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ELECTRON LOCALIZATION IN Sb-DOPED Si/SiGe SUPERLATTICES*

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Millikelvin studies of in-plane magnetoconductance in short period Si/Ge:Sb superlattices have been carried out in order to examine the effect of anisotropy on quantum localization. The field-induced metal-to-insulator transition has been observed, indicating the existence of extended states. This suggests that despite anisotropy as large as $D_{\|}/D_{\perp} \approx 10^3$ the system behaves as 3D in respect of localization by disorder.

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Heavily doped n-Si/SiGe short period superlattices [1] constitute an important variant of bulk [2, 3] or δ-doped n-Si [4], appropriate to examine the influence of the anisotropy [5–7], open Fermi surface [8, 9], and valley degeneracy [3] upon electron transport phenomena at the localization boundary. In particular, since all states are localised in 2D disordered systems whereas a metal–insulator transition (MIT) occurs in the 3D case, a question arises how behave the superlattice states in respect of electron localization.

We have carried out an experimental study of in-plane conductivity down to 50 mK and up to 8.5 T of three homogeneously Sb-doped Si/SiGe superlattices (SL), all with 150 Si wells and $\mathrm{Si}_{0.55}\mathrm{Ge}_{0.45}$ barriers, each of the widths $d_{\mathrm{w}} = 25$ Å and $d_{\mathrm{b}} = 14$ Å, respectively. The samples were grown by MBE on (001) Si substrates with a SiGe graded buffer layer. The structural properties were determined by high resolution X-ray diffraction (HR-XRD), whereas the concentration and homogeneity of the doping profile was checked by secondary ion mass spectroscopy (SIMS). Hall effect measurements between 10 and 300 K show only

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a small change of the Hall constant with temperature, and lead to the electron density in the wells in agreement with the SIMS data. The impurity concentrations in our samples ($N_{\mathrm{D}} = 2.5, 4.5$, and 6×10^{18} cm^{-3}) cover the range around the critical concentration of 3×10^{18} cm^{-3} for the MIT in bulk Si:Sb [3].

In strain symmetrized Si/SiGe SLs, the biaxially strained Si layers form the wells, in which the sixfold valley degeneracy of the Si conduction band is removed, and for the two ground state valleys the in-plane effective mass $m_{\mathrm{t}} = 0.19m_0$ is nearly factor of 5 smaller than the longitudinal mass $m_{\mathrm{l}} = 0.92m_0$. The vertical transport mobility is reduced even further by a weak coupling through the $\mathrm{Si_{0.55}Ge_{0.45}}$ barriers of a height $V_{\mathrm{b}} \approx 300$ meV [1], resulting in a rather large anisotropy of electron transport. According to self-consistent subband calculations which neglect disorder only the ground state subband is occupied. For $N_{\mathrm{D}} = 4.5 \times 10^{18}$ cm^{-3}, it is located at $E_0 = 35$ meV above the edge of the conduction band in the Si wells. The width $w = 2$ meV of the associated miniband is smaller than the Fermi energy $E_{\mathrm{F}} = 9.9$ meV. Hence, we deal with the open Fermi surface in the reciprocal space. For the above parameters tunnelling probability [10] $T_{\mathrm{t}} = [1 + (\gamma/k + k/\gamma)^2 \sinh^2(\gamma d_{\mathrm{b}})/4]^{-1}$, where $k = (2m_{\mathrm{l}}E_i)^{1/2}/\hbar$, $\gamma = [2m_{\mathrm{l}}(V_{\mathrm{b}} - E_i)]^{1/2}/\hbar$, and $E_i = E_0 + E_{\mathrm{F}}$, is evaluated to be $T_{\mathrm{t}} = 2.3 \times 10^{-3}$. This gives anisotropy of the diffusion constant as large as $D_{\parallel}/D_{\perp} \approx (T_{\mathrm{t}}m_{\mathrm{t}}/m_{\mathrm{l}})^{-1} = 2.1 \times 10^3$. It is worth noting that the in-plane electron mobility $\mu = 165$ cm^2/(Vs) at 10 K implies that the momentum relaxation time, $\tau = m_{\mathrm{t}}\mu/e = 18$ fs, is of the same order as the electron flight time between the interfaces, $\tau_{\mathrm{f}} = d_{\mathrm{w}}(m_{\mathrm{l}}/2E_i)^{1/2} \approx 19$ fs. Thus, in contrast to standard anisotropic systems, the large anisotropy in question sets in over the length scale comparable to the mean free path. Besides, our SLs are in the limit of strong disorder as scattering broadening of the density of states $\hbar/\tau = 37$ meV is much greater than the miniband width $w = 2$ meV.

We find that in all three samples the magnetoresistance results from a competition between the effect of the magnetic field on quantum interference and the effect of the spin-splitting on the electron–electron interaction [11, 12]. This is

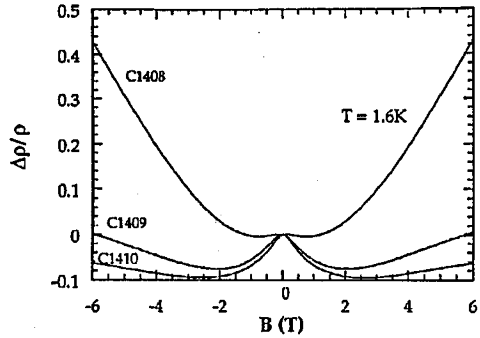

Fig. 1. Magnetoresistance in the field perpendicular to the superlattice plane for three superlattices with the Sb donor concentrations 2.5 (top), 4.5 (middle), and 6×10^{18} cm^{-3} (bottom trace).

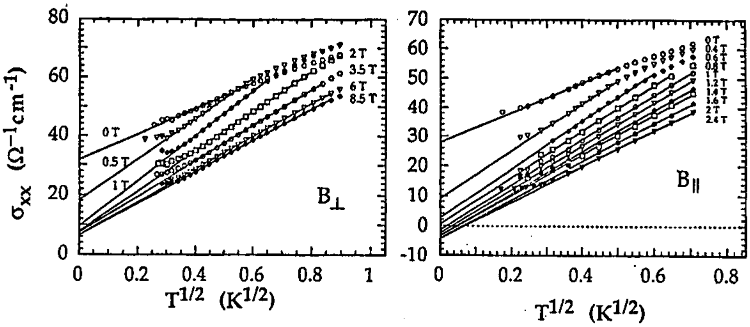

Fig. 2. In-plane conductivity vs. square root of temperature for sample with 4.5×10^{18} Sb donors per cm^3 at various magnetic fields perpendicular to the current direction but either perpendicular (left panel) or parallel (right panel) to the superlattice plane. Solid lines are guides for the eye.

shown in Fig. 1, where both the negative component due to the former effect as well as the positive contribution due to the latter are clearly seen. Moreover, our experiments in the tilted fields reveal that the negative component is anisotropic while the positive not, as expected. Since in the studied system $\hbar/\tau \gg w$, the existing theories [8, 9] of the negative magnetoresistance in superlattices do not apply. At the same time, while the data are not consistent with the 2D formulae [11], we obtain a satisfactory description of the negative term on the basis of a standard 3D theory with an anisotropic diffusion tensor [5, 11]. This gives for $N_D = 4.5 \times 10^{18}$ cm^{-3} at 4.2 K, $D_\parallel/D_\perp \approx 10^2$, a value by a factor of 20 smaller than that estimated above. We take this discrepancy as the indication that random fluctuations of the impurity potential diminish locally the barrier height, and thus enhance considerably an effective tunnelling probability. At the same time $D_\parallel/D_\perp \gg m_l/m_t$, proving that the individual wells are much too narrow to be treated as a 3D system. The latter is consistent with a recent study of a single δ-doped Si:Sb layers, in which a dimensional crossover from 2D to 3D was observed to take place for $d_w \approx 200$ Å at 2 K [4].

Our low-temperature data demonstrate that the MIT occurs in the studied system. This is documented by the insulating and metallic behaviour of the samples with the lowest and the highest donor concentration, respectively, as well as by the presence of the magnetic-field-induced MIT in the sample with 4.5×10^{18} Sb donors per cm^{-3}. As shown in Fig. 2, the transition occurs for the in-plane magnetic field of about 1 T, in which the conductivity σ extrapolated to zero temperature T tends to vanish. At the same time, a characteristic of 3D systems [2, 3, 11] square root dependence of σ on T is visible over a large temperature range. Careful measurements below 100 mK suggest, however, the presence of a shallow minimum in the σ vs. T dependence. A similar anomaly was previously noted in bulk Si:Sb and assigned, among other possibilities, to spontaneous lifting of valley degeneracy from 6 to 2 [3]. Our results for the strained SL seem to invalidate this conjecture, though we cannot rule out thermal decoupling as a reason for the anomaly we observe.

In conclusion, the presence of the MIT and thus of extended states together with the square root dependence of σ on T near the MIT indicate that the studied SLs are three-dimensional with respect to localization. This provides experimental support for scaling arguments [6], which also suggest that zero-temperature localization in anisotropic systems is governed by a rescaled diffusion constant $D = (D_{\|}^{2}D_{\perp})^{1/3}$. We suggest that at *non-zero temperatures* a SL remains 3D as long as the electron can move in the vertical direction before its phase coherence is destroyed. This occurs if an electron escape time from one well to another [13] $\tau_{\mathrm{esc}} = \tau_{\mathrm{f}}/T_{\mathrm{t}}$ is shorter than both the phase breaking $\tau_{\varphi}(T)$ and the thermal coherence time $\hbar/k_{\mathrm{B}}T$. This condition is fulfilled in the studied SLs below 1 K.

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