Charge-carrier transport anisotropy in the inversion channels on high-index silicon surfaces

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Scattering anisotropy of holes which is attributable to one-dimensional scatterers, was observed in the inversion quantum channels on high-index silicon surfaces. It is shown that the surface microscopic irregularities, which are randomly distributed in the perpendicular direction to the disorientation line of the surface, can serve as these scatterers.

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The inversion channels on the high-index surfaces of silicon have been studied intensively since the discovery of superlattice effects in these channels.[1,2] In this paper we report an effect that is typical of such channels–hole transport anisotropy caused by one-dimensional scatterers on the vicinal surfaces of silicon.

The samples studied by us were p-channel MOS transistors, which were fabricated by using standard technology on (21, 2, 2) silicon surfaces [these surfaces are inclined at an angle $\theta = 7°40'$ to the (100) surface around the $[01\bar{1}]$ direction]. The donor density in the substrate was 2×10^{14} cm^{-3}, the thickness of the field insulator (SiO_2) was 1300 Å, and the channel dimensions were 1200×400 μm^2.

The dependences of the inversion-channel conductance G_k and of the hole drift mobility μ_p in the channel on their surface excess Γ_p are shown in Figs. 1a and 1b for two current directions–parallel to the $[01\bar{1}]$ direction ($G_k^{\parallel}$ and $\mu_p^{\parallel}$) and perpendicular to it ($G_k^{\perp}$ and $\mu_p^{\perp}$)–for temperatures of 4.2 and 78 K. The conductance and the mobility coincide for both directions for $\Gamma_p < 5\times10^{11}$ cm^{-2}; at higher Γ_p values we have $G_k^{\parallel} > G_k^{\perp}$ and $\mu_p^{\parallel} > \mu_p^{\perp}$, and the difference between these values increases with increasing Γ_p. The anisotropy is almost the same for both temperatures. This effect occurs only on the vicinal surfaces of silicon, since there is no mobility anisotropy on its (100) and (111) singular surfaces.[3]

The observed effect cannot be related to a change of the dispersion law $E(k)$ of holes in the channel, since the Fermi level E_F is situated well below a possible "minigap" in their energy spectrum[4] in the entire interval of experimentally attainable Γ_p values. This forces us to assume that there is an additional scattering mechanism, in the perpendicular direction to $[01\bar{1}]$, which is characterized by a certain relaxation time τ_p^{add}. If this scattering mechanism is additive with the existing mechanism, then $\tau_p^{\text{add}} = 1/\tau_p^{\perp} - 1/\tau_p^{\parallel}$; figure 2 shows the dependence of τ_p^{add} on Γ_p obtained from this, which corresponded to the $\tau_p^{\text{add}} \sim \Gamma_p^{-n}$ law at 4.2 K, where $n = 1.6 \pm 0.1$. At 78 K the slope of this dependence slightly decreases with decreasing Γ_p.

A large decrease of τ_p^{add} with an increase in Γ_p (and, consequently, a decrease in

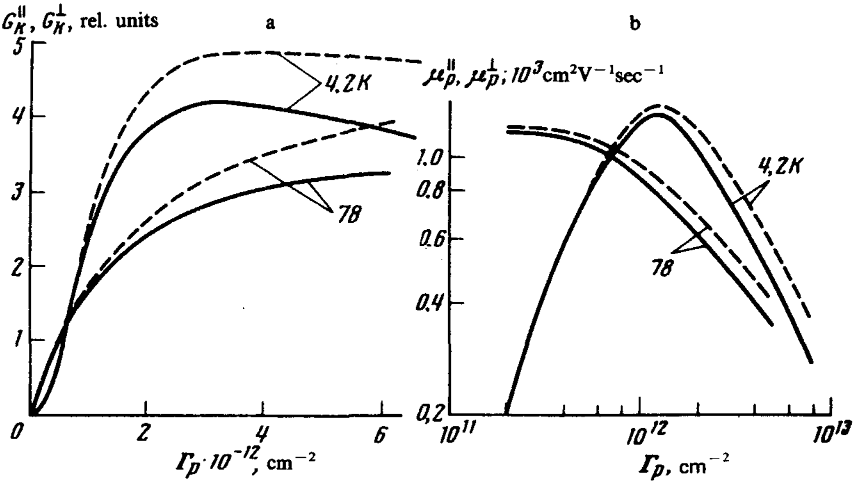

FIG. 1. (a) $G_k(\Gamma_p)$ dependence and (b) $\mu_p(\Gamma_p)$ dependence for two current directions of the hole-inversion channel (the dashed lines represent $G_k^{\|}$ and $\mu_p^{\|}$ and the solid lines denote $G_k^{\perp}$ and $\mu_p^{\perp}$).

the channel thickness $d \sim \Gamma_p^{-1/3}$) indicates that τ_p^{add} is determined by the scattering by microirregularities of the interface between the vicinal silicon surface and the silicon oxide. However, this anisotropy can occur only if these irregularities are randomly arranged only in the perpendicular direction to $[01\bar{1}]$. The scattering of charge carriers in a thin quantum film or in an inversion channel with a rough surface was examined[5,6] in the absence of particle scattering by potential fields within the film (channel) and when the only cause of scattering was a surface irregularity specified by a two-

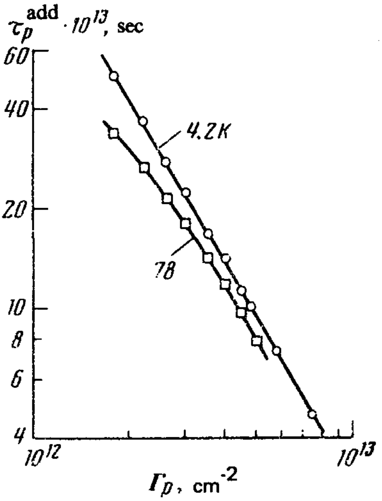

FIG. 2. Dependence of the relaxation time τ_p^{add} of the additional scattering mechanism on the surface excess of holes Γ_p.

dimensional system of irregularities with certain characteristic dimensions. It was shown that if the carriers fill only the ground subband of quantization, then their relaxation time will depend on the thickness d of the film or channel as $\tau \sim d^{-6}$. In our case the condition for filling of only the ground subband of quantization is strictly satisfied at 4.2 K in the entire range of investigated Γ_p values. Given that the irregularities in our case are randomized only in one direction, the results of Refs. 5 and 6 lead to the $\tau \sim d^{-5}$ dependence[1], or, otherwise, to $\tau \sim \Gamma^{-5/3}$. An estimate of the scattering by perturbations of the potential U_0, which are caused by one-dimensional irregularities, also gives a similar dependence. Assuming that $U_0 \sim E_s H$, where $E_s \sim \Gamma_p$ is the intensity of the electric field at the semiconductor surface and H is the characteristic height of the irregularities, we obtain in the Born approximation (for $E_F > U_0$) a scattering cross section $\sigma \sim U_0^2/E_F \sim \Gamma_p$, from which $\tau \sim \Gamma_p^{-3/2}$.

Since the experimentally obtained $\tau_p^{\mathrm{add}}(\Gamma_p)$, dependence is close to the theoretical dependence, we can assert that the observed anisotropy is attributable to a one-dimensional system of irregularities on the high-index silicon surfaces, which are randomly distributed only in the "slope" direction of the surface.

The described mechanism of hole-transport anisotropy should also lead to an electron-transport anisotropy. According to the data of Ref. 1 and according to our data, a conductance anisotropy actually exists in the electron inversion channels on these surfaces; however, in this case it may be caused by intervalley scattering,[7] which currently hinders an unambiguous investigation of the observed effect in these channels.

It is known from slow-electron diffraction data that a one-dimensional periodic system of steps with height $H = a/2$, where $a = 5.43$ Å is the silicon lattice constant, and of terraces with a length $L = H/\sin\theta$, exists on atomically clean, vicinal, silicon surfaces.[8] If these steps are retained at the Si-SiO_2 interface, we can assume that a disturbance of the periodicity in the distribution of these steps will also be evident in the role of the one-dimensional system of scattering irregularities.

In conclusion, we should note that these systems provide an opportunity for a direct investigation of the scattering by surface irregularities, since the "background"—primarily Coulomb—scattering is automatically taken into account in determining τ_p^{add}.

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[1] A. V. Chaplik brought this fact to our attention.

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[1] T. Cole, A. A. Laknani, and P. J. Stils, Phys. Rev. Lett. **38**, 722 (1977).
[2] Proc. of the 14th International Conference on Semiconductor Physics, Edinburg, 1978.
[3] O. Colman, R. Bate, and J. P. Mize, J. Appl. Phys. **39**, 1923 (1968).
[4] V. P. Petrov, Fiz. Tekh. Poluprovodn. **12**, 380 (1978) [Sov. Phys. Semicond. **12**, 219 (1978)].
[5] A. V. Chaplik and M. V. Entin, Zh. Eksp. Teor. Fiz. **55**, 990 (1968) [Sov. Phys. JETP **28**, 514 (1969)].
[6] M. V. Entin, Fiz. Tverd. Tela **11**, 958 (1969) [Sov. Phys. Solid State **11**, 781 (1969-70)].
[7] T. Ando, Proc. 3rd International Conference on Electronic Properties of Two-Dimensional Systems, Japan, 1979, p. 607.
[8] B. Z. Olshanetsky and A. A. Shklyaev, Surf. Sci. **82**, 445 (1979).

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