Electrical transport quantum effects in the $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterostructure on silicon

A. Georgakilas[a] and A. Christou
University of Maryland, CALCE Electronic Packaging Research Center, College Park, Maryland 20742

K. Zekentes
Foundation for Research and Technology-Hellas (FORTH), IESL, MRG, P. O. Box 1527, 711 10 Heraklion-Crete, Greece

J. M. Mercy and L. K. Konczewicz
University of Montpellier, CC074, Place E. Bataillon, 34095 Montpellier, France

A. Vila and A. Cornet
Universitat de Barcelona, Departamento Fisica Applicada i Electronica, LCMM, 645 Diagonal Avenida, 08028 Barcelona, Spain

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Electrical transport in a modulation doped heterostructure of $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ grown on Si by molecular beam epitaxy has been measured. Quantum Hall effect and Subnikov–De Haas oscillations were observed indicating the two-dimensional character of electron transport. A mobility of 20 000 cm^2/V s was measured at 6 K for an electron sheet concentration of 1.7×10^{12} cm^{-2}. Transmission electron microscopy observations indicated a significant surface roughness and high defect density of the InGaAs/InAlAs layers to be present due to the growth on silicon. In addition, fine-scale composition modulation present in the $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ may further limit transport properties.

The large lattice mismatch heteroepitaxial growth of ternary alloys $In_xGa_{1-x}As$ and $In_yAl_{1-y}As$ on Si substrates[1–6] presents both a challenge for molecular-beam epitaxy (MBE) growth and for the successful development of high speed electronic devices[7] and optoelectronic integrated circuits (OEICs)[8] on Si. The effect of large lattice mismatch, present in InGaAs/InAlAs-on-Si, on optimized crystalline quality and lateral electrical transport must be further investigated in order to achieve device quality structures. Successful utilization of lattice mismatch structures requires a complete understanding of the effects of crystal defects on transport properties.

In this work, we present the first low temperature electrical transport measurements in $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterostructures grown on Si. The two-dimensional transport character has been identified by the observation of quantum Hall effect and Subnikov–De Haas oscillations. The sheet carrier concentration was determined independently from the above two effects and compared to the concentration determined by low magnetic field Hall effect measurements and conclusions for the subband quantum well population were drawn. Electron microscopy observations showed a significant surface roughness and defect density in the InAlAs/InGaAs epilayers, which, however, appear to not affect the two-dimensional electron gas (2DEG) characteristic of the transport but may affect the possibility for achieving very high mobilities.

The MBE technique was used for the growth of InAlAs/InGaAs on Si(001) misoriented by 4° toward [110]. The Si substrate chemical cleaning and oxide desorption procedures have been reported elsewhere.[4,9] A layer of 0.1 μm thick GaAs was first deposited on Si by a two step growth process,[9] followed by a 0.1 μm of AlAs, grown at a temperature (T_G) of 680 °C, providing an effective annealing treatment for the GaAs/Si interfacial region. A layer of 0.6 μm $In_yAl_{1-y}As$ with continuous composition grading from $y=0$ to $y=0.52$ was subsequently deposited, while T_G was also varied linearly from 525 to 480 °C. The growth temperature was kept constant at T_G=480 °C for the growth of the remaining layers of the high-electron mobility transistor (HEMT) structure: 1.4 μm $In_{0.52}Al_{0.48}As$ buffer layer, 15 nm $In_{0.53}Ga_{0.47}As$ channel, 4 nm $In_{0.52}Al_{0.48}As$ spacer, 20 nm Si doped at 3×10^{18} cm^{-3} $In_{0.52}Al_{0.48}As$ donor layer, 10 nm $In_{0.52}Al_{0.48}As$ spacer and 10 nm Si doped at 3×10^{18} cm^{-3} $In_{0.53}Ga_{0.47}As$ contact layer.

The individual Van de Pauw patterns with ohmic contacts made by AuGe/Ni metallization and alloying at 330 °C were prepared using standard optical lithography techniques. Hall effect and transverse magnetoresistivity measurements were carried out at 6 K under various magnetic fields up to 12 T, by using the standard dc method to measure Hall voltage (V_H) and transverse magnetoresistivity. Transmission electron microscopy (TEM) of {110} cross-sectional specimens was used to assess the crystalline quality and the surface morphology of the layers.

The dependence of transverse magnetoresistivity (ρ_{xx}) and Hall voltage (V_H) on the magnetic field (B) was determined in order to initially determine the two-dimensional electron gas (2DEG) character of the electron transport at the InGaAs/InAlAs interface. Subnikov–De Haas oscillations (SDHO) are clearly shown in Fig. 1(a), from which the sheet carrier concentration (N_s) can be calculated according to the

[a]Present address: FORTH, IESL, MRG, P.O. Box 1527, 711 10 Heraklion-Crete, Greece.

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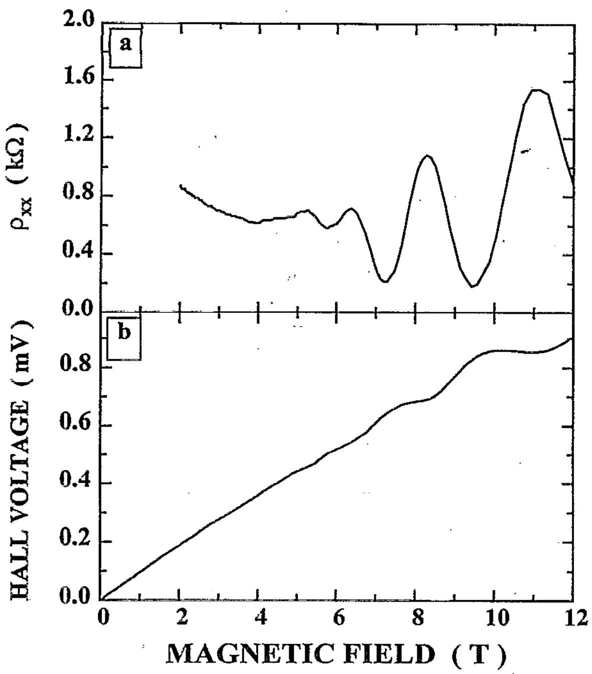

FIG. 1. Electrical transport measurements at 6 K for the $In_{0.53}Ga_{0.47}As$/$In_{0.52}Al_{0.48}As$ heterostructure on Si. (a) Transverse magnetoresistivity (ρ_{xx}) and (b) Hall voltage plotted versus the magnetic field.

simple formula[10] $N_s=2e/h[\Delta(1/B)]^{-1}$, where e is the electron charge, h the Planck constant and $\Delta(1/B)$ the periodicity of oscillations. The N_s value calculated from the SDHO was determined to be 1.4×10^{12} cm^{-2}.

The dependence of the Hall voltage (V_H) on magnetic field (B) at low magnetic fields was determined to be linear as shown in Fig. 1(b), while the quantum Hall effect plateaus were observed at the stronger magnetic fields. The N_s value was determined from both the classic Hall effect [linear $V_H(B)$] and the quantum Hall effect regions, using the relationship[10] of $N_s=2veB/h$, where v is the filing factor (number of electron occupied Landau levels) resulting in a value of $N_s=1.4\times10^{12}$ cm^{-2}. This value compares favorably on a value of $N_s=1.7\times10^{12}$ cm^{-2} determined from the classic Hall effect.

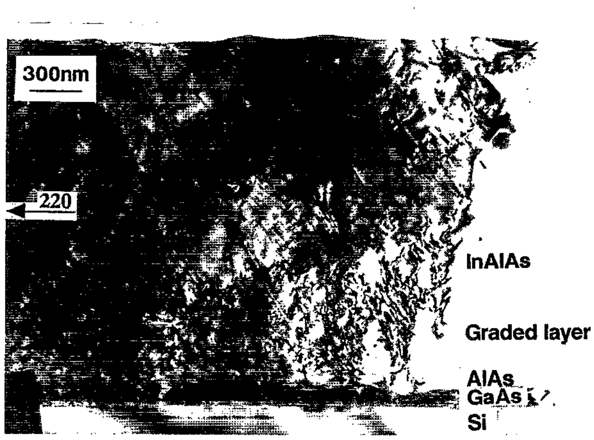

FIG. 2. Bright-field {110} cross-sectional TEM micrograph showing the entire overgrowth on Si. Threading dislocations, stacking faults, and surface roughness are visible.

Comparing the N_s values determined from different effects it is concluded that the values determined from either the SDHO or the quantum Hall effect (QHE) are in perfect agreement ($N_s=1.4\times10^{12}$ cm^{-2}). Although a higher N_s concentration ($N_s=1.7\times10^{12}$ cm^{-2}) was determined from the classic Hall effect measurements at low magnetic fields [Fig. 1(b)], this difference may be attributed to a parallel conduction in the bulk material, in the InAlAs doped region, or at the Si/GaAs interface.[11] We would suggest the latter to be the proper explanation since a similar sample grown immediately after, for comparison purpose, on InP substrate does not exhibit any discrepancy between low magnetic field determination of carrier concentration and the quantum effect determination. In this case the only carriers involved are the ones from the well at the InAlAs/InGaAs interface.

The Hall mobility of the 2DEG was calculated to be 20 000 cm^2/V s at 6 K. Such a mobility value is close to that reported for lattice matched layers on InP, and to a first approximation is determined from the width of the channel and spacer layer.[12] The growth on silicon substrates appears to present a second order limitation which would only affect transport properties once the channel and spacer layer have been optimized.

The overall crystal structure of the InGaAs/InAlAs-on-Si sample is shown in the cross-sectional TEM micrograph of Fig. 2. A high density of threading dislocations and stacking faults appears through the entire overlayer. The defect density is much higher in the first 0.6 μm of the graded composition $In_xAl_{1-x}As$ buffer layer, indicating the effectiveness of the composition grading in reducing the propagation of threading dislocations. A significant roughness of approximately 50 nm was observed as shown in Fig. 2, indicating that growth on the silicon followed a three-dimensional (3D) growth mechanism. The 3D growth would limit device transport properties. Therefore, although good electrical transport characteristics have been obtained for the InGaAs/InAlAs heterostructure the crystalline quality of the material limits its further utilization for devices.

Although crystal defects in InAlAs are present for non-optimized growth,[13,14] the origin of the defects in the present investigation are clearly related to the growth on the silicon substrate. Figure 3 shows at a higher magnification the first epilayers on Si indicating a nonplanar appearing GaAs/AlAs interface and stacking faults initiating at the GaAs layer and propagating through the overlayers. A deviation from optimized growth conditions at the first stages of heteroepitaxial growth has influenced the overall structural quality. A significant crystal improvement is possible by first achieving an absolutely smooth GaAs-on-Si surface before the growth of a composition graded $In_xAl_{1-x}As$ buffer layer. The gradual strain relaxation will suppress the generation of crystal defects due to the disturbed growth of highly strained layers,[4] while it may also inhibit the propagation of any threading dislocations.

A fine-scale contrast modulation attributed to alloy composition modulation[4] was also observed in the $In_{0.52}Al_{0.48}As$

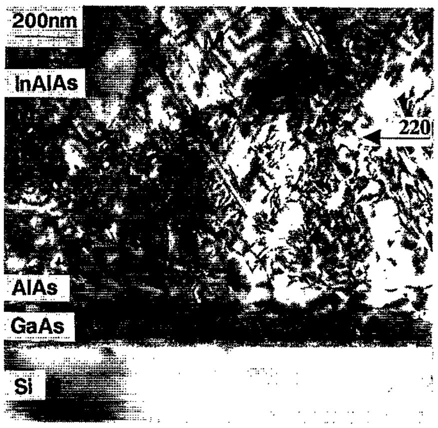

FIG. 3. Higher magnification bright-field {110} cross-sectional TEM micrograph showing the first epilayers on Si. Some stacking faults appear to start from the GaAs layer, and a fine-scale (~8 nm) quasiperiodic contrast modulation is shown in $In_{0.52}Al_{0.48}As$ (see *M*).

layers (see *M* in Fig. 3), which may further limit transport properties. However, buffer layers of $In_{0.52}Al_{0.48}As$ may be superior than buffer layers of $In_{0.53}Ga_{0.47}As$ for heteroepitaxy on Si if the coarse-scale alloy composition[4] modulation can be prevented. Such compositional modulations (coarse scale) were found to detrimentally affect device characteristics for $In_{0.53}Ga_{0.47}As$-on-Si.[4] The good transport properties of the 2DEG indicate that a coarse-scale composition modulation is probably not formed in the heteroepitaxial $In_{0.52}Al_{0.48}As$ layers. However, this issue needs to be clarified more by a systematic experimental approach consisting of planar view TEM observations on MBE $In_{0.52}Al_{0.48}As$-on-Si samples grown under various conditions.

In conclusion, we have presented low temperature transport measurements showing quantum Hall effect and Subnikov–De Haas oscillations for the 2DEG of an $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ HEMT heterostructure grown on the high lattice mismatched Si. The transport properties characteristic of the InGaAs/InAlAs interface were measured, in spite of the presence of the high defect density in the layers. In addition, optimized $In_{0.52}Al_{0.48}As$ buffers may be grown on Si without developing the coarse-scale composition modulations found in $In_{0.53}Ga_{0.47}As$-on-Si.

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