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Polarization dependence of absorption in strongly vertically coupled InAs/GaAs quantum dots for two-color far-infrared photodetector

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Abstract

Strongly vertically coupled InAs/GaAs quantum dots (QDs) with modulation doping are investigated, and polarization dependence of two-color absorptions was observed. Analysis of photoluminescence (PL) and absorption spectra shows that s-polarized absorptions at 10.0 and 13.4 μm stem from the first excited state E_1 and the second excited state E_2 in the QDs to the bound state E_{InGaAs} in the InGaAs spacer, respectively, whereas p-polarized absorptions at 10.0 and 8.2 μm stem from the first excited state E_1 and the ground E_{g} in the QDs to the bound state E_{InGaAs} in the InGaAs spacer, respectively. These measurements illustrate that transitions from excited states are more sensitive to normal incidence, which are very important in designing QD infrared detector.

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Keywords: Quantum dot; Polarization; Absorption

1. Introduction

Infrared detection is one of the major applications of self-assembly semiconductor quantum dots (QDs). The interest stems from the advantages of quantum dots infrared detector (QDIP): (i) intrinsic sensitivity to normal incident infrared light; (ii) longer excited state lifetime and relaxation times due to greatly suppressed electron–phonon (LO) scattering, higher responsivity; and (iii) low dark current and higher optical gain which will result in a potentially higher temperature operation [1]. Recently, the detectivity of $1.1\times10^{12}\,\mathrm{cm\,Hz^{1/2}\,W^{-1}}$ in QDIP has been reported and QDIP focal plane array (FPA) based on InGaAs/InGaP QDs and InAs/InGaAs/GaAs DWELL structures have been demonstrated [2–4].

However, direct absorption measurements on QDs indicate that the inter-sub-level transitions in the conduction band are predominantly polarized in the growth direction ($E_{\parallel z}$), similar to those for quantum wells. Photocurrent measurements on QDs using a 45° optically polished facet configuration also indicate that the $E_{\parallel z}$-polarized inter-sub-level transitions are at least 10 times stronger than the $E_{\parallel xy}$-polarized inter-sub-level transitions [5]. As a result, using these QDs to design infrared photodetectors to work at normal incidence is not optimum.

Vertically coupled QDs structure has been investigated. Such strongly vertically coupled QDs structure is promising for application on QDIP because of its strong in-plane polarized intraband absorption and on QDs laser because of low lasing current densities [6,7]. In this paper, we report the absorption dependence on polarization in strongly vertically coupled QDs. The results show that the absorptions peak at $\lambda_1=10.0\,\mu$m and $\lambda_2=13.4\,\mu$m when the light is s-polarized, whereas the absorptions peak at $\lambda_1=10.0\,\mu$m, $\lambda_3=8.2\,\mu$m, and $\lambda_4=3.4\,\mu$m when the light is p-polarized. Analysis of photoluminescence (PL) and absorption spectra shows that transitions from excited states are more sensitive to normal incidence.

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2. Experiments

The investigated sample was grown by solid-source molecular beam epitaxy (MBE) Riber-32P on n+ (Si-doped) (0 0 1) GaAs substrates. The coupled QDs sample consists of three double un-doped InAs QDs layer periods separated by 50 nm GaAs barriers. The period is constituted by two QDs layers separated by a 7 ML n-doped ($n = 3.2 \times 10^{11}\,\mathrm{cm}^{-2}$) $In_{0.15}Ga_{0.85}As$ spacer. The QD layer corresponds to the deposition of 2 ML InAs. The QDs and spacer were sandwiched by 500-nm-thick n-type GaAs top contact layer and bottom contact layer. These contact layers were doped with Si to $1 \times 10^{18}\,\mathrm{cm}^{-3}$. The structure is shown in the inset to Fig. 1. The QDs were grown at 480 °C, while the contacts were grown at 580 °C. The evolution of InAs QDs is monitored *in situ* by RHEED measurements. PL was excited by a 532 nm line of a solid laser; the PL spectra were detected with a Fourier transform infrared (FTIR) spectrometer operating with an InGaAs photodetector. Absorption measurements were made with FTIR system with a glowbar source and a liquid nitrogen cooled wideband HgCdTe detector with cutoff at 60 meV. The resolution of the measurements taken is $4\,\mathrm{cm}^{-1}$ corresponding to 0.5 meV. Absorbance was determined by

$$A = \ln\left(\frac{T_{\mathrm{sub}}}{T_{\mathrm{sample}}}\right),$$

where T_{sample} and T_{sub} are the transmission of the sample and the transmission of the GaAs substrate as the grown structure, respectively.

3. Results and discussion

Fig. 2 shows the 77 K PL spectra obtained from the sample. Three main peaks at 1.135 eV (1.09 μm), 1.177 eV (1.05 μm), and 1.225 eV (1.00 μm) and a weak peak at about 1.315 eV (0.94 μm) were observed. The energy differences are 42, 48, and 90 meV, respectively. At the same time, the excitation power dependence of PL spectra indicates the existence of multi-confined levels in the strongly coupled QDs other than multi-mode transitions. The multi-confined levels can be explained by the appearance of level splitting due to vertical electronic correlation. The following factors contribute to level splitting in the strongly vertically coupled QDs systems. A first natural cause of level splitting is quantum–mechanical coupling between states belonging to identical QDs that happen when the QDs are stacked closely together. A second cause is strain, because the system does not contain a symmetry plane parallel to the base of the QDs, strain does not affect the two QDs in the same way. Such anisotropy both in the strain field and associated piezoelectric potential leads to nonidentical confining potentials, possibly enhancing level splitting. Finally, experiments have suggested that, because of indium migration during the epitaxial growth, the QDs belonging to the same stack may not even be of the same size or shape, also enhancing level splitting [8].

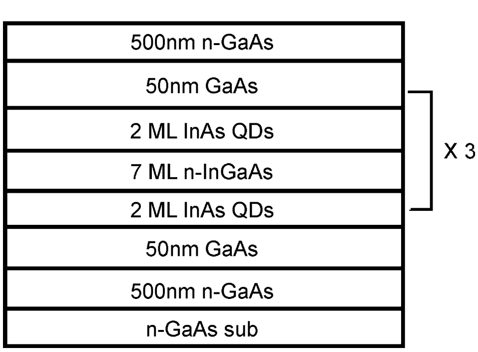

Fig. 1. Strongly coupled QDs schematic.

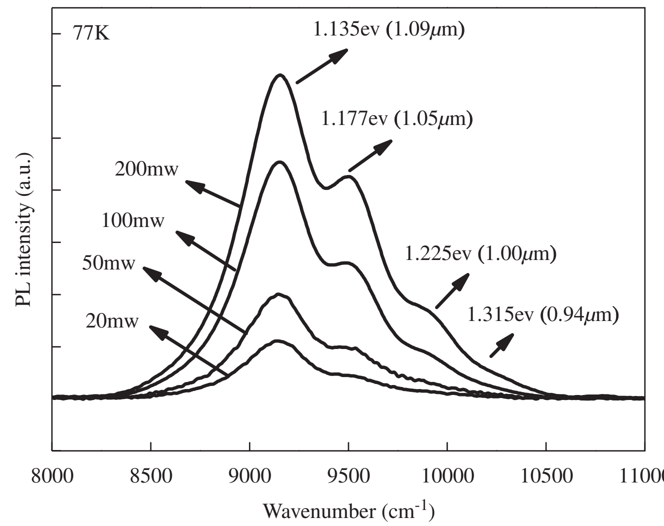

Fig. 2. Photoluminescence (PL) spectra of the sample at 77 K.

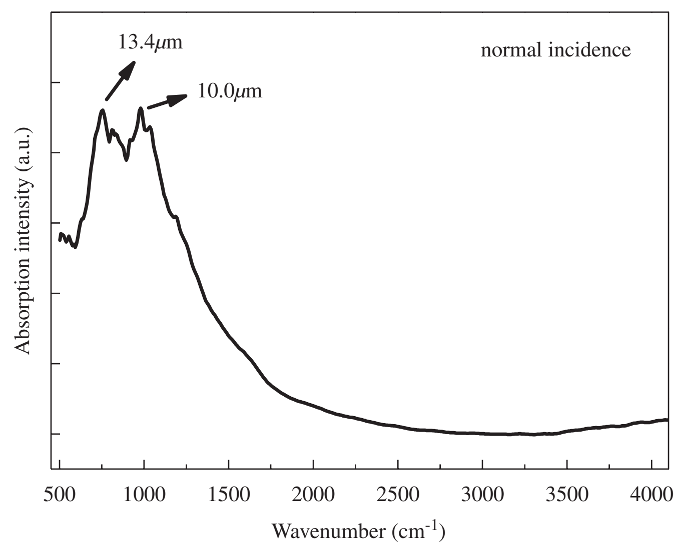

Fig. 3. Infrared absorption spectrum of the sample at room temperature under normal incident radiation.

Figs. 3 and 4 show the absorption spectra of strongly vertically coupled QDs when the light is normal incident