Low temperature characterization of modulation doped SiGe grown on bonded silicon-on-insulator

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Modulation doped pseudomorphic $Si_{0.87}Ge_{0.13}$ strained quantum wells were grown on bonded silicon-on-insulator (SOI) substrates. Comparison with similar structures grown on bulk Si(100) wafers shows that the SOI material has higher mobility at low temperatures with a maximum value of 16 810 cm ^{2}/V s for 2.05×10^{11} cm^{-2} carries at 298 mK. Effective masses obtained from the temperature dependence of Shubnikov–de Haas oscillations have a value of $(0.27\pm0.02)\ m_0$ compared to $(0.23\pm0.02)\ m_0$ for quantum wells on Si(100) while the cyclotron resonance effective masses obtained at higher magnetic fields without consideration for nonparabolicity effects have values between 0.25 and 0.29 m_0. Ratios of the transport and quantum lifetimes, $\tau/\tau_q=2.13\pm0.10$, were obtained for the SOI material that are, we believe, the highest reported for any pseudomorphic SiGe modulation doped structure and demonstrates that there is less interface roughness or charge scattering in the SOI material than in metal–oxide–semiconductor field effect transistors or other pseudomorphic SiGe modulation doped quantum wells. © *1996 American Institute of Physics.* [S0003-6951(96)04044-2]

Numerous studied have appeared in the literature looking at pseudomorphic SiGe quantum wells, modulation doped to form two-dimensional hole gases (2DHGs), in the hope of increasing the mobility and decreasing the effective mass of holes on silicon substrates.[1] The work has been driven by the hope of increasing the performance of the *p*-channel silicon field effect transistors (FETs) which limit the performance of complementary metal–oxide–semiconductor (CMOS) circuits. While the increase in mobility at room temperature has been small, the low temperature mobility in these structures can be significantly increased[2] allowing quantum effects and devices to be investigated.

Silicon on insulator (SOI) substrates have been shown to be beneficial to the performance of CMOS circuits both at room temperature and at low temperatures.[3] When growing strained SiGe layers, however, the increased defect density of the SOI substrates may be detrimental to the epitaxial growth and promote strain relaxation. Characterization of SiGe layers grown on separation by implanted oxygen (SIMOX) substrates for optoelectronic applications[4] and for increased mobility SiGe channel *p*-MOS have already been published.[5] In the present work, modulation doped 2DHGs grown on bonded SOI have been grown and electrically characterized. The material was designed to ultimately allow the substrate to be used as a backgate, controlling the Fermi energy and carrier density in the quantum well by the application of an appropriate voltage to the substrate. In this letter, the quality of the 2DHG without any substrate biasing will be investigated.

The starting substrate was a commercially bought bonded SOI wafer from SiBOND. The bulk SOI wafer was a 100-mm-diam Si(100) p^+ 0.001 Ω cm wafer with a 200 nm SiO_2 layer and a 50 nm 20 Ω cm top Si cap. The wafer was RCA cleaned before being loaded into a Vacuum Generators V90S molecular beam epitaxy system. The sample was then heated to 860 °C before growing a 200 nm undoped Si buffer followed by a 25 nm $Si_{0.87}Ge_{0.13}$ strained quantum well. A 20 nm undoped Si spacer was grown as the sample was cooled to 750 °C and then a 50 nm boron doped Si ($N_A=2\times10^{18}$ cm^{-3}) layer and 30 nm undoped Si cap were grown.

Samples of the material were etched into Hall bars using a CHF_3/H_2 reactive ion etch[6] before thermally evaporating Al (1% Si) and alloying through annealing to form ohmic contacts. Figure 1 shows the mobility and sheet carrier den-

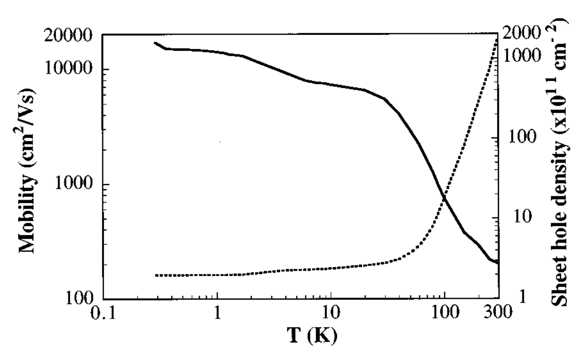

FIG. 1. The mobility (solid line) and sheet hole density (dashed line) as a function of temperature.

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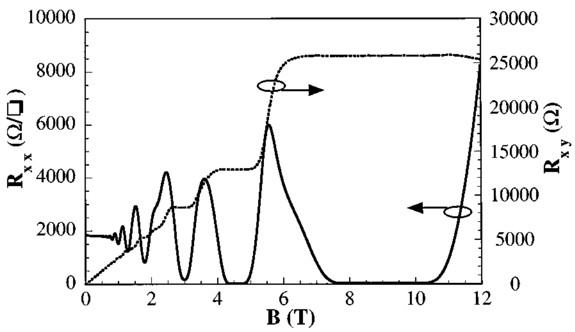

FIG. 2. The longitudinal and transverse resistivity of the 2DHG SOI wafer as a function of transverse magnetic field. The temperature was 298 mK and the mobility and sheet carrier density measured were 16 810 cm^2/V s and 2.05×10^{11} cm^2/V s, respectively.

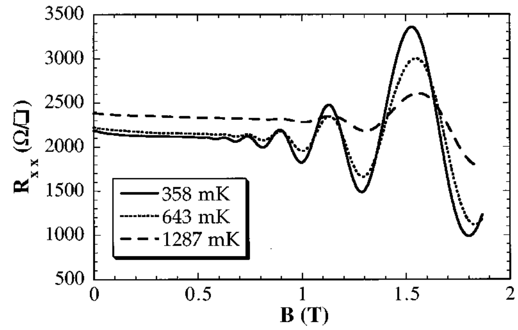

FIG. 3. The reduction of the amplitude of the Shubnikov–de Haas oscillations as the temperature was increased is demonstrated by plotting three different temperatures. The small change in hole density with temperature can be observed by the movement of each peak to higher B as the temperature increases.

sity as a function of temperature as derived from low field Hall measurements. All measurements used standard four-terminal ac lock-in techniques with appropriate currents to prevent electron heating at the lowest temperatures. The room temperature values for mobility and carrier density are 290 cm^2/V s and 1.86×10^{14} cm^{-2}. At 1.7 K (300 mK), the material has a mobility and carrier density of 12 930 cm^2/V s (16 810 cm^2/V s) and 2.06×10^{11} cm^{-2} (2.05×10^{11} cm^{-2}) that compares favorably with an identical structure grown on a Si(100) n^-substrate but without the 30 nm undoped Si cap of 11 700 cm^2/V s (12 060 cm^2/V s) and 2.12×10^{11} cm^{-2} (2.08×10^{11} cm^{-2}).[7] These values are substantially better than (to the knowledge of the authors) the best p-channel inversion or accumulation layer metal–oxide–semiconductor FET (MOSFET) values of 2500 cm^2/V s at 1.5 K.[8]

Figure 2 shows the Shubnikov–de Haas oscillations and the quantum Hall effect at 298 mK in the present SOI sample. The carrier density obtained from the Shubnikov–de Haas oscillations was $2.20(\pm 0.20)\times 10^{11}$ cm^{-2} at 1.7 K, the same within experimental error as the density measured from the Hall voltage. In addition, fast Fourier transforms of R_{xx} give a single harmonic demonstrating occupancy of one subband in the material and no parallel conduction at low temperatures.

Coleridge *et al.*[9] derived a theory to describe the low-field amplitudes and phases of the Shubnikov–de Haas oscillations. They assumed that the thermal broadening of the Landau levels can be represented by a Lorentzian with width Γ (independent of energy or magnetic field) such that the quantum lifetime

$$\tau_q=\frac{\hbar}{2\Gamma}=\frac{\hbar^2}{2\pi k_B T_D},$$

where $\hbar$ is Planck's constant divided by 2π, k_B is Boltzmann's constant, and T_D is the Dingle temperature. Provided the Fermi level $E_F \gg \hbar/\tau_q, E_F \gg \hbar\omega_c$ where $\omega_c = eB/m^*$and the oscillations in the density of states are small, the deviations in the resistivity $\Delta\rho_{xx}$ from the zero magnetic field longitudinal resistivity ρ_0 are described by

$$\frac{\Delta\rho_{xx}}{\rho_0}=\frac{4\xi}{\sinh\xi}\exp\left(-\frac{\pi}{\omega_c\tau_q}\right)\cos\left(\frac{2\pi E_F}{\hbar\omega_c}-\pi\right),$$

with $\xi=2\pi^2 k_B T/\hbar\omega_c$. An effective mass m^* may be obtained by plotting $\ln(\Delta\rho_{xx}/\rho_0)$ versus $\ln(\xi/\sinh\xi)$ and using m^* as an adjustable parameter until unity gradient is obtained.

Figure 3 shows the Shubnikov–de Haas oscillations for three different temperatures, clearly showing the decrease in amplitude of the oscillations as the temperature was raised. Background contributions to the Shubnikov–de Haas oscillations were removed by fast Fourier transform techniques before obtaining m^* as a function of magnetic field from the data. Figure 4 shows the effective masses obtained using the Coleridge formula on data taken at ten different temperatures between 358 mK and 1.3 K. Using the above mentioned approximations, the formula is only valid for $B<1.5$ T. At lower magnetic fields, specifically $B<1$ T, the smaller amplitudes of the oscillations produced a smaller signal to noise ratio and hence the error increased. The region of applicability of the theory was therefore small. A mean value of (0.27 ± 0.02) m_0 where m_0 is the free electron mass was obtained. Measurements on $Si_{0.87}Ge_{0.13}$ modulation doped samples grown on Si(100) n^- substrates with identical structures to the present SOI material but without the 30 nm undoped Si cap produced an m^* of (0.23 ± 0.02) m_0.

Dingle plots from different temperatures (Fig. 5) produced common straight lines, confirming the temperature independence of the results. The gradient of the Dingle plots

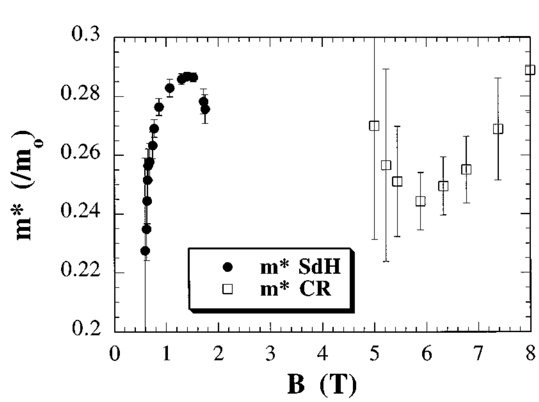

FIG. 4. The effective masses (in units of free electron mass, m_0) obtained from the temperature dependence of the Shubnikov–de Haas oscillations (solid circles) and the cyclotron resonance (open squares) measurements.

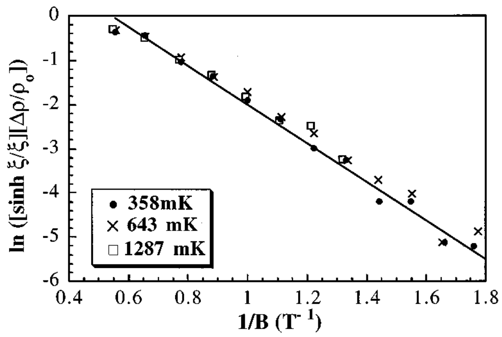

FIG. 5. Dingle plots for three temperatures.

may be written as $-\pi\tau/\tau_q\mu$ with τ the transport lifetime, allowing the ratio $\tau/\tau_q = 2.13 \pm 0.10$ to be extracted. In MOSFETs, the ratio is approximately 1 (Ref. 10) while in high mobility GaAs/AlGaAs or Si/SiGe heterostructures the ratio may be 10 or significantly higher[11] when remote ionized impurity scattering becomes the dominant scattering mechanism. Measurements on $Si_{0.87}Ge_{0.13}$ modulation doped samples with identical structures to the present SOI material but without the 30 nm undoped Si cap gave ratios of 1.0 ± 0.3.[7] Gold[12] has predicted a ratio of 1 for scattering by short range interface charge and 0.67 for short range interface roughness scattering that explain the results from MOSFETs and previous pseudomorphic $Si_{0.87}Ge_{0.13}$ modulation doped samples. The higher ratio of 2.13 and the temperature dependence of the mobility suggest that interface charge and roughness scattering have less prominence in the SOI 2DHG and remote ionized impurity scattering is beginning to be the dominant scattering mechanism.

Cyclotron resonance (CR) measurements using a Fourier transform spectrometer with unpolarized radiation were performed with wedged (about 3°) samples placed in an Oxford Instruments 1.5 K cryostat with optical windows. Both the incident radiation and the magnetic field were perpendicular to the plane of the 2DHG. To eliminate structure arising from effects not produced by the 2DHG, the transmission spectra were normalized to reference spectra obtained for zero magnetic field, Figure 4 shows the effective mass obtained from the spectra using the simple relationship $\omega_c = eB/m^*$ to transform the resonant frequency into m^* at a temperature of 3.3 K. No accounting of any nonparabolicity of the valence band was made. The values obtained range from 0.25 to 0.29 m_0 which generally agree with the Shubnikov–de Haas values obtained. Until modeling of the CR results to account for nonparabolicity are completed, little can be accurately deduced from the magnetic field dependence of the present CR results.

To conclude, pseudomorphic $Si_{0.87}Ge_{0.13}$ 2DHGs were grown on bonded SOI material. Comparison with similar 2DHGs grown on bulk Si(100) wafers shows that the SOI material has higher mobilities at low temperatures with a maximum value of 16 810 $cm^2/V\,s$ for 2.05×10^{11} cm^{-2} carriers at 298 mK. Effective masses obtained from the temperature dependence of Shubnikov–de Haas oscillations have a value of (0.27 ± 0.02) m_0 compared to (0.23 ± 0.02) m_0 for 2DHGs on Si(100) while the CR effective masses obtained at higher magnetic fields without consideration of nonparabolicity effects have values between 0.25 and 0.29 m_0. Ratios of $\tau/\tau_q = 2.13 \pm 0.10$ were obtained for the SOI 2DHG, that we believe is the highest reported for any pseudomorphic SiGe 2DHG, and demonstrate that there is less interface roughness or charge scattering in the SOI material than in MOSFETs or other pseudomorphic SiGe 2DHG.

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