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Photoluminescence studies of 2DEG confinement in InAs ultrathin layer introduced in GaAs/AlGaAs structure

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ABSTRACT

In this work we study the density and confinement effects of 2DEG InAs ultrathin layer introduced in Si-delta-doped GaAs/AlGaAs heterostructures grown by Molecular Beam Epitaxy (MBE) on (1 0 0) oriented GaAs substrates by photoluminescence (PL) measurements. Low temperature PL spectra show the optical transitions (E_{e-hh}) and (E_{e-lh}) that occur, respectively, between the fundamental states of electrons to heavy holes, and electrons to light holes, in InAs ultrathin layer. The transition energies have been theoretically calculated by solving simultaneously the Schrödinger and Poisson equations within the Hartree approximation. High 2DEG content reveals high photoluminescence efficiency. In fact, the presence of a high density of defects behaves like traps, which can be saturated by the presence of 2DEG in the InAs channel. Photoluminescence measurements as function of the temperature present an S-shape. The evolution of the temperature-dependent integrated PL intensity of the Si-delta-doped structures is governed by two regimes.

1. Introduction

The most experimentally and theoretically investigated substitution layer/host material system is the InAs/GaAs system. It has been shown that efficient optical transitions take place between band-edge electron and hole states which are localized on the InAs substitution layer. Meanwhile, the InAs/GaAs system has found a wide range of applications in optoelectronic devices. When a silicon δ-doped sheet is grown on the top of $Al_xGa_{1-x}As$ layer, a two-dimensional electron gas (2DEG) can be formed at the interface InAs/GaAs. In the plane of 2DEG, electrons have high mobility and high concentration reaching 10^{13} cm^{-2}. Such high-electron mobility and concentration are used in the fabrication of high-electron mobility transistors (HEMT). InAs ultrathin layer has been demonstrated to be an excellent channel layer for the Si-delta-doped AlGaAs/GaAs/InAs/GaAs HEMT, which have been widely studied by Photoluminescence, photoreflectance, X-ray diffraction [1–12].

Motivated by the lack of information relative to the InAs Si-delta-doping content effect in the 2DEG confinement, we focus our study on the correlation between photoluminescence experimental results and theoretical calculations, and the 2DEG confinement effect in InAs ultrathin layer introduced in the GaAs/AlGaAs structure with different Si-delta-doping content.

2. Experimental

In this work a set of two samples was grown by the molecular beam epitaxy technique on undoped (1 0 0) GaAs oriented substrates. For samples S_1 and S_2, 1000 Å-thick GaAs buffer layer was grown followed by 1 monolayer (ML) InAs channel, 10 ML GaAs spacer and an undoped $Al_{0.3}Ga_{0.7}$ As spacer layer of thickness 12 ML. Next, a 1000 Å $Al_{0.3}Ga_{0.7}$ As layer was deposited after a silicon δ-doped sheet. A second silicon δ-doped sheet and 500 Å $Al_{0.3}Ga_{0.7}$ As layer were then grown. Finally, the structures were capped by 100 Å GaAs layer. Samples S_1 and S_2 differ only by the silicon content: [Si]$=2\times10^{12}$ cm^{-2} for S_2 and [Si]$=4\times10^{12}$ cm^{-2} for S_1. A schematic cross-section of the samples structure is shown in Fig. 1.

PL measurements were carried out in order to investigate the inter-band transitions and the activation energies in the InAs/GaAs QWs. The experimental measurements were performed using a variable temperature (10–300 K) close-cycle cryostat under 514.5 nm line of an Argon ion Ar+ laser as excitation source. The signal was detected through a 250 mm Jobin–Yvon monochromator and by GaAs photomultiplier associated with a standard lock-in technique.

3. Results and discussion

Fig. 2 shows photoluminescence measurements carried out at 10 K under an excitation power of 7 W cm^{-2}. Low temperature PL spectra are essentially governed by a broad peak (P_1), situated,

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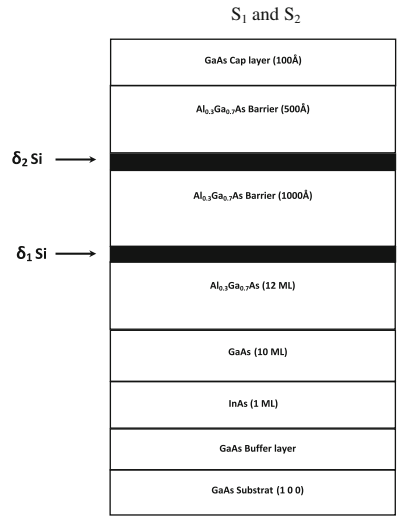

Fig. 1. S_1 and S_2 samples schematic cross-section.

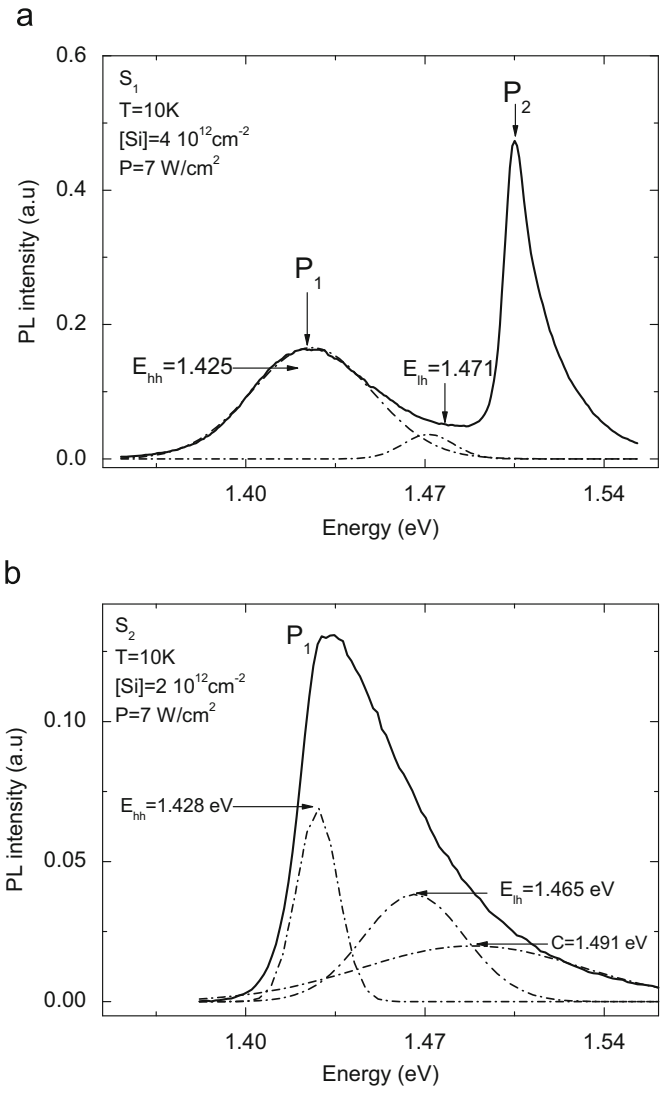

Fig. 2. 10 K photoluminescence spectra of (a) S_1 sample and (b) S_2 sample.

respectively, at 1.427 and 1.432 eV for S_1 and S_2 samples. This peak can be attributed to the transition between the lowest electron energy and the hole state in the InAs/GaAs QW [3,11]. For S_1 sample, we have observed an additional peak (P_2), situated at 1.515 eV and attributed to the 10 K GaAs band gap [7].

We note that S_1 sample's P_1 peak is broader compared to the one of S_2 sample. The increase in the PL peak broadening may originate from the electrons of the Si-delta-doped layer in the InAs/GaAs quantum well. In fact, in a Si-delta-doped heterostructure, the electrons are transferred from the $Al_{0.3}Ga_{0.7}$ As barrier to the InAs conduction band. Another observation is the dissymmetric shape of the P_1 peak toward higher energies for both samples, which can be due to the presence of the 2DEG [7,8].

The comparison of the P_1 peak position with respect to S_1 and S_2 samples shows a small shift (about 5 meV) to lower energies from 1.432 to 1.427 eV that might be due to the increase in the carrier density and the presence of two-dimensional electron gas in the InAs ultrathin layer. Since the size of the wells (1 ML) is small, the transitions appear in the GaAs layers, which is justified by the observation of the GaAs band gap PL peak at 1.515 eV. A higher photoluminescence efficiency and a more symmetric PL peak is also observed for the S_1 sample with $[Si]=4\times10^{12}$ cm^{-2}. These behaviors can be interpreted as the saturation of the strong density of defect traps by the InAs channel electrons.

In order to highlight the Si-delta-doping QW confinement, we have focused our study on the broad P_1 peak (Fig. 2). We have found that the P_1 peak can be well described by a convolution of two Gaussian peaks assigned to optical transitions that occur, respectively, between the fundamental states of electrons to heavy holes (E_{e-hh}), and electrons to light holes (E_{e-lh}), in InAs ultrathin quantum well. For the S_2 sample, we observe an additional band labeled C at 1.49 eV that can be attributed to the recombination of free excitons on residual carbon acceptor level [13].

In order to determine the energy levels associated to the confinement of 2DEG in InAs ultrathin layer under study, we have performed numerical calculations based on the resolution of the Schrödinger and Poisson equations within Hartree approximation. For each structure, the electron wave-functions $\psi_i(z)$ and the energies $EB_i(z)$ of the ith QW level were determined by self-consistently solving the set of two one-dimensional equations: Schrödinger equation (Eq. (1)) and Poisson equation (Eq. (2)), which are written as follows:

$$-\frac{\hbar^2}{2}\frac{\partial}{\partial z}\left(\frac{1}{m^*(z)}\frac{\partial}{\partial z}\psi_i(z)\right)+U(z)\psi_i(z)=E_i\psi_i(z) \tag{1}$$

$$\frac{\partial}{\partial z}\left(\varepsilon_0\varepsilon_r(z)\frac{\partial}{\partial z}Uh(z)\right)=e(N_d^+(z)-N_a^-(z)-n(z)) \tag{2}$$

The potential energy $U(z)$ consists of three terms as follows: $U(z)=Ua(z)+Uh(z)+Ue(z)$, where the 1st^{P} term $Ua(z)$ is the heterojunction conduction band discontinuity term, the 2nd^{P} term $Uh(z)$ is the Hartree electrostatic potential energy term, and the 3rd term $Ue(z)$ is the exchange-correlation term. The $Uh(z)$ electrostatic potential energy term is determined using Poisson Eq. (2) where ε_0 is vacuum permittivity, ε_r is material relative permittivity, $N_d^+(z)$ and $N_a^-(z)$ are the density of ionized donors and acceptors and $n(z)$ is the 2DEG electron density, it is illustrated through

$$n(z)=\sum_i n_i(z)\left|\Psi_i(z)\right|^2 \tag{3}$$

where $n_i(z)$ is the electron density, it is given by the following expression:

$$n_i(z)=\frac{m^*(z)}{\pi\hbar^2}(E_F-E_i) \tag{4}$$

The density is calculated with respect to the Fermi level EB_{FB}. For all samples only the lowest energy level is occupied by electrons.