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# STUDY OF TWO-DIMENSIONAL HOLE GAS AT Si/SiGe/Si INVERTED INTERFACE

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We have studied the transport properties of a two-dimensional hole gas (2DHG) at the inverted interface of a strained $Si_{0.8}Ge_{0.2}$ quantum well. By application of a bias voltage to a Schottky gate on top of this inverted heterostructure the 2DHG density $n_s$ can be controlled, in the range of $(1.5-5.2)\times 10^{11}$ cm$^{-2}$. At a temperature $T = 0.33$ K, the Hall mobility is 4650 cm$^2$ V$^{-1}$ s$^{-1}$ at the maximum carrier density. For lower sheet densities ($n_s < 2\times 10^{11}$ cm$^{-2}$) the system undergoes a transition from a weak to strongly localised phase of significantly reduced mobility. From low temperature Shubnikov–de Haas oscillation measurements we have extracted the hole effective masses $m^* = (0.25 \rightarrow 0.28)m_0$ and the ratio of transport to quantum lifetimes $\alpha = (0.92 \rightarrow 0.85)$ for the corresponding carrier density change of $n_s = (5.2 \rightarrow 2.5)\times 10^{11}$ cm$^{-2}$. These results can be explained in terms of the abnormal movement of the hole wave function towards the interface with decreasing $n_s$, short range interface charge and interface roughness scattering.

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The strained $Si/Si_{1-x}Ge_x/Si$ quantum well can be grown pseudomorphically on Si provided the alloy layer thickness is less than the critical value. If the grown Si layer is B-doped at some distance before or after the alloy layer, this remote doping induces the formation of a two-dimensional hole gas (2DHG) near to the inverted (SiGe on Si) or normal (Si on SiGe) heterointerface of the $Si/Si_{1-x}Ge_x/Si$ quantum well, respectively. The former arrangement is the so-called "inverted" modulation doped structure (MDS) but the latter is well known as the "normal" MDS. The low temperature transport study of these structures is of great interest for physics and for understanding of mobility-limiting mechanisms which are relevant to device applications [1]. When compared with "normal" SiGe MDS, less work has been reported on the transport properties in "inverted" structures [2, 3], which are believed to have a smoother active interface but which can also be affected by B-segregation.

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Gating the MDS allows one to change systematically the carrier sheet density in a single device. It has been used as an important tool for investigating the transport properties of $n$-type [4] and $p$-type [5] "normal" MDS. Here we report the low temperature transport studies of a top-gated $p$-$Si_{0.8}Ge_{0.2}$ inverted MDS. The heterostructure was grown by a solid source MBE (VG Semicon-90) on a low doped ($n$-type, 1–2 Ω cm) Si(100) substrate. The growth was started by a 200 nm Si buffer layer, followed by a 30 nm Si layer B doped at $2 \times 10^{18}$ cm$^{-3}$, then a 20 nm Si spacer. To minimise the B-segregation into the spacer and SiGe channel, we used a 40 minute growth interruption after 5 nm of the Si spacer was grown. The conduction channel grown after the Si spacer consisted of a 20 nm strained $Si_{0.8}Ge_{0.2}$ layer and was capped by a 150 nm Si layer. Contacts to the 2DHG were made by sputtering Al, and annealing in ambient nitrogen. Standard Van der Pauw and Hall bar devices (with a channel length of 3300 $\mu$m, a channel width of 315 $\mu$m and voltage probes 1260 $\mu$m apart) were made by photolithography techniques and wet etching. On the cap surface above the SiGe channel, a Schottky gate was formed using sputtered Ti/Al.

At temperatures $T = 4.2 \div 0.33$ K the small gate-channel leakage current (20 pA) allowed magnetotransport measurements with a 20 nA 17 Hz ac channel current using the lock-in method. By applying an appropriate voltage to the metal top-gate with respect to the conduction channel at 4.2 K the 2DHG sheet density could be increased from $1.5 \times 10^{11}$ cm$^{-2}$ up to $5.2 \times 10^{11}$ cm$^{-2}$ while the corresponding Hall mobility increased from $\approx 700$ cm$^2$ V$^{-1}$ s$^{-1}$ to 4650 cm$^2$ V$^{-1}$ s$^{-1}$.

A sketch of the valence band at the heterojunction for inverted MDS and plots of the variations of the 2DHG sheet density and resistivity versus gate voltage at $T = 4.2$ K and 1.6 K are shown in Fig. 1. The linear dependence of the hole sheet density with gate voltage can be explained as following. The charge neutrality through the structure implies that

$$N_{\mathrm{A}}\ell + n_{\mathrm{sp}} = n_{\mathrm{s}} + n_{\mathrm{c}}, \tag{1}$$

where $N_{\mathrm{A}}$ and $\ell$ are respectively the concentration of B atoms and the thickness of the depletion region of the doped layer, $n_{\mathrm{sp}}$ represents the density of B atoms that have migrated (segregated) into the spacer layer that are ionised, as well as implied interface charges [6]. These B-acceptor atoms supply the 2DHG sheet density $n_{\mathrm{s}}$ in the channel and the cap-side charges $n_{\mathrm{c}}$. Ignoring the depleted charges (arising from background impurities) in the cap layer, the cap-side charges mainly consist of metal–semiconductor interface charges and induced charged density $n_{\mathrm{g}}$ due to applying a voltage to the gate

$$n_{\mathrm{g}} = \frac{\varepsilon\varepsilon_0}{e}\frac{V_{\mathrm{g}}}{L}, \tag{2}$$

where $\varepsilon$ is the dielectric constant of Si, and $L$ is the cap layer thickness. So the total cap-side charges are controlled by biasing the metal gate. Our self-consistent calculations of Schrödinger and Poisson equations for this structure show a linear change in the 2DHG density $n_{\mathrm{s}}$ with $V_{\mathrm{g}}$ while the sum of $n_{\mathrm{s}}$ and $n_{\mathrm{c}}$ is almost independent of $V_{\mathrm{g}}$.

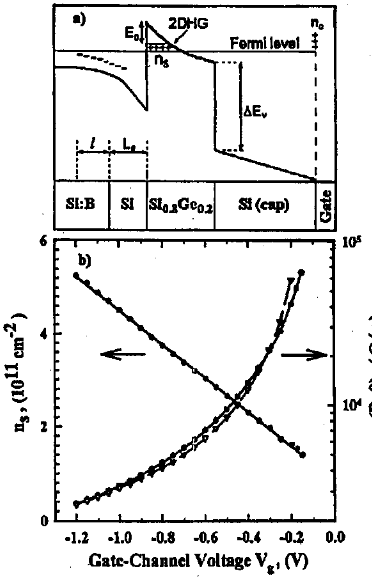


Fig. 1. Sketch of the valence band (not to scale) of an inverted modulation doped Si/SiGe/Si heterostructure (a), 2DHG Hall sheet density $n_s$ (filled) and resistivity $\rho_{xx}(B = 0)$ (hollow) measured at $T = 4.2$ K (circles) and 1.6 K (triangles) as a function of gate-channel voltage $V_g$ (b).

Similar to "normal" MDS [6, 7], the normal effective electric field $F_{\text{eff}}$ in the channel for "inverted" structure is given by

$$F_{\text{eff}} = \frac{e}{\varepsilon\varepsilon_0}\left(n_c + \frac{n_s}{n_s}2\right) \tag{3}$$

and (because of the variation of $n_c$) has its maximum at low 2DHG densities $n_s$. Also, from the average distance of the holes from SiGe on Si interface

$$z_{\text{av}} = 3\left[\frac{12m^*e^2}{\hbar^2\varepsilon\varepsilon_0}\left(n_c + \frac{11}{32}n_s\right)\right]^{-1/3}, \tag{4}$$

one can conclude that the 2DHG wave function moves towards the interface at low densities. The "inverted" MDS therefore has the interesting feature that, in contrast to the "normal" MDS, both interface charge and interface roughness scattering become more important at low carrier densities $n_s$.

Magnetotransport measurements of the longitudinal sheet resistivity $\rho_{xx}$ and Hall resistance $\rho_{xy}$ were made for different gate voltages $V_g$ in the magnetic field range $B = -0.5 \div 12$ T and $T = 0.33 \div 2.5$ K. The $\rho_{xx}(B)$ dependence for various $V_g$ is shown in Fig. 2. The shifts in positions of Shubnikov–de Haas oscillation minima reflects the dependence of 2DHG sheet density $n_s$ on gate voltage. The extracted values of $n_s$ from the periodicity of $\rho_{xx}$ vs. inverse magnetic field, are in agreement with Hall measurements of $n_s$ at $B < 0.5$ T, indicating that only the first subband has been populated. The variation of $\rho_{xx}$ with $V_g$ at $B = 0$ of about

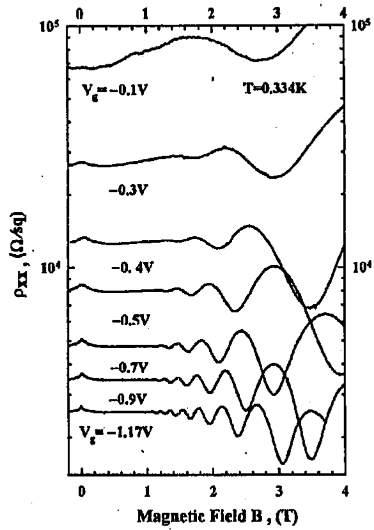


Fig. 2. Dependence of longitudinal resistivity $\rho_{xx}$ on magnetic field $B$ for different gate-channel voltages $V_g = -0.1$ V $\rightarrow -1.17$ V at $T = 0.33$ K.

two orders of magnitude reflects that the system undergoes a transition from a weakly to strongly localised phase. This transition occurs when the hole's sheet density falls below some value $n_s \approx 2 \times 10^{11}$ cm$^{-2}$ corresponding to $\rho_{xx} \approx 0.8h/e^2$.

The 2DHG effective mass $m^*$ was extracted from the temperature dependence of Shubnikov–de Haas oscillations in the longitudinal resistivity $\Delta\rho_{xx}$ according to [8]

$$\frac{\Delta\rho_{xx}}{\rho_0} = R_s V \frac{\psi}{\sinh\psi} \exp(-\pi/\omega_c\tau_q) \cos\left(2\pi\frac{E_F}{\hbar\omega_c} + \Phi\right), \quad (5)$$

where $\psi = 2\pi^2 kT/\hbar\omega_c$, $\omega_c = eB/m^*$, $\rho_0$ is the Boltzmann resistivity at $B = 0$, $\tau_q$ is the quantum lifetime. The parameters $R_s$ and $V$ are related to the spin reduction factor and scattering mechanisms, respectively and assumed to be independent of $B$ and $T$. The oscillatory component of longitudinal resistivity $\Delta\rho_{xx}$ is obtained by removing the background contribution with digital filtering. To obtain the effective mass we take $\alpha = \tau_t/\tau_q$ where the transport lifetime is related to mobility ($\mu = e\tau_t/m^*$) and plot

$$\ln(\Delta\rho_m/\rho_0) \qquad \text{vs.} \qquad \ln(\psi/\sinh\psi) - (\pi\alpha/\mu B) \quad (6)$$

for various $T$ and $B$, where $\Delta\rho_m$ is the peak value of $\Delta\rho_{xx}$, the effective mass $m^*$ and constant $\alpha$ are used as adjustable parameters until the universal straight line with a gradient of unity is obtained. Moreover the Dingle plot of

$$\ln[(\Delta\rho_m/\rho_0)(\sinh\psi/\psi)] \qquad \text{vs.} \qquad 1/\mu B \quad (7)$$

is a straight line with a slop of $-\pi\alpha$ confirming that $R_s$ and $V$ are independent of temperature and magnetic field for all $V_g$ used.

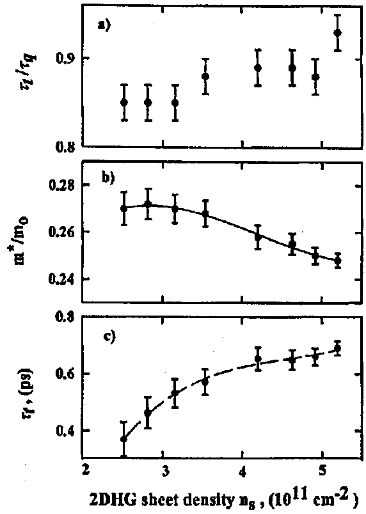


Fig. 3. 2DHG sheet density $n_s$ dependences of the parameters extracted from Shubnikov–de Haas oscillations analysis for "inverted" Si/SiGe heterostructure: (a) transport to quantum lifetime ratio $\alpha = \tau_t/\tau_q$, (b) hole effective mass $m^*$, and (c) transport lifetime $\tau_t$.

The extracted values of $m^*$, $\alpha$, and $\tau_t$ for different hole densities are shown in Fig. 3. The values of transport to quantum lifetimes ratio $\alpha = 0.92 \div 0.85$ imply that short range scattering from interface charges and roughness potentials are dominant in the inverted MDS. It is clear from Eq. (3) that by decreasing the carrier density $n_s$ the normal effective field $F_{\rm eff}$ increases, hence the 2DHG wave function moves towards the inverted interface and will be affected more strongly by interface impurities and roughness. Consequently, the system undergoes a transition to an insulating phase [9] where the transport lifetime $\tau_t$ decreases significantly [7]. The extracted values of effective mass decrease with increasing sheet density, which is in contrast to results for ungated "normal" MDS grown with different spacer thicknesses for changing $n_s$ in the range of $(0.2-1.05) \times 10^{12}$ cm$^{-2}$ [10]. The non-abruptness in the Ge profile at the inverted interface [11] and displacement of the wave function towards the interface where the Ge composition decreases, is a possible qualitative explanation of the increase in measured hole effective masses for lower 2DHG densities.

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