

Symmetric Si/Si_{1-x}Ge_x two-dimensional hole gases grown by rapid thermal chemical vapor deposition

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Single and symmetric double *p*-type modulation-doped structures have been fabricated in Si/SiGe for the first time by rapid-thermal chemical-vapor deposition. Temperature-dependent electrical measurements and high-field magnetotransport measurements demonstrate the presence of a well-confined two-dimensional hole gas in these samples. Nominally-symmetric normal and inverted structures differ in carrier density and mobility at most by 20%, indicating that there is little asymmetry due to surface segregation or autodoping effects. Measurements on double heterostructures confirm that the interfaces are symmetric to within 10 Å. Peak mobilities reached 2500 cm²/V s at 10 K, comparable to those obtained in similar samples grown by ultrahigh vacuum techniques.

Advances in Si-Ge heteroepitaxy have attracted considerable attention due to prospects of integrating high-speed heterojunction devices with conventional Si technology.¹ A critical issue for heteroepitaxial technology is interface abruptness on a near atomic scale, which is beyond the resolution of conventional characterization techniques, such as secondary ion-mass spectrometry (SIMS), etc. In this letter, we report the first fabrication of two-dimensional hole gases by modulation doping in the SiGe system by the rapid-thermal chemical-vapor deposition (RT-CVD) growth technique, and the use of these structures to probe the interface on a nanometer scale.

The RT-CVD reactor in our laboratory is described in detail elsewhere.^{2,3} In brief, it uses susceptor-free lamp heating to control the growth on a 4-in-Si wafer inside a quartz-tube reactor chamber not under ultrahigh vacuum (UHV). Typical growth conditions are 1% dichlorosilane in a 6-Torr H₂ carrier for Si growth at 700 °C (~30 Å/min), with germane added at 625 °C for Si_{1-x}Ge_x growth. The doping interfaces are achieved within the Si for the modulation-doping experiments simply by switching a diborane source on and off. Once growth is started, the sample is not cooled until the final structure is complete. For all experiments described in this letter, 4-in-diameter *n*-type wafers (~1.0 Ω cm resistivity) were used. Shown in Fig. 1 is a typical "normal" structure, with the doped layer above the SiGe channel. "Inverted" structures, with the doping below the channel, were also fabricated. A key issue in CVD on an atomic scale is any autodoping, slow-gas transients, or dopant surface segregation which would cause the undoped-Si spacers in the normal and inverted structures to vary in thickness. Such a variation would affect the density and mobility of the two-dimensional hole gas. For example, calculations show that for the normal structure of Fig. 1, a 1 nm change in the spacer thickness would cause a 10% change in the channel-carrier density.

The single heterostructures consist of a Si layer doped to 1×10¹⁸ cm⁻³ with boron, and separated from the undoped-Si_{0.85}Ge_{0.15} alloy layer by a 150 Å spacer. Doping levels and layer thicknesses are estimated from SIMS and calibrated growth conditions. All structures have a doped-

Si cap layer to prevent surface depletion of the channel. After growth, Van der Pauw and Hall patterns were lithographically defined by a simple process. Aluminum was evaporated and annealed at 500 °C in a forming-gas atmosphere to form ohmic contacts good to 2 K. Resistivity and Hall measurements were carried out in a closed-cycle He refrigerator system using a sensitive lock-in detection technique. The results for the single heterostructures are shown in Fig. 2. The carrier mobility increases monotonically as the temperature is lowered, reaching about 2500 cm²/V s at 10 K. At the same time, the carrier density decreases and saturates at about 6×10¹¹ cm⁻², showing no freeze-out, confirming the presence of a modulation-doped two-dimensional hole gas in both samples. Also shown in Fig. 2 are published peak mobilities in samples with approximately similar doping levels, Ge fractions, and spacer thicknesses grown by molecular-beam epitaxy (MBE) and UHV-CVD. Our data is in close agreement with these values, demonstrating the excellent quality of the RT-CVD technique. Mobilities as high as 6000 cm²/V s have been measured in MBE-grown samples at 2 K,⁴ but our com-

NORMAL	DOUBLE
p + Si Cap 200 Å	p + Si 300 Å
i - Si 200 Å	i - Si spacer 50 Å
p + Si 50 Å	+++++ 2DHG +++++
i - Si spacer 150 Å	i - Si _{0.8} Ge _{0.2} 500 Å
+++++ 2DHG +++++	+++++ 2DHG +++++
i - Si _{0.85} Ge _{0.15} 500 Å	i - Si spacer 50 Å
	p + Si 300 Å
i - Si buffer = 1 μm	i - Si buffer = 1 μm

FIG. 1. Normal and double modulation-doped structures. The doping levels in the two samples are 1.5×10¹⁸ cm⁻³ and 3.0×10¹⁸ cm⁻³, respectively. The position of the two-dimensional hole gas (2DHG) is schematically indicated.

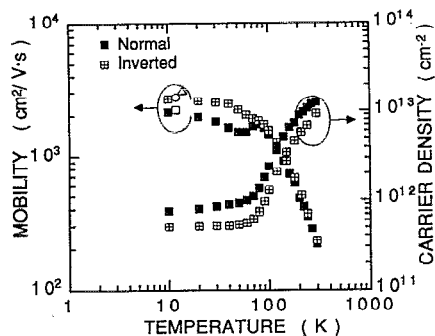


FIG. 2. Electrical results for the normal and inverted structures. The open symbols represent mobility data obtained from similar samples grown by other techniques: \circ UHV-CVD,⁷ Δ MBE,⁴ \square MBE.⁸

parisons were made around 10 K so that the UHV-CVD data could also be included.

High magnetic field measurements at low temperatures were also performed. The longitudinal resistivity of the sample exhibits the well known Shubnikov-deHaas (SdH) oscillations, which are periodic in the reciprocal field.⁵ From the period, assuming a nondegenerate strain-split valence band, we obtain a carrier density of $4.7 \times 10^{11} \text{ cm}^{-2}$ at 4.2 K, which agrees very well with $4.8 \times 10^{11} \text{ cm}^{-2}$, obtained from the Hall slope. These results further confirm that a two-dimensional hole gas exists at the heterointerface with no parallel conduction elsewhere. Although nominally of similar structure, the mobility and carrier concentrations were not identical in the normal and inverted structures, but were 20% higher and 15% lower in the inverted structure, respectively. This is contrary to what one would expect if autodoping or surface segregation caused a smaller spacer in the inverted structure. Since the samples were grown three weeks apart, it was not known if this difference was a real physical effect, or due to a small change in growth conditions. Therefore, we grew a double heterostructure incorporating both the normal and inverted interfaces at the same time.

The double heterostructure, shown in Fig. 1, has an active $\text{Si}_{0.8}\text{Ge}_{0.2}$ layer with $3 \times 10^{18} \text{ cm}^{-3}$ doped layers on both sides, separated by undoped 50 Å spacers. Mobility and carrier-density measurements were carried out as before, and the results are displayed in Fig. 3. Again, modulation-doping characteristics are observed, with a peak mobility of $1000 \text{ cm}^2/\text{V s}$ at a carrier density of $3.2 \times 10^{12} \text{ cm}^{-2}$. The higher density and lower mobility compared to the single heterostructures is due to the higher doping, more Ge, and smaller spacer layers. The sample also exhibits magnetoresistance oscillations at low temperatures, as shown in Fig. 4. If the magnetic field is tilted away from the normal to the sample, the oscillation minima shift to higher fields. A plot of minima position as a function of the tilt angle reveals that the oscillations are sensitive only to the normal component of the field. This verifies the strong two-dimensional confinement of holes at the interfaces. The periodic nature of the oscillations is evident from a Fourier analysis, shown in Fig. 5. The single peak corresponds to a density of $1.3 \times 10^{12} \text{ cm}^{-2}$. This value is half of

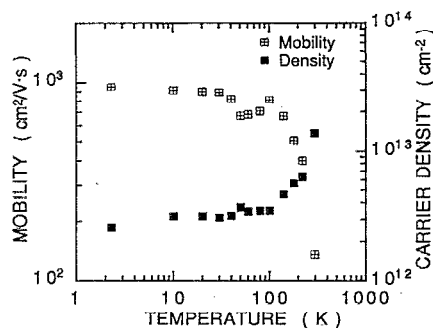


FIG. 3. Carrier density and mobility as a function of temperature for the Si/SiGe/Si double modulation-doped structure.

the density $2.6 \times 10^{12} \text{ cm}^{-2}$ obtained from the high-field Hall slope, indicating *two* parallel two-dimensional hole gases with similar densities. To rule out any other parallel conduction accounting for the difference, we studied the Hall resistance of the sample under high-magnetic fields. As shown in Fig. 4, the sample exhibits the Quantized Hall Effect. The quantized plateau values are normally given by $R_H = h/e^2\nu$ where h is Planck's constant, e is the electron charge, and ν is an even integer.⁶ In our case, however, we find plateaus for $\nu = 12, 16,$ and 20 but are missing $\nu = 14$ and $\nu = 18$. Equivalently, the quantized resistance is given by $R_H = h/2e^2\nu$, which is half that of a single two-dimensional system. This unequivocally demonstrates that the double-heterostructure sample has two symmetric-parallel channels. From the width of the Fourier-transform peak in Fig. 5, we estimate the densities to differ at most by 10%. Numerical simulations indicate that this potential difference in carrier density correlates to a maximum change in spacer thickness of 10 Å. This means that any B segregation or autodoping effect during growth is of this order. Similar symmetric-interface results have been obtained with the UHV-CVD growth technique at 550°C ,⁷ but not by MBE.^{4,8} In UHV-CVD conditions, under the hydrogen-desorption temperature of $\sim 550^\circ\text{C}$, the surface is hydrogen covered,⁹ which may explain the lack of segregation and presence of symmetric interfaces. Our Si-growth temperature at 700°C , when the boron interfaces were formed, is well over the hydrogen-desorption temperature. This suggests that the high-H overpressure (6 Torr) or the Cl

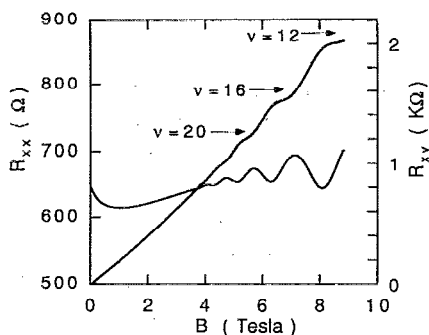


FIG. 4. Longitudinal resistance (R_{xx}) and Hall resistance (R_{xy}) for the double heterojunction sample as a function of the magnetic field.

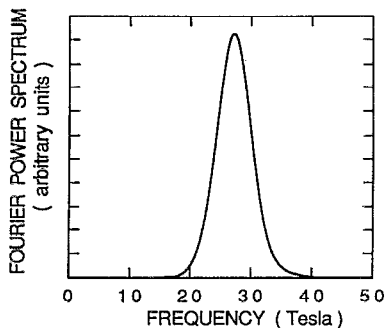


FIG. 5. Fourier spectrum of the periodic Shubnikov-deHaas oscillations shown in Fig. 4. The peak corresponds to a carrier density of $1.3 \times 10^{12} \text{ cm}^{-2}$.

from the dichlorosilane source is playing an important role in the surface chemistry and resulting segregation.

In summary, we have demonstrated the first normal, inverted, and double modulation-doped structures in Si/SiGe grown by rapid-thermal chemical-vapor deposition. Peak-carrier mobilities measured in these structures are comparable to those obtained in similar samples grown by UHV techniques. An interface symmetry in the double

heterostructures to within 10 \AA is inferred from the electrical measurements.

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