Two-dimensional hole gas in a one-dimensional superlattice

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A minigap has been detected in the energy spectrum of two-dimensional holes in inversion channels on high-index silicon surfaces. This discovery furnishes the first direct experimental evidence for the existence of a one-dimensional superlattice on such surfaces.

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In 1977, Cole *et al.*[1] observed some anomalous features in the electron transport in inversion channels on high-index surfaces of silicon. These features were a consequence of a minigap in the spectrum of two-dimensional (2D) electrons. Cole *et al.* suggested that the effect was caused by the existence of a one-dimensional superlattice of an unknown nature on such surfaces. At the same time, and working independently, Petrov[2] showed that a new translational period on semiconductor surfaces with high Miller indices should lead to the appearance of a superlattice with a period dependent on the orientation of the surface (an "orientational" superlattice). Initially, however, two facts in Ref. 1 seemed to strongly contradict the idea of a one-dimensional superlattice: First, there was a sharp disagreement between the theoretical and experimental periodicities; second, no minigap was observed in the *p*-type channels under the same conditions. Sham *et al.*[3] consequently proposed an alternative model of valley–valley splitting, which correctly predicts the position of the minigap in $\mathbf{k}_{\parallel}$ space. All the experiments, which have been reported to date, have dealt with the minigap in *n*-type channels (see the review article by Volkov *et al.*[4]), and all the results (see Ref. 5, among the recent papers) have been interpreted in the model of valley–valley splitting, although Volkov and Sandomirskiĭ[6] have shown that the contradictions which arose in Ref. 1 were illusory, simply a consequence of an incorrect construction of the 2D Brillouin zones for electrons. It thus turned out that the model of valley–valley splitting and the one-dimensional superlattice lead to identical predictions for *n*-type channels. Accordingly, it has remained an open question whether there is a one-dimensional superlattice on high-index silicon surfaces which can lead to observable effects. Only the observation of a minigap in *p*-type channels could resolve this question.

In this letter we are reporting the first observation of a minigap which is definitely caused by a one-dimensional superlattice, in the energy spectrum of 2D holes in inversion channels on high-index silicon surfaces.

The experimental samples were *p*-channel metal-oxide-semiconductor field-effect transistors, fabricated by the standard technique on silicon surfaces tilted at angles $\theta = 2.2^\circ$, 2.5°, or 3° from the (111) surface toward the (110) surface around the

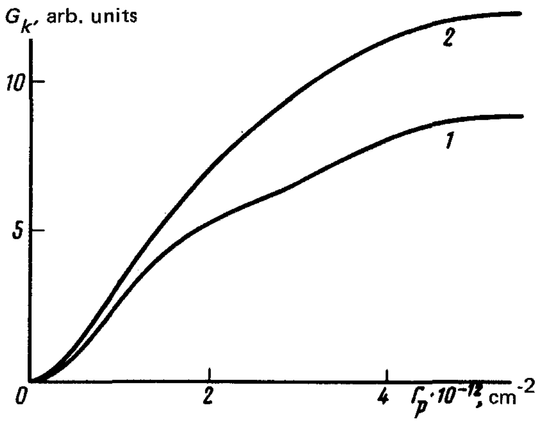

FIG. 1. The dependence of $G_k(\Gamma_p)$ for two hole-current directions. $1-G_k^{\perp}(\Gamma_p)$; $2-G_k^{\parallel}(\Gamma_p)$.

$[01\bar{1}]$ direction. The thickness of the dielectric field-effect region was 1100–1300 Å; the hole mobility at the maximum at 4.2 K was 1000–1300 cm^2/(V · s). Figure 1 shows the conductivity of the inversion channel as a function of the hole excess near the surface, Γ_p, at 4.2 K for the angle $\theta = 2.2°$ and for two current directions: parallel to the $[01\bar{1}]$ direction ($G_k^{\parallel}$) and perpendicular to this direction ($G_k^{\perp}$). We see that the conductivity is anisotropic, with $G_k^{\parallel} > G_k^{\perp}$, and the difference between these conductivities increases with increasing Γ_p. An anisotropy of this sort could, in principle, be caused by one-dimensional scattering centers; we shall not discuss it here. Furthermore, we can clearly see on the $G_k^{\perp}(\Gamma_p)$ curve a slight dip near $\Gamma_p = 2 \times 10^{12}$ cm^{-2}. On the $G_k^{\parallel}(\Gamma_p)$ curve, on the other hand, there are no such features. Curve 2 in Fig. 2 shows the Γ_p dependence of $dG_k^{\perp}/d\Gamma_p$; the position of the anomalous feature on this curve can be determined considerably more accurately. If we attribute this feature to a minigap, which arises because of a one-dimensional superlattice,[2] we can conclude that in $\mathbf{k}_{||}$ space it

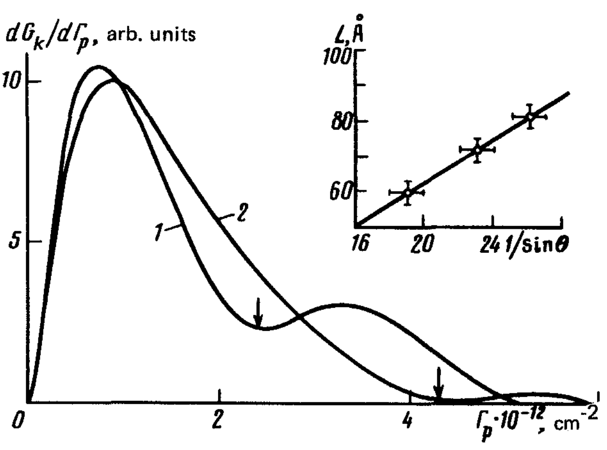

FIG. 2. The Γ_p dependence of $dG_k^{\perp}/d\Gamma_p$ for two surface tilts: $1-\theta = 2.2°$; $2-\theta = 3°$. The arrows show the anomalous features. The inset shows the dependence of the superlattice period on ($\sin\theta^{-1}$) [Points–experimental; line–the theoretical behavior $L_T = a/(\sqrt{3}\sin\theta)$].

should be determined unambiguously by the period L_T (this period is properly identified as the period of the superlattice also) in the direction of the surface "jump." In our case, we have $L_T = a/(\sqrt{3}\sin\theta)$, where $a = 5.43$ Å is the silicon lattice constant. For the (111) surface, the condition that only the ground quantization subband be occupied holds rigorously in p-type channels at 4.2 K at concentrations up to 5.5×10^{12} cm^{-2} (Ref. 8). Accordingly, for the threshold values k_F^Δ and Γ_p^Δ corresponding to the beginning of the "anomalous features" on the curves of $G_k^\perp$ and $dG_k^\perp/d\Gamma_p$ vs Γ_p, we find $k_F^\Delta = \pi/L = (\pi\sqrt{3}/a)\sin\theta$ and $\Gamma_p^\Delta = (k_F^\Delta)^2/2 = \pi/2L^2$, where L is the period of the one-dimensional superlattice. Using these relations, we can determine L from the experimental value of Γ_p^Δ and compare it with L_T. For $\theta = 2.2°$ we have $L_T = 82$ Å, and this period is essentially equal to the experimental superlattice period, $L_e = 80$–85 Å. The clearest evidence for the existence of a superlattice, however, is the shift of the anomalous feature as a function of the angle θ in accordance with $\Gamma_p^\Delta \sim \sin^2\theta$. This shift is illustrated by curve 2 in Fig. 2 as we switch to an angle of 3°. The inset in this figure shows the superlattice periods found from the experimental data for all three angles studied. We see that the measured values conform well to the straight line $L_T = a/(\sqrt{3}\sin\theta)$. This behavior of the anomalous feature in the hole conductivity gives us a firm basis for asserting that this feature is a consequence of a minigap caused by a one-dimensional superlattice whose period is equal to the period of the vicinal surface of silicon.

From the shape of the feature we can estimate the value of Δ for the minigap (admittedly, this estimate is not very accurate, because of the pronounced blurring resulting from the scattering of holes): $3\ \text{meV} < \Delta < 6\ \text{meV}$. The value of Δ is thus comparable to the size of the minigap in the spectrum of two-dimensional electrons for the same level of the surface carrier excess. Consequently, the effect of the one-dimensional superlattice must definitely be taken into account in analyzing data on the minigap in the spectrum of 2D electrons.

In conclusion, we should point out that a one-dimensional superlattice may be caused not only by the appearance of a new translational symmetry on a high-index silicon surface but also by the one-dimensional periodic structure which was recently discovered by Ol'shanetskiĭ and Rzhanov.[9] Further experiments will be necessary to determine the relative importance of these two factors.

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