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Dependence of the electronic parameters on the $In_yGa_{1-y}As$ quantum well width in modulation-doped $Al_xGa_{1-x}As$/$In_yGa_{1-y}As$/GaAs strained single quantum wells

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Abstract

The variation of the electronic parameters in the subband as a function of the $In_yGa_{1-y}As$ quantum well width in modulation-doped strained $Al_xGa_{1-x}As$/$In_yGa_{1-y}As$/GaAs single quantum wells were investigated by means of Shubnikov-de Haas (S-dH) and Van der Pauw Hall-effect measurements. The fast Fourier transform (FFT) of the S-dH oscillations and the Hall-effect data showed that the carrier density and the mobility of the two-dimensional electron gas (2DEG) occupied in the subband increased as the quantum well width increased. The increase in the 2DEG density with increasing the $In_yGa_{1-y}As$ well width originated from an increase in the energy difference between the energy level of the electronic subband and Fermi energy, and the increase in the 2DEG mobility is attributed to a decrease of the scattering source. The electronic subband energies, the corresponding wavefunctions, and the Fermi energies in the $Al_xGa_{1-x}As$/$In_yGa_{1-y}As$/GaAs single quantum wells were calculated by a self-consistent method taking into account the exchange-correlation effect together with the strain and nonparabolicity effects. These results indicate that the electronic parameters in $Al_xGa_{1-x}As$/$In_yGa_{1-y}As$/GaAs strained single quantum wells are significantly dependent on the quantum well width.

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1. Introduction

Modulation-doped $Al_xGa_{1-x}As$/$In_yGa_{1-y}As$/GaAs strained quantum well structures have attracted interest due to their many promising electronic and optoelectronic device applications because the con-

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duction-band discontinuity and the carrier confinement in $Al_xGa_{1-x}As/In_yGa_{1-y}As$ quantum wells are larger than those in $Al_xGa_{1-x}As/GaAs$ quantum wells [1–5]. After charge carriers ionized from the modulation-doped $Al_xGa_{1-x}As$ layer with the large energy gap are transferred to the $In_yGa_{1-y}As$ quantum well with the small energy gap, they are confined to the narrow $In_yGa_{1-y}As$ quantum well due to the built-in electrostatic potential. Recently, a study on the electronic parameters of the two-dimensional electron gas (2DEG) dependent on the spacer-layer thickness in modulation-doped $Al_xGa_{1-x}As/In_yGa_{1-y}As/GaAs$ asymmetric single quantum wells has been performed [6], and they are significantly dependent on the spacer-layer thickness [6]. Even though many studies concerning the electrical and the optical properties in modulation-doped $Al_xGa_{1-x}As/In_yGa_{1-y}As/GaAs$ quantum wells have been carried out [1–8], to the best of our knowledge, a systematic work on the electronic parameters of the 2DEG dependent on the $In_yGa_{1-y}As$ well width have not been performed yet. Furthermore, an investigation on the electronic parameters dependent on the quantum well width are also very important for enhancing high speed electronic device efficiency.

This paper reports the dependence of the electronic parameters of 2DEG on the $In_yGa_{1-y}As$ quantum well width in $Al_xGa_{1-x}As/In_yGa_{1-y}As/GaAs$ strained quantum wells. Electronic subband energies, wavefunctions, and Fermi energies in the $Al_xGa_{1-x}As/In_yGa_{1-y}As/GaAs$ quantum wells were calculated by a self-consistent method taking into account exchange-correlation effects together with strain and nonparabolicity effects.

2. Experimental details

The samples used in this work were grown on semi-insulating (1 0 0)-oriented GaAs substrates by using molecular beam epitaxy (MBE) and consisted of the following structures: a 100-Å Si-doped (2.0×10^{18} cm^{-3}) GaAs capping layer for ohmic contact, a 330-Å undoped $Al_{0.25}Ga_{0.75}As$ layer, a 50-Å modulation-doped (1.0×10^{18} cm^{-3}) $Al_{0.25}Ga_{0.75}As$ layer, a 40-Å undoped $Al_{0.25}Ga_{0.75}As$ spacer layer, a undoped $In_{0.18}Ga_{0.82}As$ quantum-well layer (t = 30, 45, 60, and 80 Å), and a 5000-Å undoped GaAs layer. The compositions of the layers were measured by using double-crystal X-ray diffraction and photoluminescence measurements, and the thicknesses of the layers were determined from the growth rate and the transmission electron microscopy (TEM) measurements.

The Shubnikov-de Haas (S-dH) and Hall-effect measurements were carried out at a temperature of 1.5 K in magnetic fields up to 18 T in an Oxford superconducting magnet system by using a Keithley 181 nanovoltmeter. Ohmic contacts to the samples were made by diffusing a small amount of indium through several layers at 450 °C in a hydrogen atmosphere for approximately 10 min.

3. Results and discussion

The cross-sectional high-resolution TEM images of the $Al_{0.25}Ga_{0.75}As/In_{0.18}Ga_{0.82}As/GaAs$ single quantum wells with a quantum well width of the 30, 45, 60, and 80 Å show that the $Al_{0.25}Ga_{0.75}As/In_{0.18}Ga_{0.82}As/GaAs$ single quantum wells are grown pseudomorphologically on the GaAs buffer layer with an epitaxial relation. There are no defects on the layers and at the heterointerfaces. Even though the perpendicular components of the lattice constants in the $In_{0.18}Ga_{0.82}As$ layer change due to the strain [9], the $In_{0.18}Ga_{0.82}As$ layer is pseudomorphologically grown on the GaAs layer.

The existence of free electrons with high mobility in the $Al_{0.25}Ga_{0.75}As/In_{0.18}Ga_{0.82}As/GaAs$ strained quantum wells was observed by the Van der Pauw Hall-effect measurements at 1.5 K. S-dH measurements were performed in order to investigate the nature of the free carriers providing the low resistance at 1.5 K. The results of the S-dH measurements on $Al_{0.25}Ga_{0.75}As/In_{0.18}Ga_{0.82}As/GaAs$ quantum wells with the $In_{0.18}Ga_{0.82}As$ quantum well widths of 30, 45, 60, and 80 Å with the magnetic field oriented normal to the interface are shown in Fig. 1. These oscillations varied dramatically with the angle between the magnetic field and the surface normal, indicative of the 2DEG occupying the $In_{0.18}Ga_{0.82}As$ quantum well. The period of the S-dH oscillations changed remarkably with varying the $In_{0.18}Ga_{0.82}As$ quantum well width.