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Mobility asymmetry in InGaAs/InAlAs heterostructures with InAs quantum wires

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Abstract
Strong asymmetry of electron mobility in InGaAs/InAlAs heterostructures (lattice matched to InP) with the presence of InAs quantum wires was observed. Self-assembled InAs quantum wires, embedded in an InGaAs matrix close to the hetero-interface, has a strong effect in electron conduction in the interface channel. The low temperature mobility for electrons moving parallel to the quantum wires is much higher than that of electrons moving perpendicular to the wires. The asymmetry in mobility is attributed to the difference in scattering cross section of the quantum wires in these two directions.

(Some figures in this article are in colour only in the electronic version)

Semiconductor nanostructures have been widely studied in recent years for their potential device applications and new physical phenomena. Using self-assembly and strain engineering, various kinds of nanostructures can be formed for materials with lattice constants very different from those of the host materials. InAs quantum dots in GaAs are the most widely studied structures [1]. Other structures that have attracted people's attention in recent years are the nanowires formed on materials lattice-matched to InP [2–5]. In the presence of such nanostructures, the electron transport properties will certainly be affected. While quantum dots, like artificial atoms, may act as scattering centres or traps, quantum wires, a one-dimensional structure, should give an orientation-dependent transport characteristic. We have reported an asymmetric transport in an InGaAs two-dimensional electron channel when GaAs anti-wires were nearby [6]. Walther *et al* also reported an asymmetric electrical transport for InAs quantum wires embedded in InP [7]. Scattering behaviour of transport carriers in the quantum wire was investigated theoretically [8]. People also theoretically studied the tunnelling behaviour of the coupled quantum wire system [9].

In this work, we studied the influence of InAs quantum wires, embedded near an InGaAs/InAlAs heterointerface, on the electrical transport behaviour of the 2D channel.

The samples used in this study were grown on (001) oriented semi-insulating InP substrates using a Varian Gen II solid source MBE system. Three samples were prepared. All of them have the same modulation doped structure as shown in figure 1. Lattice-matched InGaAs/InAlAs heterostructures were grown to form a two-dimensional electron gas channel. A 40 nm Si-doped InAlAs was used to supply the carriers to the 2D channel. Sample A, without quantum wires, was used as a reference. Samples B and C, each with an additional InAs quantum wire layer near the 2D channel, were used for the transport study.

The quantum wires in samples B and C were formed with four monolayers of InAs. The growth mechanism for the wires has been discussed in [5]. The wires in Sample B were located 3 nm below the InGaAs/InAlAs interface, while in sample C the wires were grown right at the interface.

After growth, Hall bars oriented along [110] and [$1\bar{1}0$] directions were fabricated for the transport measurement. The Hall measurement was carried out from 10 to 300 K.

Figure 2 is the AFM picture of the InAs wires formed on InGaAs. They are elongated along the [$1\bar{1}0$] direction. Their width and height were about 30 and 2.5 nm, respectively. The average distance between nanowires was about 5 nm. The length varied from about 0.2 to 1 μm. The distinct adatom diffusion coefficient and different reactivity of step edge along the [110] and [$1\bar{1}0$] directions should be the two main factors for the formation of a wire-like structure [10, 11].

Figure 3 shows the electron mobility versus temperature curves along and perpendicular to the wires for all samples. For sample A, where there are no quantum wires, we did

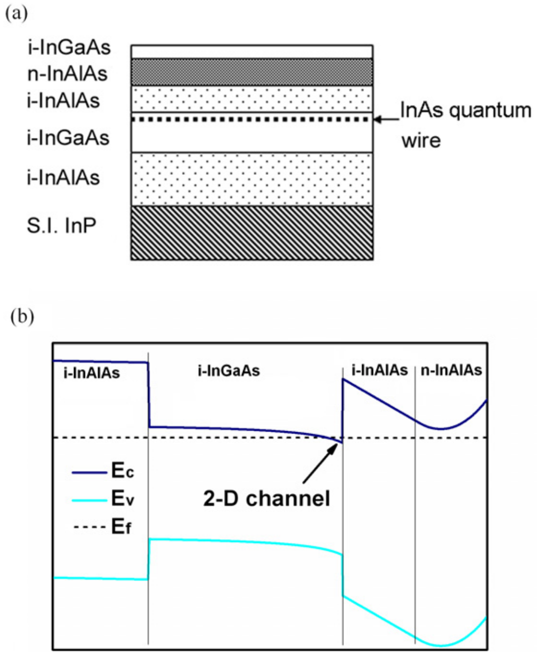

Figure 1. (a) The InGaAs/InAlAs heterostructures used in this study: sample A had no InAs quantum wires; sample B had an extra InAs wire layer 3 nm below the hetero-interface; sample C had the InAs wire layer right at the interface. (b) The band diagram of sample A.

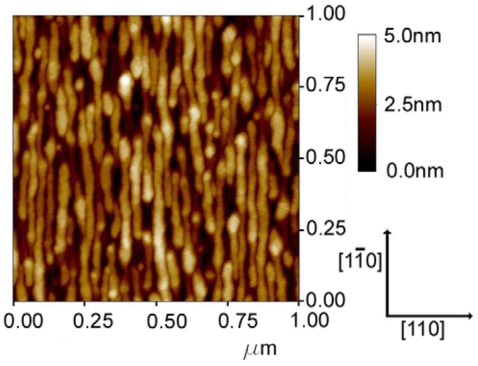

Figure 2. AFM picture of the InAs wires on InGaAs lattice-matched to InP.

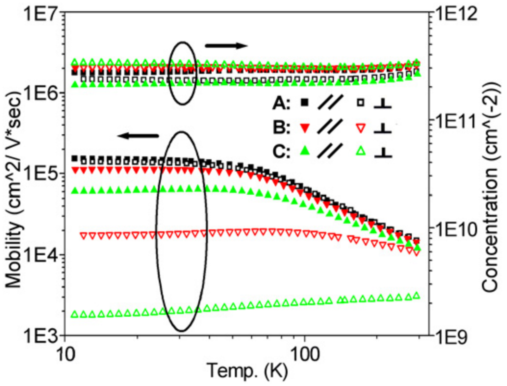

Figure 3. The electron mobility and sheet carrier density as functions of temperature for the three samples parallel and perpendicular to the quantum wires.

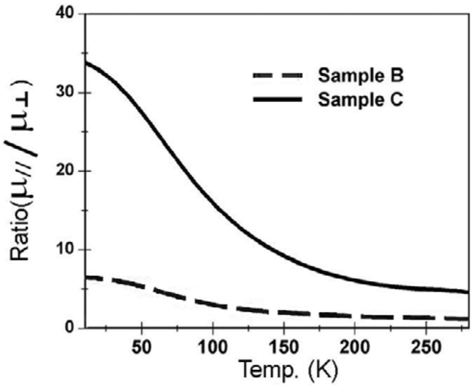

Figure 4. The electron mobility ratio as a function of temperature for samples B and C.

not see any orientation dependence for the mobility. But for samples B and C, the electron mobility showed a clear orientation dependence. The electron mobility was much higher when the transport direction is parallel to the wires. The remarkable difference between [110] and $[1\bar{1}0]$ directions was clearly due to the presence of the wires.

The sheet carrier concentration as a function of temperature for the three samples is also shown in figure 3. Samples A and B had about the same density while sample C had a slightly lower sheet density. There was a small sheet concentration difference between two directions of sample A. This small concentration difference came from the measurement error. The conduction channel of our samples actually consists of a 2D channel at the InGaAs/InAlAs interface and the InAs quantum wires. The fact that the sheet density did not differ very much for different samples and for different conduction directions indicates that the conduction carriers are mainly due to those in the 2D channel at the InGaAs/InAlAs interface. The electrons in the quantum wires played only a minor role. Because of the elongated structure, the electron energy in the quantum wires, unlike quantum dots, is quasi-continuous above the ground quantized state. Furthermore, because of the smaller barrier in the InAs/InGaAs system (as compared with the conventional InAs/GaAs system), the electrons in the wires are weakly confined [12, 13]. The electrons are likely to move around easily and couple together with the 2D electrons in the interface channel. So in this way, the wires behave more like scattering centres instead of conduction channels.

The anisotropy in mobility with the presence of quantum wires, therefore, can be explained by the difference in scattering cross section of the quantum wires. When the electrons move parallel to the wires, the scattering cross section is much smaller than that when the electrons move perpendicular to the wires simply due to the geometry of the wires. The mobility ratio, $\mu_\parallel/\mu_\perp$, for sample B at low temperature is around 6.5 while that for sample C is 33.5. The larger ratio for sample C is probably due to the fact that the quantum wires are right at the heterointerface, which is very close to the conduction channel.

Figure 4 shows the mobility ratio, $\mu_\parallel/\mu_\perp$, for samples B and C as a function of temperature. As the temperature increases, the anisotropy in mobility becomes less. This is reasonable since the role of scattering centres played by quantum wires becomes less important as temperature increases and the orientation-independent phonon scattering takes over as the dominant scattering mechanism.

In conclusion, we were able create an anisotropic conduction medium using quantum wires. Self-assembled InAs quantum wires in InGaAs/InAlAs heterostructures cause mobility asymmetry for the electron conduction in the 2D channel. At low temperatures, electron mobility parallel to the wires is much higher than that perpendicular to the wires. The asymmetry in mobility is attributed to the difference in scattering cross section of the quantum wires in these two directions. In the presence of the wires, if designed properly, the mobility of the 2D channel parallel to the wires can be made nearly as high as the channel without the wires, while at the same time an order of magnitude lower in mobility exists for conduction perpendicular to the wires. This possibility of creating an artificial asymmetric conduction medium should find interesting applications in electronic devices.

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