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Anisotropic Mobility of Two-Dimensional Electron Gases Containing Linearly Ordered 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 $[\bar{1}10]$ and [110] directions. The mobility in the $[\bar{1}10]$ direction was found to be up to twice that in the [110] direction. It is suggested that the observed linear ordering of the self-assembled InAs quantum dots in the $[\bar{1}10]$ direction is the cause for the large mobility anisotropy.

I. INTRODUCTION

The electronic and the 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 the optical properties of the self-assembled quantum dots, little has been reported on their electron transport properties.

In this paper, we investigate the transport lifetimes of electrons in GaAs quantum wells with *in situ* InAs self-assembled quantum dot. Here, the InAs self-assembled dots form a lateral linear structural arrangement in the $[\bar{1}10]$ direction. Samples are measured with a range of InAs self-assembled quantum dot densities. We find that the transport lifetime in the $[\bar{1}10]$ direction is significantly higher than that in the [110] direction.

II. EXPERIMENTS

The self-assembled InAs dots are grown in an n-AlGaAs/GaAs heterojunction on an undoped GaAs (001) substrates. 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) is grown (Stranski-Krastanov growth) into the central part of the GaAs quantum well. The InAs self-assembled quantum dots are covered with either a 50 Å (wafer A) or a 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 is grown at 580 °C. Before growing these wafers, in order to determine the growing conditions, we studied ultra-high vacuum *in-situ* scanning tunneling microscopy (STM) and atomic force microscopy (AFM) images from more than 15 wafers.

The wafers are processed into an orthogonally patterned Hall bar geometry, which has the current channels in the (110) and the $(\bar{1}10)$ directions: each Hall bar has a width of 80 μm and length of 800 μm. Ohmic contacts are formed from an annealed thermally evaporated AuGeNi alloy and a transparent NiCr/Au gate is evaporated onto the top of the structure. A bias applied to the gate affects the conduction band, varying the carrier density n_s in the two-dimensional electron gas (2DEG).

All measurements were performed after brief illumination of the device with a red light-emitting diode. The magnetoresistance was measured using standard four-terminal ac phase sensitive techniques at a temperature of 1.6 K with a constant source-drain current of 100 nA at 73 Hz. Transmission electron microscopy (TEM) images of the InAs dots were obtained using a JEOL-2000EX (200 kV) microscope. The plan view [in Fig 1] specimens were prepared using conventional mechanical polishing followed by ion milling on a liquid-nitrogen-cooled

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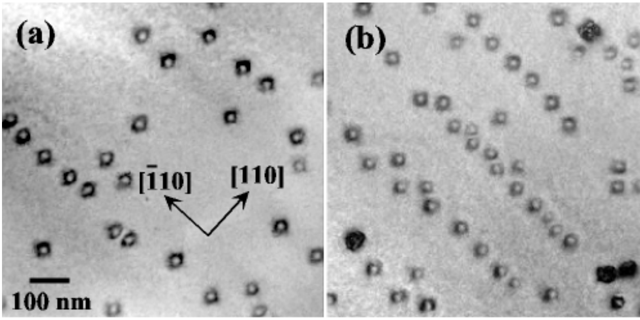

Fig. 1. Plan view TEM images of sample for (a) GaAs capping layer d_c = 50 Å (the centre of wafer A) and (b) d_c = 100 Å (the centre of wafer B).

stage.

III. RESULTS AND DISCUSSION

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 larger dots. We carried out an extensive study to characterize the growth of self-assembled dots [5]. Figure 1 shows plan view TEM images from wafers Ac and Bc, each with a different dot density n_d. These samples were taken from the center of the wafers. The experimental dot densities for Ac [Fig. 1(a)] and Bc [Fig. 1(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 $\sim$ 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 [$\bar{1}$10] 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 [$\bar{1}$10] and [110] directions. Figure 2 shows typical magneto-resistance data in the two orthogonal directions for samples Ac and Bc at 1.6 K. In these measurements, n_s was 3.0×10^{11} cm^{-2}. The mobility in wafer A, for the same direction and positions on the wafers, is more than twice that in wafer B. This difference is due to a reduction in mobility caused by increased short-range scattering [6,7] from the higher dot density. For both sample Ac in Fig. 2(a) and sample Bc in Fig. 2(b), the longitudinal resistivity at zero magnetic field is larger in the [$\bar{1}$10] direction. However, comparison of Fig. 2(a) with Fig. 2(b) shows that the ratio of anisotropic mobility in the two directions increases as the density of InAs dots increases. For the reference sample, which are the same structures without InAs self-assembled dots in the GaAs quantum well, the ratio of the anisotropic resistance is 17 % in the two orthogonal directions. However, as shown in Fig. 2(a) and Fig. 2(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 dots.

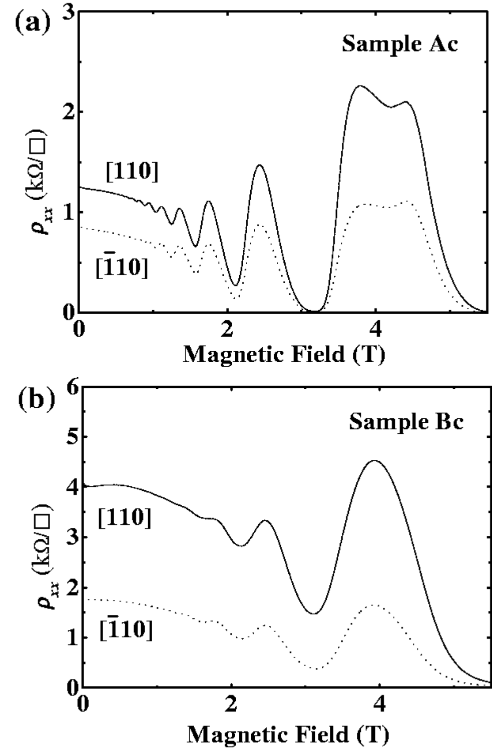

Fig. 2. Showing the longitudinal resistivity at a carrier density of 3.0×10^{11}cm^{-2} in the [$\bar{1}$10] and [110] directions for samples from the centre of wafers (a) A and (b) B.

We determined the transport and the 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 [$\bar{1}$10] direction and 0.63 ps in the [110] direction. For sample Bc, the transport lifetimes are 0.41 ps and 0.19 ps in the [$\bar{1}$10] and [110] directions, respectively. 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; hence, the quantum lifetime has no directional dependence. We determined that the quantum lifetimes were 0.22 ps and 0.08 ps for samples Ac and Bc, respectively, and are direction independent. At very low magnetic fields, where the transport lifetimes are determined,

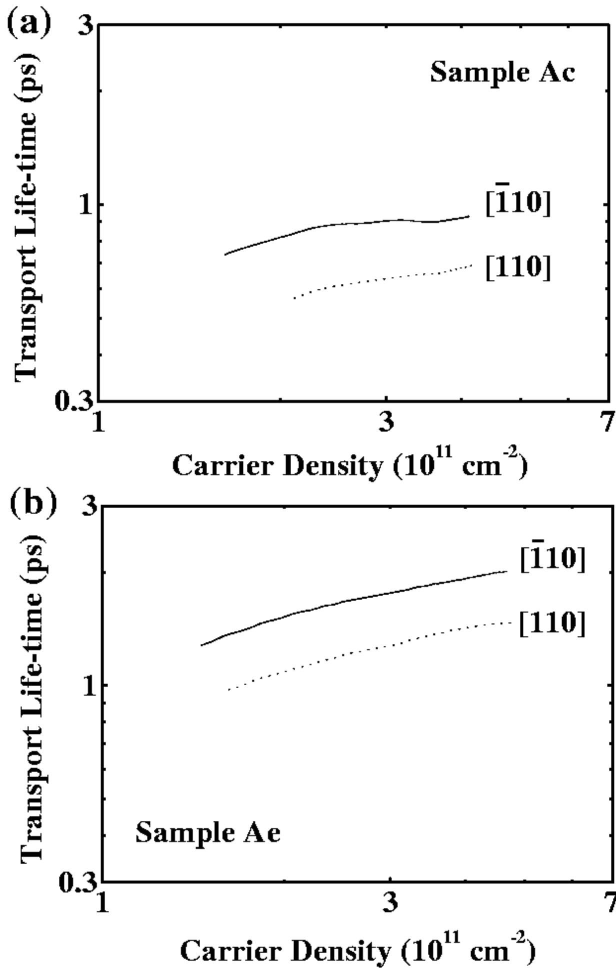

Fig. 3. Transport lifetimes measured in samples from the center and edge of wafer A in the [$\bar{1}$10] and [110] directions as a function of carrier density at 1.6 K.

the electron predominantly moves in one direction; 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 [$\bar{1}$10] direction.

Figure 3 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 those 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. 3(a), the transport lifetimes in the [$\bar{1}$10] direction are approximately 31 % larger than those in the [110] direction at $n_s = 3.0 \times 10^{11}$ cm^{-2}. Increasing the electron density (n_s) decreases in the ratio of anisotropic transport lifetimes [8]. For sample Ae in Fig. 3(b), the ratio of the anisotropic transport lifetimes ($\sim$ 27 %) is 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 the edge of the wafer [6]. For the edge devices used in this work, only the wetting layer remains.

A possible cause for the anisotropic transport lifetimes is that [110] surface steps caused by an unintentional, very small, angular miscut of the GaAs (001) wafer. Therefore, the initial growth of the sub-monolayer InAs islands on the GaAs surface are elongated in the [$\bar{1}$10] directions, as seen in *in-situ* STM and AFM images. Such behavior has been reported by Tillmann *et al*. [9] for InGaAs islands grown on GaAs (001) substrates. During the initial InAs growth, the elongated islands form, and upon increasing the InAs coverage above 1.61 ML, the InAs dots nucleate at the step edges. Therefore, InAs dots become linearly ordered in the [$\bar{1}$10] directions, as may be observed in Fig. 1. This increases the electron scattering in this direction, thereby modifying the mobility. The ratio of the anisotropic transport lifetimes increases with increasing InAs self-assembled dot density.

IV. CONCLUSIONS

We have measured the anisotropic mobility in 2DEGs containing InAs self-assembled quantum dots with a lateral linear structural arrangement. The mobility anisotropy depends on the InAs dot density, where the mobility in the [$\bar{1}$10] 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.

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