The anomalous Hall factor in electron inversion channels in germanium

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Anomalously large values for the Hall factor, $r_H = 3.3$–1.8, have been detected in electron inversion channels in germanium. These values had not been observed earlier during studies of the migration of charge carriers at the surface of a semiconductor.

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The most complete information concerning the scattering mechanisms and the energy spectrum of charge carriers in near-surface inversion semiconductor channels may be obtained from temperature and density relationships for the Hall effect and conductivity.[1] One of the fundamental parameters in such studies is the Hall factor $r_H = \mu_H/\mu_{ns}$, where μ_H and μ_{ns} are the Hall and drift mobility of the charge carriers, respectively. The usually observed closeness of r_H to unity is an indication of the relatively weak relationship between the relaxation time τ and the energy of the charge carriers in the bands E. For currently well-studied inversion channels in silicon, the value for r_H actually differs from unity by more than 10% in the region of near-surface electron excess $\Gamma_n = 10^{11} - 10^{13}/\text{cm}^2$.[2,3]

In this work anomalously large values of the Hall factor r_H have been found for near-surface channels for the first time.

The samples were MDS transistors with Hall contacts prepared from p-type ger-

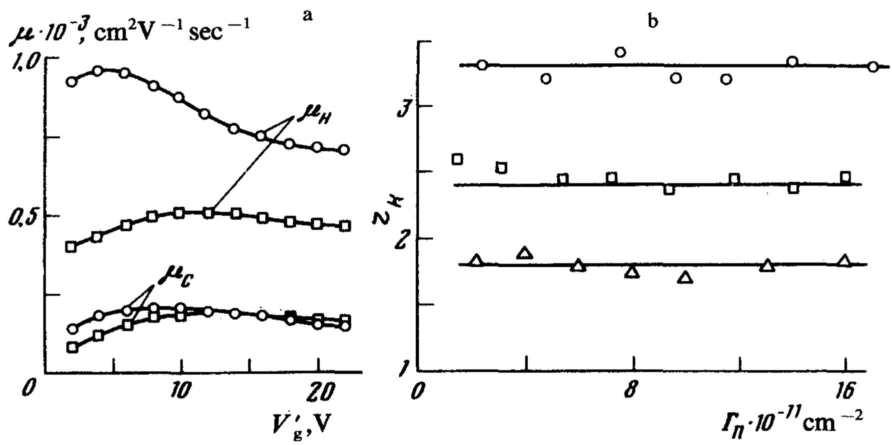

FIG. 1a—The relationships $\mu_H(V'_g)$ and $\mu_c(V'_g)$ for two temperatures (O—247 K and □—110 K); b—the function $r_H(\Gamma_n$ for three temperatures (O—247 K, □—155 K, and p—110 K).

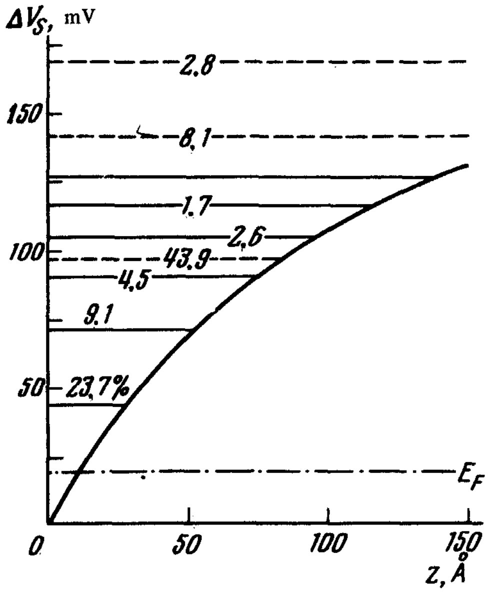

FIG. 2. The curve for the potential, the spectrum of quantized subbands, and their populations in an inversion channel at the (111) surface of germanium.

manium with an acceptor density $N_A = 8\times 10^{15}/\mathrm{cm}^3$, surface orientation (111), and channel dimensions $750\times 250\ \mu\mathrm{m}^2$. [4]

Figure 1a shows the Hall and effective (μ_c) mobilities as a function of the voltage difference $V_g' = V_g - V_t$ (V_g is the voltage at the gate, and V_t is the transistor threshold voltage) for two temperatures. It can be seen that μ_H greatly exceeds μ_c and falls with decreasing temperature.

As long as μ_c is determined by the total value of the induced charge, the true value of r_H is less than the ratio μ_H/μ_c because of the capture of a certain fraction of the induced charge in the surface states (SS). In the presence of surface capture r_H may be determined from the equation

$$r_H = C_n/(C_n + C_{ss} - C_{ss}^{(H)}),$$

which is valid under the condition that r_H varies with the bending of the bands Y_s more weakly than $C_n(Y_s)\sim\exp Y_s/2$. Here C_n and C_{ss} are the capacitances of the ON3 and SS respectively; $C_{ss}^{(H)}$ is some fictitious capacitance of the SS defined by the equation

$$C_{ss}^{(H)} = (C_n + C_{ss})(1 - q\Delta\Gamma_n^{(H)}/C_g\Delta V_g'),$$

where q is the absolute value of the electron charge, $\Delta\Gamma_n^{(H)}$ is the change in the Hall near-surface electron excess in the channel corresponding to a change in the voltage V_g' by a differentially small value $\Delta V_g'$; and C_d is the dielectric gap capacitance. The value of C_{ss} is determined by the same value of Y_s in terms of the infinitesimally small temperature shift of the relationships $G_k(V_g')$, where G_k is the channel conductivity.[3] The final value for r_H is obtained by the method of successive iterations. It is clear that $C_{ss} = C_{ss}^{(H)}$ for $r_H = 1$.

The relationships between r_H and Γ_n determined in this way for three temperatures are given in Fig. 1b. It is easily seen that the value for r_H substantially exceeds unity, is nearly independent of Γ_n, and decreases with decreasing temperature.

There is a unique work[5] in which, based on classical concepts, the possibility of the occurrence of r_H values which greatly exceed unity in the near-surface channels in the presence of a sufficient fraction of diffusivity from surface scattering is shown. However, the theory predicts an exponential increase in r_H with increasing band bending as well as with a decrease in the temperature according to a law of the form

$$r_H \sim (qV_{sc}/kT)^{-2} \exp (qV_{sc}/2kT)$$

(where $V_{sc} = kT/qY_s$), which is in contradiction with the experimental data given above.

We shall assume that the behavior found for r_H is a consequence of the quantization of the electron energy spectrum in the germanium inversion channel. The simultaneous numerical solution of the Poisson and Schroedinger equations has shown that quantization significantly alters the electron energy spectrum in the inversion channel over the entire range of temperatures and near-surface excesses Γ_n which have been studied. As an example Fig. 2 shows the shape of the potential, the spectrum of quantum subbands, and their population density for a (111) surface orientation with $N_A = 1.5\times 10^{16}/\text{cm}^3$, $T = 300$ K, $Y_s = 19.7$, and $\Gamma_n = 1.2\times 10^{12}/\text{cm}^2$. In this case two groups of subbands occur for two effective masses in the direction of quantization—$1.58m_0$ (solid lines) and $0.082m_0$ (dashed), where m_0 is the mass of a free electron.

In a similar situation we will have r_H values which exceed unity by more the higher the rate of increase in the relaxation time τ_{is} for the electrons in the subbands with energy E_i (i being the subband number) becomes. At the same time, since the population of the upper subbands decreases with decreasing temperature (for one and the same value of Γ_n), r_H should decrease with decreasing temperature. In the limiting case (at sufficiently low temperatures) when only one subband—the fundamental one—is filled, the Hall factor is close to unity and is independent of the temperature for all known scattering mechanisms.[6]

In this connection it should be noted that a correct description of the migration of charge carriers in the inversion channels of germanium-type semiconductors at temperatures of 77–300 K requires the development of a surface scattering theory taking into account the population of several quantum subbands and not one, as is usually assumed in practice in all theoretical work (see, e.g., Ref. 7).

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