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9th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 18–22, 2001

QWR/QD.05p

Modulation of the optical absorption in self-organized InAs/GaAs quantum dots

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Abstract. Capacitance and photocurrent spectroscopy are used to investigate a Schottky barrier structure containing a single layer of self-organized InAs/GaAs quantum dots. We show that applying a bias to the structure it is possible to change the electron occupation of the dot levels. This in turns is used for controlling the intensity of the light absorbed by the dots and proposed as a novel way for realizing optical modulators operating in the infrared ($\sim$ 1.1 μm) wavelenght range.

Introduction

Nowadays InAs/GaAs self-organized quantum dots (QDs) are of great interest because of their zero-dimensional properties, which open up wide possibilities to develop new optoelectronic devices such as low-threshold lasers, infrared detectors and high-density optical memory devices [1]. Recently it was shown that the photocurrent (PC) spectroscopy can be used to measure the absorption of QDs [2]. In this paper we show that using capacitance [3, 4] and PC spectroscopy it is possible to control the electron occupation of the dot levels and correspondingly the dot absorption.

1. Experimental details

The QDs structures were grown by molecular beam epitaxy (MBE) on n^+–GaAs (001) substrates. The formation of InAs QDs was monitored by reflection high-energy electron diffraction (RHEED) patterns, and the average thickness of InAs deposited was 4 ML at 485 °C. The InAs QDs were sandwiched between a 0.4 μm-thick GaAs cap and a 1 μm-thick GaAs buffer layer. The cap and buffer layers were uniformly doped with Si at a level of 2.0×10^{16}cm^{-3} except for 10 nm thick undoped spacers on each side of the QD layer. The excitation source for PC measurements was a tungsten-halogen lamp dispersed by 0.25 m monochromator and the PC signal was recorded with standard lock-in technique. The C(V) characteristics of the devices were measured using an HP4275A LCR meter.

2. Results and discussion

Figure 2(a) shows C(V) characteristic of the QD structure at $T = 80$ K. The C(V) characteristic at 80 K has two plateaux with a small step between them at -2.0 V, indicating that there are two filled electron states in the QD plane [4]. At a given temperature, the charge located in the QDs is determined by the sheet concentration $N_{\rm QD}$ of QDs and the relative positions of the electron level in the QDs (E_{ei}) and chemical potential (μ) in the GaAs

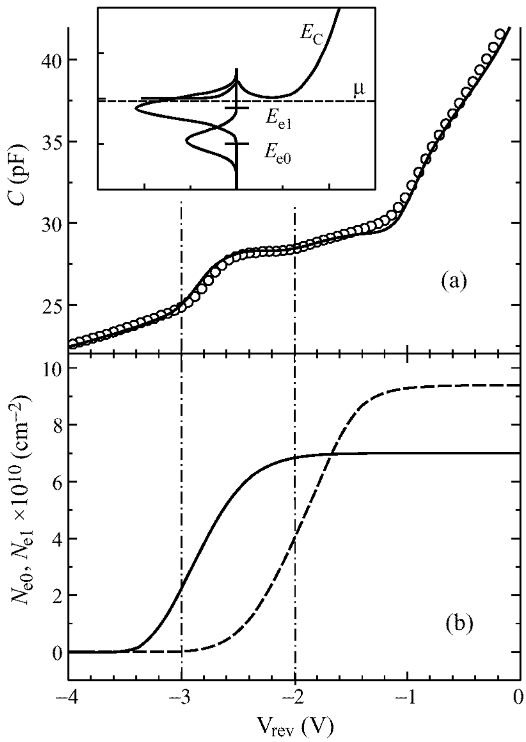

Fig. 1. (a) C–V characteristics measured at 1 kHz and 80 K and simulated with a quasi-static model. (b) Simulated occupations of the electron ground (solid line) and first excited (dashed line) states in QDs as a function of the reverse bias at $T = 80$ K. The insert shows the conduction band diagram of the QD structure. The horizontal lines represent the electron energy levels E_{ei} in the QDs, broadened by the size distribution.

matrix (see insert in the Fig. 1(a)). We use a Gaussian distribution to describe the DOS associated with the distribution of QD sizes. The density of charge Q_{QD} accumulated in the QD plane may be written as [3, 4]:

$$Q_{\text{QD}} = q \sum_i \int \frac{g_i N_{\text{QD}}}{\Delta E \sqrt{\frac{\pi}{2}}} \exp\left(\frac{-2(E-E_{ei})^2}{(\Delta E)^2}\right) \frac{1}{1+\exp\left(\frac{E-\mu}{k_B T}\right)} dE \qquad (1)$$

where k_B is the Boltzmann constant, g_i is a spin degeneracy factor, q is electron charge, and T is temperature. Summation is provided over all i subbands.

Figure 1(a) shows the fit to the C(V) characteristic at 80 K by a quasi-static charging model [3, 4]. The numerical analysis indicates that at $V_{rev} = 0$ V there are two filled electron states in the QDs at $E_{e0} = 140$ meV and $E_{e1} = 60$ meV below the bottom of the GaAs conduction band (see insert in the Fig. 1(a)). We use a value of $\Delta E = 50$ meV as deduced from the broadening of the photoluminescence (PL) QD band. Also the value of N_{QD} was taken from plan-view transmission electron microscopy studies, which reveals a uniform distribution of dot sizes with mean QD diameter of 15 nm and a density $N_{\text{QD}} = (3.5 \pm 0.5) \times 10^{10}\text{cm}^{-2}$.

Figure 2(a) shows PC spectra of our sample measured at $T = 200$ K as a function of the reverse bias (positive biased substrate). At $V_{rev} = 0$ V one can see only step at 1.45 eV

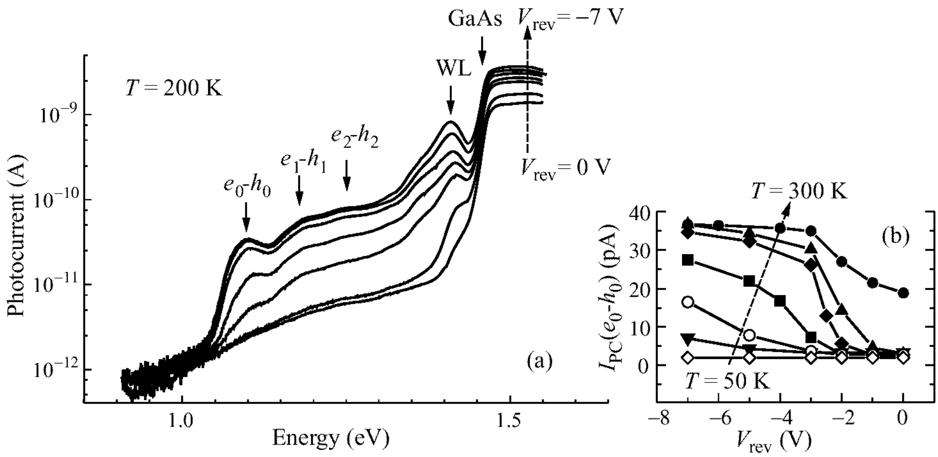

Fig. 2. (a) Photocurrent spectra of the QD structure as a function of reverse bias V_{rev} at $T = 200$ K: from the bottom to the top traces are 0, −1, −2, −2.5, −3, −5, −7 V, respectively. (b) Dependence on the temperature and the reverse bias V_{rev} intensity of the PC ground state peak $I_{PC}(e_0 - h_0)$: from the bottom to the top traces are 50, 100, 125, 150, 200, 250, 300 K, respectively.

related with the band-edge absorption of GaAs. Increasing the the reverse bias up to −7 V results in the appearance of the resonance peak at 1.41 eV related with optical absorption in InAs wetting layer and three additional features at 1.102 eV, 1.182 eV and 1.240 eV, which originate from the photon absorption in the ground and excited states of InAs QDs, respectively [2]. The position of the last three features agrees quite well with the position of the corresponding PL peaks [4].

At $T = 200$ K the PC signal from QDs monotonically grows up with increasing of the reverse bias and saturates at $|V_{rev}| > -3$ V (Fig. 2(a)). The same behaviour is observed in the temperature range from 150 K to 300 K (Fig. 2(b)). With decreasing the temperature below 150 K voltage modulation of the PC signal becomes weaker and below 100 K there is no PC signal from QDs (Fig. 2(b)).

The PC signal from QDs is proportional to the absorption coefficient of QDs. Also it depends on the recombination rate $(1/\tau_{rec})$ of carriers from the dot levels and on the escape rates $(1/\tau_{esc})$ of carriers out of the dots [2]. To a first approximation, the PC signal due to QDs can be expressed in the following form:

$$I_{PC} = G/(1 - \tau_{esc}/\tau_{rec}) \quad (2)$$

where G is the carrier generation rate in QDs.

Time-resolved PL studies revealed that the recombination time constant is about 1 ns for this type of QDs [1]. Also time-resolved capacitance spectroscopy revealed that the carrier emission from the InAs QDs to the GaAs barrier is faster then 1 ns at temperatures above 150 K [5]. Therefore suppression of the PC signal from QDs below 150 K (Fig. 2(b)) is probably due to the fast recombination of photo-generated carriers in the QDs relative to the escape time of carriers out of the dots.

Analysis of the C(V) characteristic of the QD structure showed that at $V_{rev} = 0$ V two lowest electron states are filled in the QDs (Fig. 1(b)). The increasing of the value of the reverse bias $|V_{rev}|$ from 0 V to −3 V results in successive depopulation of the levels E_{e1} and E_{e0}, respectively (Fig. 2(b)). Note that the PC signal from QDs grows up in this voltage range (Fig. 2(b)). It is found that at $|V_{rev}| > -3$ V there are no electrons on ground state level in QDs (Fig. 1(b)). And this value of the reverse bias agrees very well with the start of saturation of the PC signal from QDs (Fig. 2(b)). Thus through the change of electron occupation in the QDs one can control photon absorption in QDs. At 300 K voltage modulation of the PC signal from QDs are weaker (Fig. 2(b)), because the concentration of electrons on electron ground state in the QDs decreases with increasing temperature [3].

3. Conclusions

In summary, we showed that through the change of electron occupation in the QDs one can control the photon absorption in QDs, thus opening a possibility for optical modulators based on QDs and operating in the infrared wavelength range.

Acknowledgements

The work is supported by the International Russian-Ukrainian project on nanoelectronics. Two authors, P.N.B. and L.E., gratefully acknowledge support from the Royal Society and EPSRC, respectively.

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