Transport properties of two-dimensional electron gases containing linear ordering InAs self-assembled quantum dots

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We present a study of the anisotropic properties of two-dimensional electron gases formed in GaAs/AlGaAs heterostructures in which InAs self-assembled quantum dots have been inserted into the center of a GaAs quantum well. We observe an anisotropic mobility for the orthogonal [110] and [1$\bar{1}$0] directions. The mobility in the [110] direction was found to be up to approximately twice that in the [1$\bar{1}$0] direction. It is suggested that the interface roughness scattering due to the inserted InAs material could be a cause for the large anisotropies in mobility. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1378801]

The electronic and structural properties of self-assembled quantum dots have attracted a great deal of interest during the past years. Research has been directed towards both their fundamental physics and device applications such as quantum dot optical memory devices,[1] lasers,[2] infrared photodetectors,[3] and single-electron transistors.[4] While a great deal of work has been undertaken on the structural and optical properties of the self-assembled quantum dots, little has been reported on their electron transport properties.

In this letter, we investigate the transport lifetimes of electrons in GaAs quantum wells with *in situ* InAs self-assembled quantum dots. Here, the InAs self-assembled dots form a lateral linear structural arrangement in the [1$\bar{1}$0] direction. Samples are measured with a range of InAs self-assembled quantum dot densities. We find that the transport lifetime in the [1$\bar{1}$0] direction is significantly higher than that in the [110] direction.

Figure 1(a) shows a cross sectional schematic illustration of a molecular beam epitaxial grown *n*-AlGaAs/GaAs heterojunction on an undoped GaAs (001) substrate. The structure consists of a 0.6 μm thick undoped GaAs buffer layer, followed by a 500 Å undoped $Al_{0.33}Ga_{0.67}As$ barrier, a 200 Å undoped GaAs quantum well, a 400 Å undoped $Al_{0.33}Ga_{0.67}As$ spacer layer, a 400 Å Si-doped (1×10^{18} cm^{-3}) $Al_{0.33}Ga_{0.67}As$ layer, and finally, a 170 Å GaAs capping layer.

During a growth interrupt, an InAs layer with a coverage of 2.15 monolayers (ML) was grown (Stranski–Krastanov growth) into the central part of the GaAs quantum well. The InAs self-assembled quantum dots were covered with either a 50 Å (wafer A) or 100 Å (wafer B) GaAs cap grown at a substrate temperature of 530 °C as measured by an optical pyrometer. The remainder of the structure was grown at 580 °C. Before growing these wafers, in order to determine the growing conditions, ultrahigh vacuum *in situ* scanning tunneling microscopy (STM) and atomic force microscopy (AFM) images were studied from more than 15 wafers.

The wafers were processed into an orthogonal patterned Hall bar geometry, which had the current channels in the (110) and (1$\bar{1}$0) directions. Ohmic contacts were formed from an annealed thermally evaporated AuGeNi alloy and a transparent NiCr/Au gate was evaporated onto the top of the structure. A bias applied to the gate affects the conduction band in Fig. 1(b) varying the carrier density n_s in the two-dimensional electron gas (2DEG). All measurements were performed after a brief illumination of the device. The magnetoresistance was measured using standard four-terminal ac phase sensitive techniques at a temperature of 1.6 K. Transmission electron microscopy (TEM) images of the InAs dots were obtained using a JEOL-2000EX (200 kV) microscope. Both cross section [in Fig. 1(c)] and plan view (in Fig. 2) specimens were prepared using conventional mechanical polishing followed by ion milling on a liquid nitrogen cooled stage.

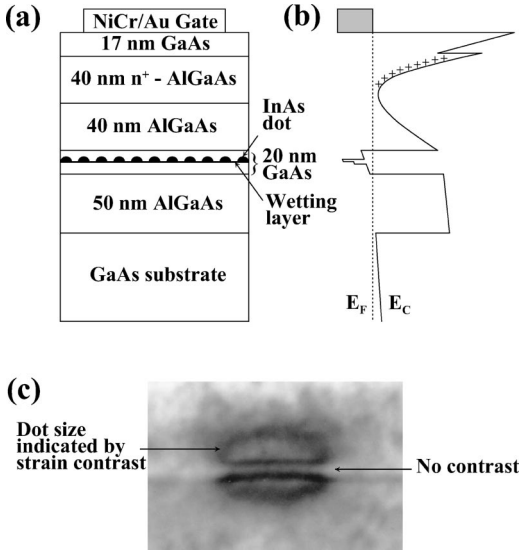

FIG. 1. The cross section of a *n*-AlGaAs/GaAs heterojunction grown on a GaAs (001) substrate is illustrated in (a), conduction band diagram (b), and a cross sectional TEM image of a coherent InAs cluster formed in the GaAs well (c).

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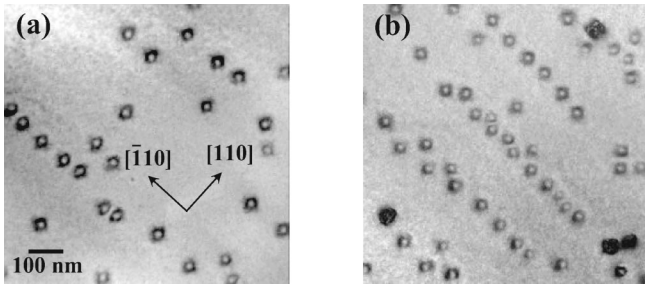

FIG. 2. Plan view TEM images of sample for (a) GaAs capping layer $d_c = 50$ Å (the center of wafer A) and (b) $d_c = 100$ Å (the center of wafer B).

When InAs is grown on a GaAs layer, the first few atomic layers of InAs arrange themselves in a planar layer called the wetting layer. As epitaxial growth proceeds, the atoms tend to bunch up and form clusters. Plastic relaxation of the clusters reduces the strain energy within the dots and is energetically favorable over the growth of pseudomorphic quantum dots, for the larger dots. We have carried out an extensive study to characterize the growth of self-assembled dots.[5] Figure 1(c) shows a cross sectional strain field TEM image of an unrelaxed InAs dot buried in a GaAs quantum well, consistent with the prediction of the elastic theory. By symmetry, the lattice plane bisecting the quantum dots is not bent. Therefore, there is a line of no contrast in the strain imaging. The existence of a significant strain field in the vicinity of InAs strained dots means that the transport of electrons is also affected by the strain field.[4] Figure 2 shows plan view TEM images from wafer Ac (wafer center) and Bc, each with different dot densities n_d. These samples were taken from the center of the wafers. The experimental dot densities for Ac [Fig. 2(a)] and Bc [Fig. 2(b)] are $n_d = 3.0 \times 10^9$ and 5.8×10^9 cm^{-2}, respectively, counting from an area of 12 μm^{-2}. The average dimensions of the dots are ~280 Å wide and ~40 Å high in sample Ac and ~360 Å wide and ~80 Å high in sample Bc. The number of incoherent (plastically relaxed) clusters in sample Bc is approximately 12% of the total clusters present, whereas no incoherent clusters are observed in the Ac samples. The InAs dots are aligned in the [110] direction on the GaAs(001) surface, for both samples.

Resistivity measurements of our samples suggest a marked anisotropy in the transport lifetime between the orthogonal [110] and [110] directions. Figure 3 shows typical magnetoresistance data in the two orthogonal directions for samples Ac and Bc at 1.6 K. In these measurements, the carrier density n_s was 3.0×10^{11} cm^{-2}. The mobility in wafer A, for the same direction and positions on the wafers, is more than twice that of wafer B. This difference is due to the reduction in mobility caused by the increased short range scattering[6] from the higher dot density. For both sample Ac in Fig. 3(a) and sample Bc in Fig. 3(b), the longitudinal resistivity at zero magnetic field is larger in the [110] direction. However, a comparison of Figs. 3(a) and 3(b) shows that the ratio of anisotropic mobility in the two directions increases as the density of InAs dots increases. In the inset of the Fig. 3, the carrier density was 2.6×10^{11} cm^{-2} for the reference sample, which are the same structures without InAs self-assembled dots in the GaAs quantum well. This ratio of the anisotropic resistance is 17% in the two orthogonal directions. However, as shown in Figs. 3(a) and 3(b), for two typical mobilities, the anisotropy ratio of the inserted InAs self-assembled quantum dots has much higher values of 31% and 56%, respectively. This mobility anisotropy is caused by an anisotropy in scattering from the planar arrangements of InAs material.

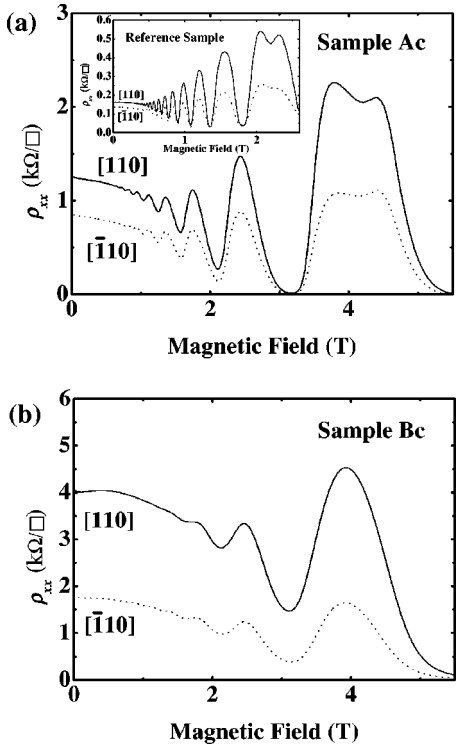

FIG. 3. Showing the longitudinal resistivity at a carrier density of 3.0×10^{11} cm^{-2} in the [110] and [110] directions for samples from the center of wafers (a) A and (b) B. In the inset, for the reference sample, the carrier density 2.6×10^{11} cm^{-2} in the two orthogonal directions.

We have determined the transport and quantum lifetimes from the mobility and an analysis of Shubnikov–de Haas (SdH) oscillation amplitudes, respectively. The anisotropic transport lifetimes in sample Ac are found to be 0.91 ps in the [110] direction and 0.63 ps in the [110] direction. For sample Bc, transport lifetimes are 0.41 and 0.19 ps in the [110] and [110] directions, respectively. For the reference sample, the transport lifetimes are 6.62 and 5.67 ps in the [110] and [110] directions, respectively. These determine the transport lifetimes through the empirical relation from the mobility $\mu = e\tau/m^*$, where e is the electron charge, τ is the transport lifetime, and m^* is the effective mass. The observation of SdH oscillations at high fields presupposes that the electrons are moving in cyclotron orbits, whose coherence is defined by the quantum lifetime. Thus, the electron experiences scattering in all directions as it travels on its circular trajectory and hence the quantum lifetime has no directional dependence. We determined that the quantum lifetimes are 0.22 and 0.08 ps for samples Ac and Bc, respectively, and are direction independent. For samples Ac and Bc, the ratio of the transport to the quantum lifetime is approximately five, which is short range scattering due to the InAs.[6] In our previous study[4] of single electron transistor measurements, the potential barrier with the self-assembled quantum dots is induced by strain between InAs/GaAs. This transport results can be explained by assuming that the InAs dots introduce as

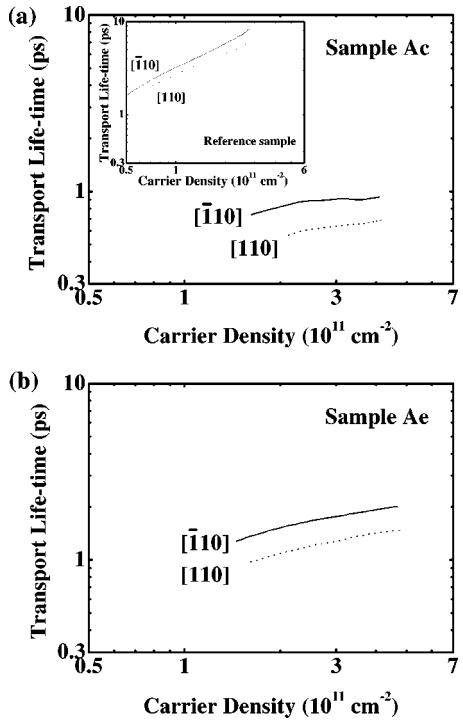

FIG. 4. Transport lifetimes measured in samples from the center (the ratio of the anisotropic transport lifetimes: ~31%) and edge (~27%) of wafer A in the [110] and [1$\bar{1}$0] directions as a function of carrier density at 1.6 K. In the inset, for the reference sample, the ratio of anisotropic transport lifetimes is ~17%.

the scatters. In the sample with more InAs, there is greater disorder,[4] and the observed increase in the anisotropy is induced by the presence of InAs. At very low magnetic fields, where the transport lifetimes are determined, the electron predominantly moves in one direction and thus anisotropic scattering will affect the transport lifetimes. This difference supports the proposal that the mobility anisotropy originates from the lateral alignment of InAs dots in the [110] direction.

Figure 4 shows the transport lifetime at 1.6 K as a function of n_s for samples Ac and Ae (wafer edge). We determined the transport lifetimes from the mobilities and n_s, from low field Hall measurements. The transport lifetimes in sample Ac are approximately half that of sample Ae for the same direction. As the sampling point moves towards the wafer center, the InAs dot density increases, reducing the transport lifetime.[6] For sample Ac in Fig. 4(a), the transport lifetimes in the [110] direction are approximately 31% larger than those in the [1$\bar{1}$0] direction at $n_s = 3.0 \times 10^{11}$ cm^{-2}. By increasing the electron density (n_s), there is a decrease in the ratio of anisotropic transport lifetimes.[7] The inset of Fig. 4(a) shows the transport lifetime as a function of n_s for the reference sample (without the insertion of a InAs self-assembled dots in the GaAs quantum well). The ratio of the anisotropic transport lifetime is ~17% in the two orthogonal directions for the reference sample in contrast to 31% for sample Ac. It is well known that for 2DEGs grown on the (001) surface of GaAs, the mobility in the [110] direction can be higher than that in the [1$\bar{1}$0] direction, under certain growth conditions due to the formation of elongated islands at the GaAs/AlGaAs interface.[8] However, any potential barrier due to the island formation at this heterointerface is sufficiently small that it does not manifest itself in the two orthogonal directions.

For sample Ae in Fig. 4(b), the ratio of the anisotropic transport lifetimes (~27%) are almost constant values over all n_s. The cause of this invariance is apparent from TEM images and photoluminescence measurements from the edge of wafer A which show that the InAs coverage decreases towards edge of the wafer.[6] For the edge devices used in this letter, only the wetting layer remains.

A possible cause for the anisotropic transport lifetimes is that [110] surface steps are caused by an unintentional very small angular miscut of the GaAs (001) wafer. Therefore, the initial growth of the submonolayer InAs islands on the GaAs surface are elongated in the [110] directions, as seen in *in situ* STM and AFM images. Such behavior has been reported by Tillmann *et al.*[9] for InGaAs islands grown on GaAs (001) substrates. During the initial InAs growth, the elongated islands form, and upon increasing the InAs coverage above 1.61 ML, the InAs dots nucleate at the step edges. Therefore, InAs dots become linearly ordered in the [110] directions as may be observed in Fig. 2. This increases the electron scattering in this direction thereby modifying the mobility. The ratio of the anisotropic transport lifetimes increases with an increase of InAs self-assembled dot density.

In summary, we have measured the anisotropic mobility in 2DEGs containing InAs self-assembled quantum dots with a lateral linear structural arrangement. We have prepared samples with varying amounts of dots (two of 14 were presented here) and without dots (reference samples). From the electron transport results, we can determine the anisotropic transport lifetime as a function of carrier density and find that the anisotropy ratio of the mobilities for samples Ac and Bc are 56% and 31%, respectively. The results demonstrate that the mobility anisotropy increases with an increasing InAs dot density, where the mobility in the [110] direction is much higher than that in the [1$\bar{1}$0] direction. We propose that the linear arrangement of self-assembled InAs quantum dots results in reduced mobilities for motion perpendicular to the lines. This enables direct calculations to be made of the scattering properties of the dots.

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[7] The electron scattering decreases as the electron wavelength is reduced upon increasing the carrier density. The peak of the Fang–Howard wave function is shifted from the center of the GaAs quantum well towards the edge (away from the InAs scattering centers) with increasing carrier density. Therefore, the ratio of the anisotropic scattering is reduced at higher carrier density.
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