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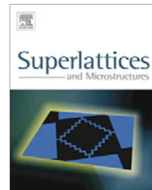

Silicon doping effects on optical properties of InAs ultrathin layer embedded in GaAs/AlGaAs:δSi high electron mobility transistors structures

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Micro-Raman scattering measurements were used to study the silicon delta-doped layer density variation effect on InAs ultrathin layer embedded in silicon-delta-doped GaAs/AlGaAs high electron mobility transistors (HEMTs) structures properties. These structures were grown by molecular beam epitaxy on GaAs substrates with different silicon (Si) delta-doped layer densities. Two coupled plasmon–longitudinal optical (LO) phonon modes (L− and L+) were observed in the micro-Raman spectra of the Si-delta-doped samples, and both their wave numbers and intensities were dependent on the silicon delta-doped layer density. There is evidence to suggest that the increase of the Si doping level results in the increase of exciton–phonon scattering which is mainly due to the incorporation of Si and the increase of the two-dimensional electron gas (2DEG) in the InAs/GaAs interface. From fitting the temperature-dependence of full width at half maximum (FWHM) of quantum well's photoluminescence peak (P_1) by the exciton–photon coupling model, it was found that the interaction between exciton and phonon in Si-delta-doped quantum wells was higher than that in the undoped sample. This result was confirmed as resulting from the increase of plasmon–phonon scattering which is attributed to the increase of free carriers donated from implanted Si dopant. The self-consistent Poisson–Schrödinger model calculation results are in good agreement with the experimental results, where the 2DEG densities increase linearly with increasing the Si-delta-doped layer density.

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1. Introduction

The InAs/GaAs system has become one of the most popular heterostructures for its applications in the high-speed devices and optoelectronic devices [1–4]. The advanced material growth technologies such as molecular beam epitaxy (MBE) and metal-organic vapor phase epitaxy (MOVPE) enable the growth of very thin highly doped layers and these will play an important role in future photonic and quantum electronic devices like high electron mobility transistors HEMTs, modulation doped quantum wells (QW). Electrons are released from the delta (δ)-doped layer (silicon) and then confined by the potential well. Because of the electrostatic attraction these carriers remain close to their ionized donors and form a two-dimensional electro gas (2DEG) [4–6]. InAs ultrathin layer has been demonstrated to be an excellent channel layer for the InAs/GaAs HEMT [7–9].

Among the many parameters for the growth of high quality InAs two-dimensional electron gas (2DEG) on GaAs [10–12], we focus here on the Si-delta-doping density effect. Micro-Raman spectroscopy is a powerful technique for the investigation of modulation doped quantum wells. In semiconductors the incorporation of donors leads to the formation of electron plasma, the plasmon mode couples with the LO phonon resulting in two coupled plasmon LO-phonon modes L+ and L−. These coupled modes have been extensively studied by Raman spectroscopy in several III–V semiconductors [13]. Raman scattering from coupled phonon–plasmon modes in n-type semiconductor is a valuable tool for the characterization of semiconductor devices, and device processing [14,15].

In this study, we have investigated the effect of Si delta-doping content in Si-delta-doped AlGaAs/GaAs/InAs/GaAs HEMT structures properties using micro-Raman scattering at $T = 300$ K. Temperature-dependent photoluminescence measurement and self-consistent Poisson–Schrödinger model calculation were also very much used to better understand and confirm the micro-Raman scattering results.

2. Experimental details

In this work, a set of four samples grown by molecular beam epitaxy technique on undoped GaAs substrates were used. The undoped N_4 Sample consists of 1000 Å-thick GaAs buffer layer on top of which we deposited 200 Å $Al_{0.2}Ga_{0.8}As$ barrier layer, 500 Å GaAs spacer layer, 1 monolayer (ML) InAs channel, 500 Å GaAs spacer layer, 200 Å $Al_{0.2}Ga_{0.8}As$ barrier layer and finally 50 Å GaAs cap layer. Doped samples (N_1, N_2 and N_3) consist of 1000 Å-thick GaAs buffer layer, followed by 1 ML InAs channel, 5 ML GaAs spacer and an undoped $Al_{0.3}Ga_{0.7}As$ spacer layer of thickness 50 Å. 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 50 Å GaAs layer. N_1, N_2 and N_3 samples differ only by the silicon δ-doping density [Si]: $[Si] = 4 \times 10^{12}\ cm^{-2}$ for N_1, $[Si] = 2 \times 10^{12}\ cm^{-2}$ for N_2 and $[Si] = 4.5 \times 10^{10}\ cm^{-2}$ for N_3. A schematic structure of all samples is shown in Fig. 1.

The micro-Raman measurements were performed at room temperature using the 514.5 nm Ar^+ laser line. The power excitation is 60 mW. Raman spectra were recorded in near-backscattering configuration on the (0 0 1) surface and out of resonance. The excitation energy is well above the band gaps of the active layers. The scattered light was dispersed using a triple monochromator and detected by a multi- channel CCD camera.

The photoluminescence 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

The Raman spectra taken at room temperature for InAs/GaAs/AlGaAs:δSi HEMTS structures with different silicon doping levels are shown in Fig. 2(a).

It is seen that the GaAs LO phonon dominates all spectra. The spectral features at 374 and 377 cm^{-1} are related to AlAs-like LO mode in $Al_xGa_{1-x}As$ barrier for the aluminum molar fraction $x = 0.2$ and 0.3,

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