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Effects of two-dimensional electron gas on the optical properties of InAs/GaAs quantum dots in modulation-doped heterostructures

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The Shubnikov–de Haas data showed that the carrier density of two-dimensional electron gas (2DEG) in the GaAs active region containing InAs quantum dot (QD) arrays embedded between modulation-doped $Al_{0.25}Ga_{0.75}As$/GaAs heterostructures increased with increasing doping concentration in the modulation layer. The transmission electron microscopy images showed that the sizes of the self-assembled InAs vertically stacked QD arrays inserted in the GaAs did not change significantly with increasing carrier density of the 2DEG. The photoluminescence (PL) spectra showed that the peaks corresponding to the interband transitions from the ground electronic subband to the ground heavy-hole subband of the InAs QDs shifted to the higher energy side with increasing density of the 2DEG and that the full width at half maximum of the PL spectrum increased slightly with increasing density of the 2DEG. © *2005 American Institute of Physics*.
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Potential applications of electronic and optoelectronic devices and investigations of the fundamental physics utilizing self-assembled quantum-dot (QD) structures grown by using the Stranski–Krastanov (SK) growth mode have driven extensive and successful efforts to grow various kinds of QDs.[1–10] Recently, the carrier dynamics of QDs have become particularly interesting because of promising applications to optoelectronic devices such as injection lasers,[11,12] wavelength switching devices,[13] and optical memories.[14] Since the microstructural properties of QDs significantly affect their optical and electrical properties, which are important for fabricating of high-efficiency optoelectronic and electronic devices, studies of the physical properties are very important for optoelectronic and electronic devices based on QD structures. Some studies concerning the influences of the QDs close to the two-dimensional electron gas (2DEG) on the electrical properties have been investigated.[15–18] Very few works on the effect of the density of the 2DEG on the microstructural and the optical properties of InAs QD arrays inserted into GaAs embedded between modulation doped $Al_xGa_{1-x}As$/GaAs heterostructures have been studied.

This letter reports data for the magnetotransport, the microstructural, and the optical properties of InAs QD arrays inserted in GaAs layers embedded between modulation-doped $Al_xGa_{1-x}As$/GaAs heterostructures which had various doping densities and which were grown by using molecular beam epitaxy (MBE). Shubnikov de Haas (SdH) measurements were carried out in order to determine the carrier density in the GaAs layer. Transmission electron microscopy (TEM) measurements were performed to characterize the microstructure in the InAs QD arrays inserted into the GaAs layers, and photoluminescence (PL) measurements were carried out in order to investigate the interband transitions in the sample.

The samples used in this work were grown on semi-insulating (100)-oriented GaAs substrates by using MBE. The InAs and the GaAs growth rates were set to 0.19 and 1.42 monolayer (ML)/s, respectively. The whole growth process was controlled *in situ* by using reflection high energy electron diffraction (RHEED). First, a 100-nm-thick GaAs buffer layer was grown at 530 °C, which was followed by 20 periods of an $Al_{0.25}Ga_{0.75}As$/GaAs superlattice buffer layer and then by a 200 nm undoped GaAs buffer layer. After a 40 nm $Al_{0.25}Ga_{0.75}As$ layer, a Si delta-doped layer, and a 6 nm $Al_{0.25}Ga_{0.75}As$ layer had been grown, the substrate temperature was lowered to 410 °C for the QD superlattice growth. For each period, a 2.5 ML InAs layer was deposited followed by a GaAs spacer layer after a 20 s growth interruption. The RHEED pattern became spotty after an InAs deposition of 1.8 ML, indicating three-dimensional island formation. The GaAs spacer layer thickness was 6 nm. After the substrate temperature had been increased to 430 °C, a 10 nm undoped GaAs layer, a 6 nm $Al_{0.25}Ga_{0.75}As$ spacer layer, and a Si delta-doped layer were grown sequentially. Four Si delta-doped concentrations were used: 1.26, 1.98 2.25 and 2.41 $\times 10^{12}$ cm^{-2}, which were denoted by S1, S2, S3, and S4, respectively. Then, a 40 nm undoped $Al_{0.25}Ga_{0.75}As$ layer was grown, followed by a 5 nm Si-doped GaAs capping

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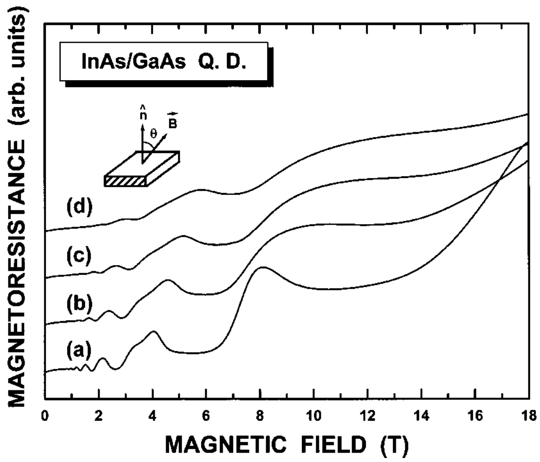

FIG. 1. Shubnikov–de Haas results at 1.5 K of the InAs quantum dots inserted in the GaAs barriers embedded between modulation doped $Al_{0.25}Ga_{0.75}As/GaAs$ heterostructures with different modulation doping concentrations.; (a) S1, (b) S2, (c) S3, and (d) S4.

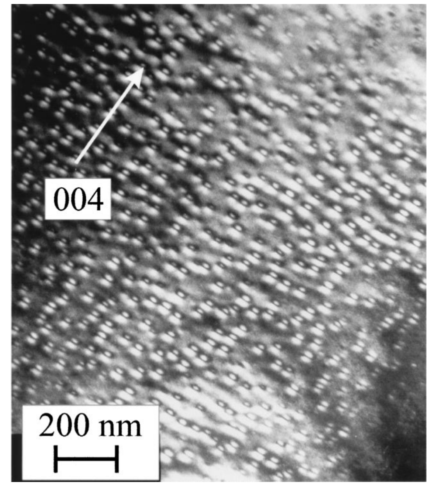

FIG. 2. Plan-view bright-field transmission electron microscopy image for [004] two-beam diffraction from InAs quantum dots inserted into GaAs barriers embedded between Si-doped $Al_{0.25}Ga_{0.75}As/GaAs$ heterostructures with a doping concentration of 1.26×10^{12} cm^{-2}.

layer. Five periods of the InAs self-assembled QD arrays were grown at 410 °C via the SK mode.[19]

The results of the SdH measurements with the magnetic field oriented normal to the interface are shown in Fig. 1. The 2DEG carrier densities determined from the SdH measurements increased with increasing doping concentration in the modulation layer. However, it is not possible to determine from the present measurements with certainty whether how many electrons are occupied in the InAs QDs.

Figure 2 shows a plan-view bright-field TEM image for [004] two-beam diffraction from InAs QDs inserted in an undoped GaAs matrix embedded between Si-doped $Al_{0.25}Ga_{0.75}As/GaAs$ heterostructures with a doping concentration of 1.26×10^{12} cm^{-2}. Strained QDs are clearly observed, as indicated by the characteristic dark and bright contrast related to an inhomogeneous lattice deformation in a three-dimensional structure.[20] The sizes of the QDs are approximately between 20 and 30 nm, and the real surface density of the QDs is approximately 3×10^{10} cm^{-2}. The morphology observed in Fig. 2 can be explained by the thermodynamics of island growth.[21] Even though the formation of the QDs releases the strain energy, they might build up a local stress concentration; thus, the central white and black contrast in the InAs QD islands originate from the strain effects for the transition from two-dimensional to three-dimensional nucleation.[22]

Figure 3 shows plan-view bright-field TEM images of the [001] zone of the InAs QDs inserted in the GaAs barriers embedded between modulation doped $Al_{0.25}Ga_{0.75}As/GaAs$ heterostructures for different modulation doping concentrations. The size and the shape of the QDs do not change significantly with varying doping carrier concentration. The density of the 2DEG and the Si-doping seed layer with different doping concentrations are independent of the microstructures of the InAs QDs. The 2DEG forming in the GaAs layer side which is separated by the spacer layer from the ionized donors in the $Al_{0.25}Ga_{0.75}As$ layer might not affect the formation of the size of the InAs QDs.

Figure 4 shows PL spectra measured at 26 K for InAs/GaAs QD arrays embedded in GaAs barriers inserted between Si modulation doped $Al_{0.25}Ga_{0.75}As/GaAs$ heterostructures. The PL spectra at 26 K shows that the peaks corresponding to the interband transition in the InAs/GaAs QDs shift to the higher energy side with increasing Si doping concentration. These peaks are related to the interband transition from the ground electronic subband to the ground heavy-hole subband $(E_1\text{-}HH_1)$ of the InAs/GaAs QDs. The blueshift of the peak corresponding to the $(E_1\text{-}HH_1)$ interband transition of the InAs/GaAs QDs with increasing Si doping concentration might be attributed to the more occupation by the electrons of the subband level in the InAs/GaAs QDs.[23] The full widths at half maximum of the PL peaks of InAs/GaAs QDs is approximately 80–90 meV. The broadness of the PL peaks might originate from the various sizes of the quantum dots or from the electrons in the Si modulation layer that move into InAs QDs. In Si-doped modulation-doped heterostuctures, electrons are transferred from $Al_{0.25}Ga_{0.75}As$ barriers to the GaAs conduction band. Therefore, while 2DEGs occupy the GaAs layer, few electrons occupy the subband level in the InAs/GaAs QDs.

PL spectra measured at 300 K depict that the peaks corresponding to the $(E_1\text{-}HH_1)$ interband transition of the InAs/GaAs QDs shift to the low energy side with increasing temperature and that the distribution of carriers in the InAs/

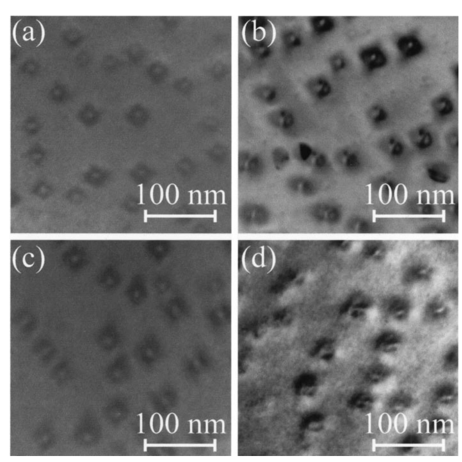

FIG. 3. Plan-view bright-field transmission electron microscopy images of the [001] zone of the InAs quantum dots inserted in the GaAs barriers embedded between modulation doped $Al_{0.25}Ga_{0.75}As/GaAs$ heterostructures with different modulation doping concentrations.; (a) S1, (b) S2, (c) S3, and (d) S4.

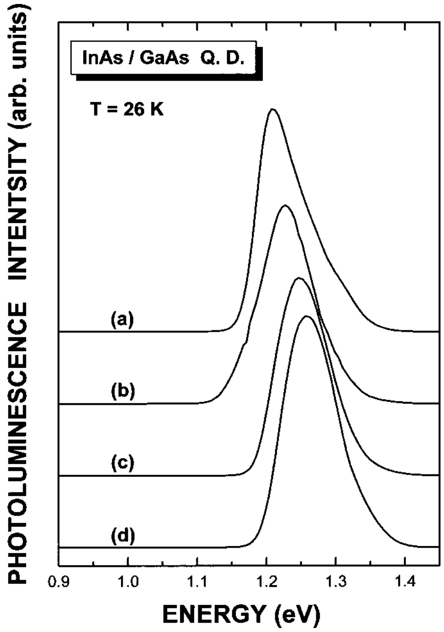

FIG. 4. Photoluminescence spectra measured at 26 K for InAs quantum dot arrays embedded into GaAs barriers with different modulation doping concentrations; (a) S1, (b) S2, (c) S3, and (d) S4.

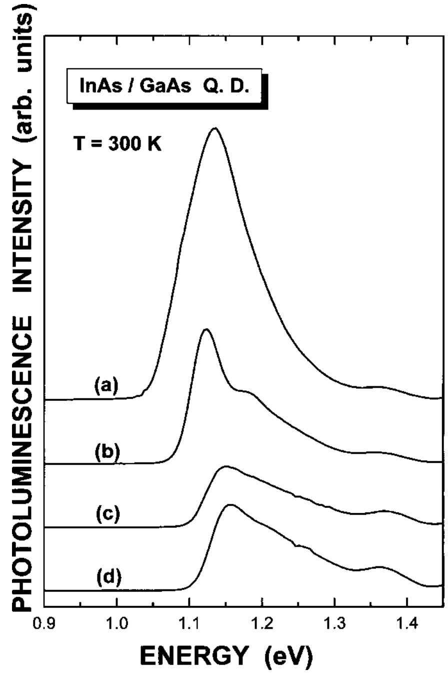

FIG. 5. Photoluminescence spectra at 300 K for InAs quantum dot arrays embedded into GaAs barriers with different modulation doping concentrations; (a) S1, (b) S2, (c) S3, and (d) S4.

GaAs QDs varies with changing temperature, as shown in Fig. 5. The PL spectra at 300 K for the S1 sample shows a broad luminescence peak at 1.124 eV, together with two shoulders, one at 1.185 and the other at 1.359 eV; the peak has an asymmetric shape with a tail on the high energy side. The separation between the ground-state and the excited-state peaks is approximately 60 meV, which is similar to the value reported for InAs/GaAs QDs in other literature.[24] The broad dominant PL peak at 1.124 eV and the shoulder at 1.185 eV are attributed to $(E_1\text{-}HH_1)$ transitions of the large and the small InAs QDs, respectively. The broad PL peak at 1.359 eV is related to the wetting layer. The PL spectra at 300 K for samples S3 and S4 are similar to that of S1, except both the ground-state and excited-state energy positions shift to higher energy.

In summary, the results of SdH measurements showed that the carrier density of 2DEG in the GaAs active region containing InAs QD arrays embedded between modulation-doped $Al_{0.27}Ga_{0.73}As$/GaAs heterostructures increased with increasing doping concentration. The TEM images showed that the self-assembled InAs vertically stacked QD arrays inserted in the GaAs layers had no dislocations and that the microstructures of the InAs QDs were not affected significantly by the 2DEGs. The PL spectra showed that the peaks corresponding to the $(E_1\text{-}HH_1)$ interband transitions of the InAs/GaAs QDs shifted to higher energy with increasing Si doping concentration in the $Al_{0.27}Ga_{0.73}As$ barrier. The full width at half maximums of the PL spectra were approximately 80–90 meV.

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