range of voltages on the gate V. As the inverting voltage is increased, the activation energy decreases and for $V > V_t$, where V_t is the so-called threshold voltage, the temperature dependence of the conductivity acquires a metallic nature. As V is increased, some decrease is observed in the pre-exponential Σ_0. We note that the value of the pre-exponential—hole $\Sigma_0^p \approx 10^{-4}\ \Omega^{-1}$ for a square and, especially, electronic $\Sigma_0^n \approx 10^{-3}\ \Omega^{-1}$ for a square—differ considerably from the magnitude of the so-called minimum metallic conductivity $\Sigma_{mm} \approx e^2/2\pi\hbar \approx 10^{-5}\ \Omega^{-1}$ for a square. At a fixed temperature the dependences of the conductivity on the voltage on the gate are superlinear, but not exponential.

The experimental data obtained are explained well by a fluctuation potential of the relief, mobility threshold (flow level), and localized and delocalized electronic states, defined specifically for MIS structures in Ref. 1. According to Ref. 1, for $V < V_t$ the conductivity of the inversion channel (for definite type) is proportional to the surface density of delocalized electrons:

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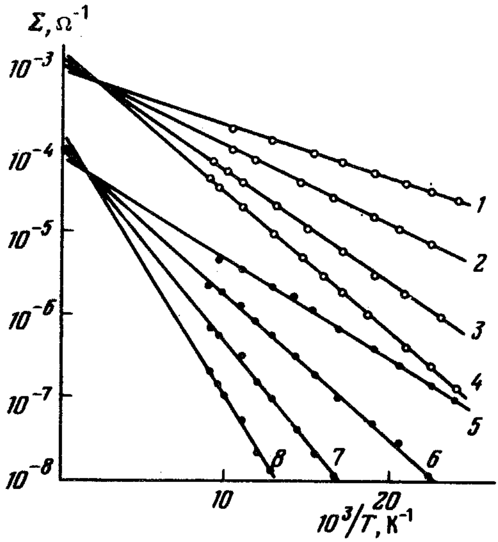

FIG. 1. Temperature dependences of the conductivity of *n*-type (1)–(4) and *p*-type (5)–(8) inversion channels for different voltages $|V - V_0|$ V. 1—1.54; 2—1.29; 3—1.17; 4—1.0; 5—3.31; 6—2.63; 7—2.0; 8—1.31.

$$\Sigma^n = \mu_n \left(\frac{\sigma}{\pi a_n^2}\right)^{3/4} \frac{kT}{\mathscr{E}} \exp\left\{-\frac{E_c - E_F - e\phi}{kT}\right\}, \tag{1}$$

where ϕ is the average surface potential (band bending) μ_n is the effective mobility, $\sigma = \sigma^+ + \sigma^-$ is the charge density fixed on the semiconductor-insulator boundary, including spatial fluctuations in the potential in the near-surface layer of the semiconductor, $a_n = \hbar^2\epsilon/me^2$ is the Bohr radius, $\mathscr{E}$ is the average electric field pressing the electrons to the interface, E_F is the Fermi level, and the average position of the bottom of a conduction band at the interface, $E_c - e\phi$, is the flow level.

The voltage on the gate of the structure V is spread between the semiconductor ϕ and the insulator according to the magnitude of the charge present in the structure:

$$V = V_{FB} + \phi + C_0^{-1}\left[\left(\frac{e\epsilon_s \phi N}{2\pi}\right)^{1/2} - Q_p(\phi) + Q_n(\phi)\right]. \tag{2}$$

Here V_{FB} is the so-called flat-band voltage, at which all the charges in the insulator and on the semiconductor interface are canceled out. Its magnitude is determined experimentally from the shape of the capacitance–voltage characteristic. In addition, in (2) $C_0 = \epsilon_i/4\pi d$ is the specific capacitance of the insulator, ϵ_i is the dielectric constant of the anodic oxide, which is close to the constant of InSb ($\epsilon_i = 11$, $\epsilon_s = 15.5$), while $d = 3\times10^{-5}$ cm is its thickness; $(e\epsilon_s \phi N/2\pi)^{1/2}$ is the charge of the depleted layer, and Q_n and Q_p are the charges localized on the interface between the bound electron and hole states, the surface states. As shown in Ref. 1, the bound charges Q_n and Q_p depend exponentially on the band bending ϕ:

$$Q_n(\phi) = Q_n^0 \exp\left\{-\frac{E_c - E_F}{2\Delta}\right\}(e^{e\phi/2\Delta} - 1),$$
$$Q_p(\phi) = Q_p^0 \exp\left\{\frac{E_v - E_F}{2\Delta}\right\}(e^{-e\phi/2\Delta} - 1), \tag{3}$$

where $\Delta = (e^2/\kappa)\sqrt{\pi\sigma}$ is the scale fluctuation energy ($\kappa = (\epsilon_i + \epsilon_s)/2$), and the pre-exponential $Q^0_{n,p} = e(\sigma/\pi)^{5/8}(2a_{n,p})^{-3/4}$. We did not include in (2) the charge of delocalized (mobile) electrons (Σ/μ), since for $V < V_t$ it is much smaller than $Q_n(\phi)$. From (2) and (3) we find the relationship between the activation energy of conductivity and the applied voltage:

$$\epsilon_a = E_c - E_F - e\phi = 2\Delta \ln \frac{Q^0_n}{C^0(V - V_0)}, \tag{4}$$

where

$$V_0 \cong V_{FB} + (E_c - E_F)/e + C_0^{-1}\left[\left(\frac{\epsilon_s N(E_v - E_F)}{2\pi}\right)^{1/2} + Q^0_p \exp\left(\frac{E_v - E_F}{2\Delta}\right)\right].$$

This approximate solution of Eq. (2) is valid so long as $(V - V_0) \gg 2\Delta$.

It turned out that the experimental dependences of the activation energy ϵ_a for conductivity of n- and p-inversion channels indeed straighten out on a logarithmic scale (Fig. 2), in accordance with Eq. (4). The tangent of the slope of the straight lines gives the value $2\Delta_n = 0.047$ eV and $2\Delta_p = 0.042$ eV, which corresponds to $\sigma = (1.3 - 1.5) \times 10^{12}$ cm^{-2}. We note that similar values of 2Δ are also obtained from measurements of the density of surface states in the same structures by the method of high-frequency C-V characteristics. The intersection of these straight lines with the abscissa axis gives the threshold voltage V_t. We note that the experimental values

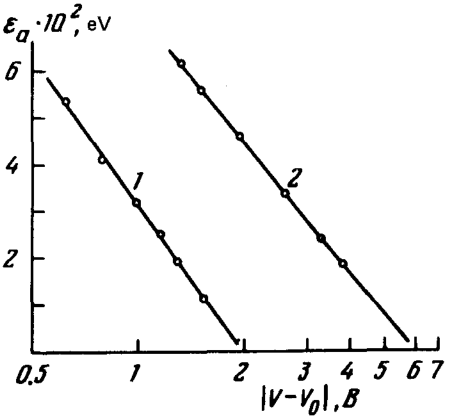

FIG. 2. Dependence of activation energy of conductivity on voltage for n-type (1) and p-type (2) inversion channels.

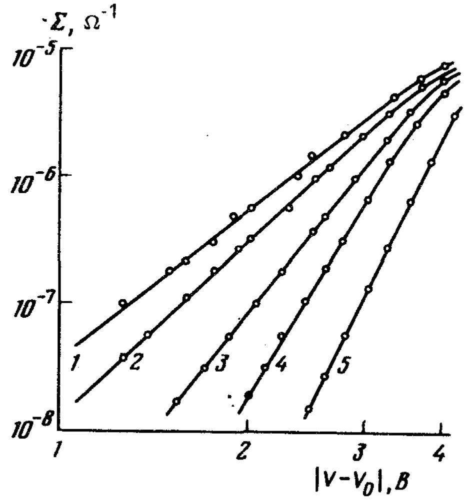

FIG. 3. Dependence of conductivity of p channel on voltage $|V - V_0|$ for different temperatures T, K. 1—104; 2—91; 3—78; 4—65; 5—48.5.

$(V_t - V_0)_p = 6$ V and $(V_t - V_0)_n = 1.9$ V obtained in this manner differ from the quantities corresponding to the pre-exponentials of the theoretical expressions (3) by a factor 0.7 and 3.5, respectively.

Substituting (4) into (1) and using the fact that in the situation being examined $\mathscr{E} \cong (2\pi/\epsilon_s) Q_n(\phi) \sim (V - V_0)$ (this dependence of $\mathscr{E}$ on V leads to the observed decrease on the pre-exponential Σ_0 with increasing degree of inversion, which is related to the decrease in the effective thickness of the inversion layer), we obtain the voltage dependence of the conductivity:

$$\Sigma(V) = \sqrt{2}\,\mu \frac{kT}{\Delta} C_0 (V_t - V_0) \left(\frac{V - V_0}{V_t - V_0} \right)^{\frac{2\Delta}{kT} - 1} . \tag{5}$$

The family of experimental dependences of the conductivity of the p channel on voltage, shown in Fig. 3 on a double logarithmic scale, confirms the validity of Eq. (5) on the subthreshold section of the characteristic. Analysis of the changes in slope of the straight lines with temperature give the quantity $2\Delta_p = 0.046$ eV, close to the value determined previously from the voltage dependence of the activation energy ϵ_a (Fig. 2).

It is now also possible to determine, from the pre-exponential of the conductivity, the magnitude of the effective mobility, which gives $\mu_p \approx 600$ cm^2 V^{-1} s^{-1} for holes and $\mu_n \approx 10^5$ or 2×10^4 cm^2 V^{-1} s^{-1} for electrons (depending on whether to use in this case the Bohr radius $a_n (m = 0.014 m_0) = 500$ Å or to express the corresponding surface density in terms of the experimentally determined quantity $(V_t - V_0) = 1.9$ V). Of course, this cannot be viewed as a method for determining the surface mobility. The completely reasonable values of μ obtained in this case indicate that the pre-exponential theoretical expressions (1) and (3) are completely reasonable.

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