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Effective mass and quantum lifetime in a $Si/Si_{0.87}Ge_{0.13}/Si$ two-dimensional hole gas

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Measurements of Shubnikov de Haas oscillations in the temperature range 0.3–2 K have been used to determine an effective mass of 0.23 m_0 in a $Si/Si_{0.87}Ge_{0.13}/Si$ two-dimensional hole gas. This value is in agreement with theoretical predictions and with that obtained from cyclotron resonance measurements. The ratio of the transport time to the quantum lifetime is found to be 0.8. It is concluded that the 4 K hole mobility of 11 000 $cm^2\,V^{-1}\,s^{-1}$ at a carrier sheet density of 2.2×10^{11} cm^{-2} is limited by interface roughness and short-range interface charge scattering.

One of the most important consequences of the presence of strain and confinement in SiGe/Si heterostructures is the predicted reduction of the hole effective mass caused by the lifting of the degeneracy of the light and heavy hole bands. For a completely decoupled system, which occurs for high strain and low carrier densities the heavy hole mass is expected to fall to values of approximately $0.2m_0$.[1] Shubnikov de Haas (SdH) and cyclotron resonance measurements[2–4] have recently been used to determine the effective mass of carriers in the $Si/Si_{1-x}Ge_x/Si$ two-dimensional hole gas (2DHG). For $x=0.15$ and a carrier sheet density of the order of 1×10^{12} cm^{-2} (Refs. 3 and 4) there is agreement that $m^*\approx0.4m_0$. This value is considerably larger than the theoretical value for the decoupled band near $k=0$, probably due to its large nonparabolicity at relatively high carrier densities. Lower mass values of $0.3m_0$ were found in the first report of a p-type modulation-doped Si/SiGe heterostructure by People *et al.*,[2] who studied a structure with $x=0.2$ and a carrier sheet density of 4×10^{11} cm^{-2}, and in the recent report of cyclotron resonance[4] on a quantum well with $x=0.37$. In the present work we show that effective mass values can be observed as low as $0.23m_0$, in structures with $x=0.13$, when careful studies of SdH oscillations are made on low density and high mobility structures. We also demonstrate that the effective mass so determined is independent of magnetic field and temperature, in contrast to the behavior seen at higher carrier densities in silicon inversion layers,[5,6] and obtain information on the carrier scattering mechanisms. This has been made possible by the achievement of record hole mobilities in $Si/Si_{1-x}Ge_x/Si$ structures.[7]

The magnetic field dependence of the longitudinal resistance (ρ_{xx}) has been measured in a sample of concentration $x=0.13$, and 4 K carrier mobility of 11 000 $cm^2\,V^{-1}\,s^{-1}$. Figure 1 shows ρ_{xx} plotted against B for a range of temperatures. A carrier sheet density of 2.2×10^{11} cm^{-2} is obtained from the period of ρ_{xx} vs $1/B$ in low fields, in agreement with that obtained from Hall measurements. From our previous work[8] we expect single subband occupancy at this sheet density and the present SdH data are consistent with this view. The oscillatory component of the magnetoresistance has been obtained by removing the background contribution which is quadratic in B and which is believed to be associated with hole–hole interactions.[9] Fast Fourier transform techniques have then been used to eliminate any harmonics, leaving a fundamental component which is assumed to be given by[10,11]

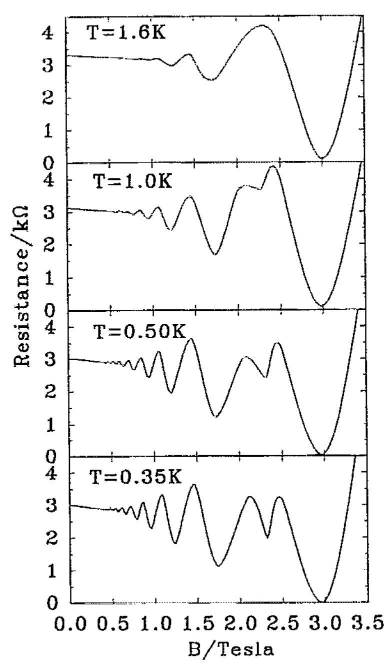

FIG. 1. Longitudinal resistance ρ_{xx} plotted vs magnetic field B for a range of temperatures.

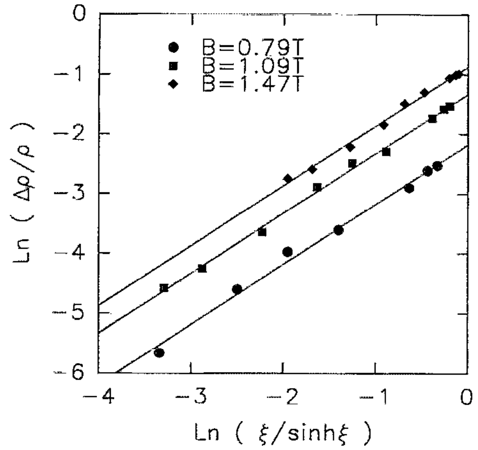

FIG. 2. $\ln(\Delta\rho_m/\rho_0)$ plotted vs $\ln(\xi/\sinh\xi)$ for various magnetic fields.

$$\frac{\Delta\rho_{xx}}{\rho_0}=R_s V\frac{\xi}{\sinh\xi}\exp\left(\frac{-\pi}{\omega_c\tau_q}\right)\cos\left(2\pi\frac{E_f}{\hbar\omega_c}+\phi\right) \tag{1}$$

for low enough fields, where ρ_0 is the resistance at zero B, τ_q is the quantum lifetime, $\xi=2\pi^2kT/\hbar\omega_c$, and $\omega_c=eB/m^*$. The prefactor R_s is associated with Zeeman splitting[11] while V is usually set equal to 4.[10] We will assume that R_s and V are independent of magnetic field and temperature in which case they are not involved in the following analysis. This procedure is justified below. Figure 2 shows plots of $\ln(\Delta\rho_m/\rho_0)$ vs $\ln(\xi/\sinh\xi)$ in the temperature range 0.3–2 K, for various values of B, where $\Delta\rho_m$ is the peak value of $\Delta\rho_{xx}$. Using m^* as an adjustable parameter, a gradient of unity is obtained in each case, for a field independent value of $m^*=(0.23\pm0.02)m_0$. In Fig. 3 Dingle plots of $\ln[(\Delta\rho_m/\rho_0)(\sinh\xi/\xi)]$ vs $1/B$ with $m^*=0.23m_0$ give a universal straight line for various temperatures, confirming that the experimentally determined m^* is also independent of temperature. Noting that the gradient of the line is $-\pi\alpha/\mu$ where α is the ratio τ/τ_q of the transport time τ to the quantum lifetime τ_q and μ is the Hall mobility, we obtain $\alpha=0.8$.

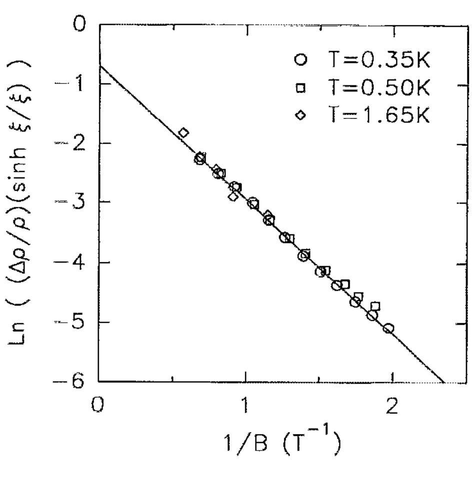

FIG. 3. Dingle plots of $\ln[(\Delta\rho_m\sinh\xi)/(\rho_0\xi)]$ vs $1/B$ for various temperatures.

This value should be compared with Gold's predictions[12] of $\alpha=1$ for scattering by interface charge and $\alpha=0.67$ for short-range interface roughness scattering. Therefore, it is consistent with our recent work in which we have concluded that both mechanisms are present for comparable mobilities and sheet densities.[7] The presence of alloy scattering could also lead to similar values of α, but recent calculations by Emeleus *et al.*[8] and Gold[12] of screened alloy scattering suggest that it is comparatively small for structures of the present composition and mobility.

In carrying out this analysis we have assumed that V and R_s are independent of magnetic field and temperature. The good straight lines in Figs. 2 and 3 provide strong evidence that these assumptions are justified. V is commonly assumed to be a constant,[10] but Bocklemann and co-workers[13] have derived an expression for V which is a function of α, B, and T. The incorporation of such a term into Eq. (1) can be shown to have a negligible effect because α is close to unity. Since the spin splitting factor $R_s=\cos(\pi g m^*/2m_0)$,[11] the behaviors shown in Figs. 2 and 3 suggest that exchange enhancement of the splitting factor g, which could give rise to a temperature and magnetic field dependence of g, is small in the present case.[14] It should be noted, however, that the spin splitting is large in this p-type system, since the dominant resistivity minima at approximately 1.8 T correspond to the occupancy of an odd number of spin split Landau levels (see Fig. 1). The weaker, higher field, minima appearing at low temperatures and at a field of approximately 2.3 T are at an even occupancy, corresponding to the Fermi level lying between the spin up and spin down states of adjacent Landau levels. This implies that the spin splitting $g^*\mu_B B>0.5\hbar\omega_c$, and thus using our measured mass value of $0.23m_0$ we find that $g^*>4.3$. This is consistent with the conclusions of Fang *et al.*,[15] and of Glaser *et al.*[16] who found from optically detected magnetic resonance a g factor of 4.5. Finally, we have also ignored screening effects which lead to a temperature dependent τ_q (Refs. 12, 17, and 18) and weak-localization and hole–hole interaction effects[18] in determining ρ_0 and μ, on the basis that these corrections are small in the temperature range considered and for the present mobilities.

In conclusion, we obtain $m^*=(0.23\pm0.02)m_0$ for $x=0.13$ independent of temperature and magnetic field, in good agreement with theoretical predictions[19,20] which range from 0.2 to $0.25m_0$, and with a value of $0.26m_0$ obtained from cyclotron resonance measurements on similar structures.[21] The ratio of the transport time to the quantum lifetime has been found to be 0.8, which suggests that the mobility is limited by both interface charge and short-range interface roughness scattering, in agreement with our previous work.[7]

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