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ːtraction of the recombination lifetimes from the forward current characteristics of $_{SiGe}$-i_{SiGe}-n_{Si}, p^{+}_{SiGe}-n_{SiGe}-n_{Si} and p^{+}_{Si}-n_{SiGe}-n_{Si} diodes has been presented. A mparison of the maximum lifetimes, τ_{max}, which can be extracted from such structures discussed. Neglecting the peripheral current component and assuming identical layer icknesses for all diodes, the p^{+}_{Si}-n_{SiGe}-n_{Si} diode has the highest τ_{max} , with a agnitude on the order of 30 µsec at 300K. However, with the typical peripheral current nsity, which is on the order of $1X10^{-9}$ A/cm at 0.1V bias, the maximum lifetime which n be extracted from the p^{+}_{Si}-n_{SiGe}-n_{Si} diode drops to 3 µsec. These diode structures ve been fabricated in order to evaluate the effect of the oxygen incorporation on the combination lifetime in the $Si_{1-x}Ge_x$. Results indicate that oxygen plays a key role in termining the recombination lifetime in the $Si_{1-x}Ge_x$ at concentrations above $3X10^{17}$ n^{-3}. The magnitude of the recombination lifetime increases from 4 psec at an oxygen ncentration of $2X10^{20}$ cm^{-3} to above 0.5 µsec at concentrations below $3X10^{17}$ cm^{-3}.

cknowledgements

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SINGLE AND SYMMETRIC DOUBLE TWO-DIMENSIONAL HOLE GASES AT Si/SiGe HETEROJUNCTIONS GROWN BY RAPID THERMAL CHEMICAL VAPOR DEPOSITION

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ABSTRACT

Two dimensional hole gases have been investigated in Si/SiGe modulation doped heterostructures grown by RT-CVD for the first time. Single, both normal and inverted, and double heterostructures were studied. The results suggest that any asymmetry due to dopant segregation or autodoping between the normal and inverted structures occurs on a scale of less than 1 nm.

INTRODUCTION

The last few years have seen enormous advances in our understanding of the Si/SiGe material system for its potential applications in the fabrication of high-speed devices and optoelectronic circuits on Si [1]. Rapid Thermal CVD (RT-CVD) has emerged as a competing growth technology for fabricating these structures. Unlike MBE or UHV-CVD, this does not require ultrahigh vacuum techniques, and the growth temperature can be optimised for each individual layer. State-of-the-art devices like the MODFET and the resonant tunneling diode place stringent requirements on doping profiles and interface quality. It is therefore very desirable to characterize interface abruptness of epitaxial films grown in such an environment. Material analysis techniques like SIMS and RBS lack resolution on the scale of angstroms. The two dimensional hole gas confined at a modulation doped interface is however very sensitive to the heteroepitaxial interface region , making it an excellent probe for characterization. No previous modulation doping results have been reported for RT-CVD. Initial double heterostructures grown by MBE showed good carrier confinement and low temperature mobilities [2]. Further investigations of single heterostructures by SIMS showed that dopant segregation in MBE destroys the symmetry of the normal and inverted interfaces [3] resulting in different carrier mobilities. This is reminiscent of the well established AlGaAs/GaAs system, where an order of magnitude difference in mobility has been observed for a number of years in the best quality structures. Si/SiGe structures grown by a UHV-CVD technique apparently did not show this effect [4].

We have fabricated p-type modulation doped structures using RT-CVD and characterized the two interfaces using electrical measurements. Double heterojunction structures were also investigated using low-temperature magnetoresistance experiments. The results are described in the next section.

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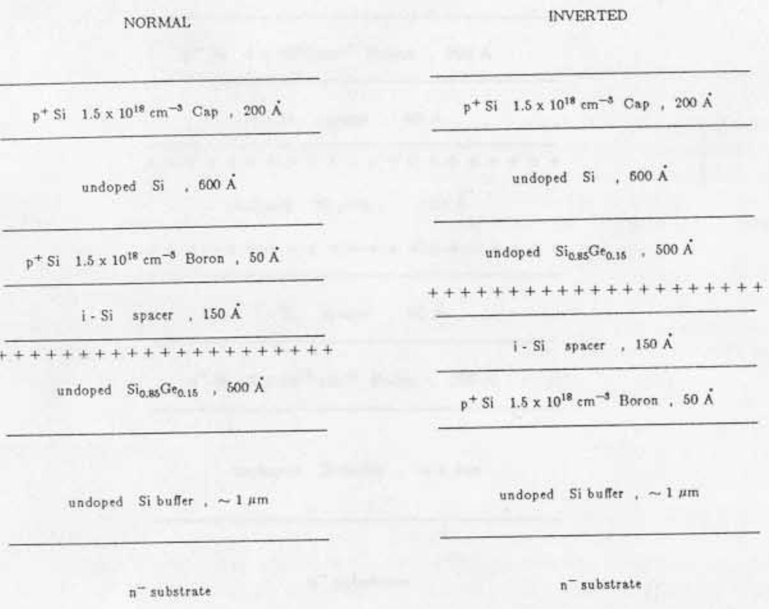

Fig. 1. Normal and inverted modulation doped heterostructures.

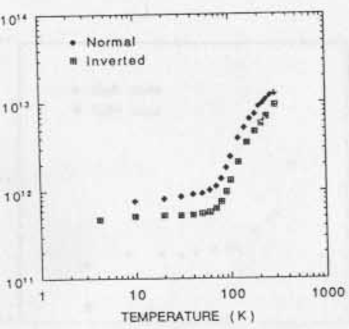

Fig. 2. Carrier concentration as a function of temperature for the normal and inverted heterostructures.

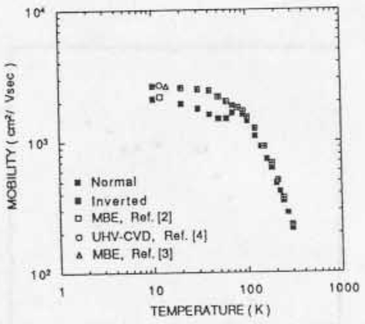

Fig. 3. Mobility as a function of temperature. The open symbols represent data from similar structures grown by MBE and UHV-CVD obtained from references [2],[3], and [4].

EXPERIMENT AND RESULTS

The growth system used is an RT-CVD reactor. The wafer sits on a quartz stand inside a cold wall quartz tube and is heated by a bank of tungsten halogen lamps. Dichlorosilane and germane are used as source gases while diborane is used for the p-type doping. The temperature of the wafer is accurately monitored using a novel infrared transmission technique with resolution of one degree [5]. All structures are grown on lightly doped n-substrates. Growth of epitaxial films is controlled by switching gas flows, not wafer temperature. The growth temperature is optimised individually for each layer. Growth starts with a silicon buffer layer grown at 1000 °C. The subsequent Si layers are grown at 700 °C while the SiGe alloy layers are grown at 625 °C. Single modulation doped heterostructures are shown in Fig. 1. The normal and inverted structures had a spacer width of 150 Å , doping concentrations 1.5 x 10^{18} cm^{-3} and germanium fractions of 15%. The doping and thicknesses are estimated from SIMS and calibrated growth conditions.

Standard van der Pauw and Hall bar geometries were lithographically defined and mesa-etched using a plasma etching system. Aluminum contacts were then evaporated and annealed at 500 °C for 20 minutes in a forming gas atmosphere. This yielded good ohmic contacts down to very low temperatures. Gold wires were bonded to the contacts for external electrical measurements.

Hall measurements were carried out from room temperature down to 10 K in a magnetic field of 0.2 T. Mobility is calculated from the measured resistivity and carrier density of the sample. The results are plotted in Figs. 2 and 3. The mobility rapidly increases as the temperature is lowered and saturates at about 2500 $cm^2/V{\cdot}s$ for the single heterostructures. The carrier concentration at the same time decreases and saturates at about 5 x 10^{11} cm^{-2}. No freeze-out is observed even at 4.2 K. This indicates a degenerate system of carriers well separated from ionized impurities. The peak mobilities at 10 K in these structures compare very well with those reported in similar structures grown by UHV-CVD and MBE techniques [2,3,4]. To confirm the two-dimensional carrier confinement at the heterointerface, magnetoresistance experiments were carried out at liquid He temperatures in high magnetic fields. The longitudinal resistance of the sample shows well defined Shubnikov-deHaas oscillations which are periodic in the reciprocal field [6]. From the period , we obtain a carrier density of 4.8 x 10^{11} cm^{-2} which agrees very well with 4.7 x 10^{11} cm^{-2} obtained from the Hall slope. This indicates little parallel conduction and a single carrier channel as expected. The low temperature mobilities and carrier densities in the normal and inverted structures however differ by 20%. This could either be due to small changes in growth conditions between the two samples or some physical asymmetry induced during growth. In order to resolve this, we carried out measurements on a symmetric double heterojunction structure shown in Fig. 4. The sample had a 50 Å spacer with a doping level of 3 x 10^{18} cm^{-3} and a germanium fraction of 20%. Electrical results are shown in Figs. 5 and 6.

The double heterostructure shows lower mobility and higher carrier density because of the smaller spacer width and higher doping level. The mobility saturates at 1000 $cm^2/V{\cdot}s$ with no carrier freeze-out. Tilted field Shubnikov deHaas experiments were carried out at 2.3 K in magnetic fields upto 9 T. The oscillations follow the component of the magnetic field perpendicular to the sample, indicating good two dimensional confinement of the carriers. Fig. 7 shows the longitudinal resistivity of the sample as a function of magnetic field normal to the surface. The periodic nature of the oscillations is evident from the calculated fourier spectrum shown in Fig. 8. The single peak indicates one carrier channel or two or more channels with

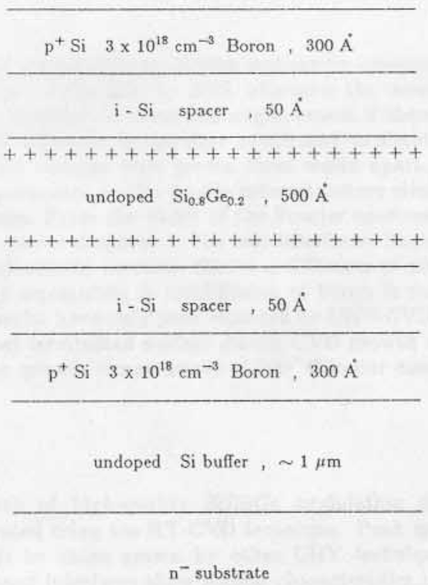

Fig. 4. Symmetric double heterostructure.

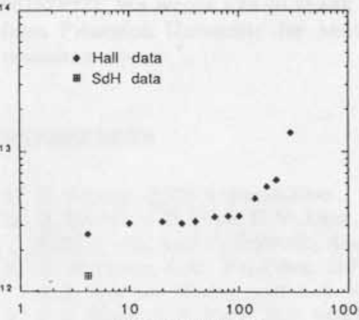

Fig. 5. Carrier density as a function of temperature for the double heterostructure. For comparison, the density obtained from the Shubnikov deHaas oscillations is also shown.

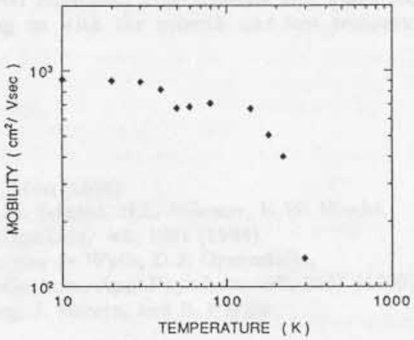

Fig. 6. Mobility as a function of temperature for the double heterostructure.

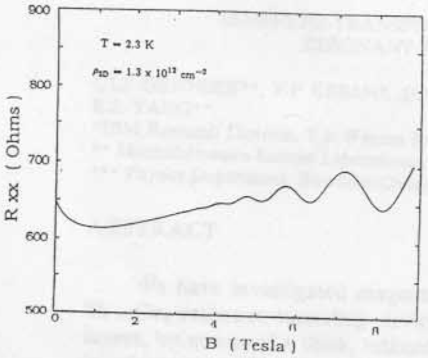

Fig. 7. Longitudinal resistivity of the double heterostructure sample as a function of the normal magnetic field, showing well known Shubnikov deHaas oscillations.

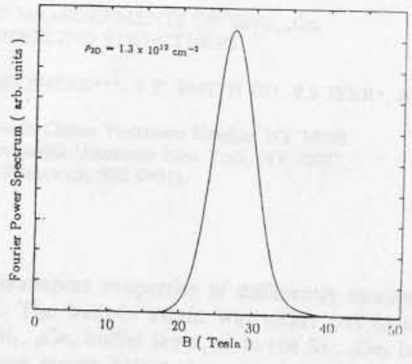

Fig. 8. Fourier analysis of SdH oscillations for the double heterostructure.

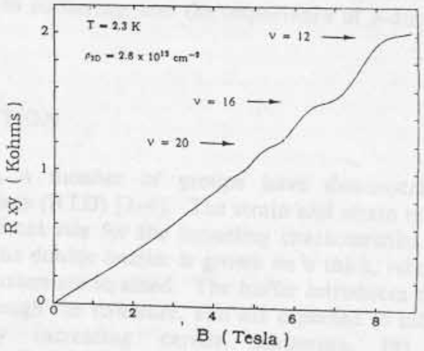

Fig. 9. Quantized Hall Effect in the double heterostructure. The plateau values are quantized at $R_H = h/e^2\nu$, where ν is even.

similar densities. From the position of the peak , we obtain a carrier density of 1.3 x 10^{12} cm^{-2} which is half of the value 2.6 x 10^{12} cm^{-2} obtained from the Hall slope. This indicates that the double heterostructure has two symmetric hole gases at the two interfaces, as expected. To rule out any parallel conduction accounting for the difference, we examined the high field Hall data shown in Fig. 9 more carefully. The sample shows the Quantized Hall plateaus with the resistance value, without resolving spin degeneracy, 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. The data shows plateaus for $\nu = 12, 16, 20$ but is missing $\nu = 14$ and $\nu = 18$. The fact that we see only even multiples of even integers confirms that we indeed have two symmetric 2-D channels with no parallel conduction elsewhere, since two symmetric channels in parallel would have resistance plateaus at $R_H = h/2e^2\nu$. Similar results for symmetric double heterostructures have been obtained by UHV-CVD growth at a temperature of 550 °C [4].

ISCUSSION

The low temperature mobilities and carrier concentrations of the normal and nverted structures differ only by 20%. Moreover the inverted structure shows lower arrier density, contrary to what one might expect if there was any dopant segregaion. The small difference is therefore attributed to slightly different growth condiions, as the two samples were grown three weeks apart. Low temperature magneoresistance experiments on the double heterostructure clearly reveal the symmetry of he two interfaces. From the width of the Fourier spectrum, we estimate a difference f 10% in the carrier densities at the two interfaces. Simulations of band structures f single heterojunctions correlate this to a difference of 10 Å in spacer widths, indiating that any segregation or outdiffusion of boron in our samples is of this order. That similar results have only been reported by UHV-CVD [4] suggests that a hydroen (or chlorine) terminated surface during CVD growth suppresses dopant segregaion, even up to growth temperatures of 700 ° C in our case.

SUMMARY

Growth of high-quality Si/SiGe modulation doped heterostructures has been demonstrated using the RT-CVD technique. Peak mobilities in these structures are comparable to those grown by other UHV techniques. Normal and inverted modulation doped interfaces show similar characteristics indicating negligible dopant segregation, which may be due to a hydrogen or chlorine terminated growth surface. Abrupt doping profiles for high-speed device applications can thus be achieved.

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MAGNETO-TRANSPORT MEASUREMENTS ON $Si/Si_{1-x}Ge_x$ RESONANT TUNNELING STRUCTURES

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ABSTRACT

We have investigated magneto-transport properties of differently strained Si/$Si_{1-x}Ge_x$ resonant tunneling devices. The built-in strain was either put in the Si layers, by means of a thick, relaxed $Si_{1-x}Ge_x$ buffer layer, or in the $Si_{1-x}Ge_x$ layers, in which case all $Si_{1-x}Ge_x$ layers were grown below the critical thickness, and a $Si_{1-x}Ge_x$ spacer layer with graded Ge content was used. Magnetic fields parallel to the interface have been employed to probe the in-plane dispersion in the quantum well. This is used to study the effect of band-mixing in the two strain configurations. A field perpendicular to the interface resolves some Landau level splitting. Most strikingly, however, is the similarity in the spectra with the case when the magnetic field is applied parallel to the interfaces. This indicates broadening of the levels, possibly due to scattering, and the importance of 3-dimensional band structure effects.

INTRODUCTION

Recently, a number of groups have demonstrated $Si/Si_{1-x}Ge_x$ resonant tunneling devices (RTD) [1-4]. The strain and strain relaxation in these structures play an important role for the tunneling characteristics. Two basic RTDs are of interest: (a) The double barrier is grown on a thick, relaxed $Si_{1-x}Ge_x$ layer, so that only the Si barriers are strained. The buffer introduces dislocations, some of which propagate through the structure, and are expected to influence the tunneling characteristics by increasing carrier scattering. (b) Structures which are pseudomorphically grown, with the strain in the $Si_{1-x}Ge_x$ well. The critical thickness of the $Si_{1-x}Ge_x$ layers limits the thickness to which the layers can be grown. Due to dopant diffusion, it is necessary to introduce an undoped spacer layer in front of the Si barriers. Preferably, this is made as large as possible, to limit any interference in carrier transport by the band offset at the interface between the Si contact and the $Si_{1-x}Ge_x$ spacer layers. In order to reduce the constraint imposed by the critical thickness, it is possible to use graded $Si_{1-x}Ge_x$ spacer layers. By adjusting the Ge gradient and placing of the p^+ doping interface, nearly flat equilibrium valence band profiles on either side of the double barrier structure can be achieved.

The I-V characteristics of hole-RTDs display complicated resonance spectra due to the light-hole and heavy-hole valence bands. Strain affects both the positions and the band-mixing between the two sets of resonances. Magnetic field transport studies provide a valuable tool to study the carrier conduction through these struc-

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