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 [110] directions. The mobility in the [110] direction was found to be up to approximately twice that in the [110] 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, lasers, infrared photodetectors, and single-electron transistors. 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 [110] direction. Samples are measured with a range of InAs self-assembled quantum dot densities. We find that the transport lifetime in the [110] 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 Al0.33Ga0.67As barrier, a 200 Å undoped GaAs quantum well, a 400 Å undoped Al0.33Ga0.67As spacer layer, a 400 Å Si-doped (1 × 1018 cm−3) Al0.33Ga0.67As 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 (110) 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 hetero junction 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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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. 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. 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 \( 5.8 \times 10^9 \) cm\(^{-2}\), respectively, counting from an area of 12 \( \mu m^2 \). The average dimensions of the dots are \( \sim 280 \) Å wide and \( \sim 40 \) Å high in sample Ac and \( \sim 360 \) Å wide and \( \sim 80 \) 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 [\( \overline{1}10 \)] 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 \( 3.0 \times 10^{11} \) 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 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 [\( \overline{1}10 \)] 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 \( 2.6 \times 10^{11} \) 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.

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 [\( \overline{1}10 \)] direction. For sample Bc, transport lifetimes are 0.41 and 0.19 ps in the [110] and [\( \overline{1}10 \)] directions, respectively. For the reference sample, the transport lifetimes are 6.62 and 5.67 ps in the [110] and [\( \overline{1}10 \)] directions, respectively. These determine the transport lifetimes through the empirical relation from the mobility \( \mu = e \tau / m^* \), where \( e \) is the electron charge, \( \tau \) 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. In our previous study 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
As the sampling point moves towards the wafer edge, the InAs coverage decreases towards edge of the wafer. For the edge devices used in this letter, only the wetting layer remains.

A possible cause for the anisotropic transport lifetimes is that the [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. 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-assembly 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 [110] 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.

8 The electron scattering decreases as the electron wavelength is reduced sufficiently small that it does not manifest itself in the two orthogonal directions.
9 For sample Ae in Fig. 4(b), the ratio of the anisotropic transport lifetimes (~27%) are almost constant values over all n_x. 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. For the edge devices used in this letter, only the wetting layer remains.

![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 [110] directions as a function of carrier density at 1.6 K. In the inset, the reference sample, the ratio of anisotropic transport lifetimes is ~17%.](image-url)