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Light absorption and emission in InAs/GaAs quantum dots and stepped quantum wells

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Abstract. The results of optical phenomena investigations in quantum dot and quantum well structures under interband optical pumping are presented. Interband and intraband light absorption in nanostructures with quantum dots has been studied experimentally and theoretically. Photoluminescence and interband light absorption in stepped quantum wells have been investigated including PL studies under picosecond optical pumping. Experimental results have been compared with results of calculation of energy spectrum and transition probabilities. It is shown that inversion of population exists between the third and second excited levels of stepped quantum well.

Introduction

The feasibility of bipolar mid-infrared laser based on intraband carrier transitions in QWs and QDs was considered elsewhere [1–4]. The first experimental studies of spontaneous mid-infrared emission under simultaneous generation of stimulated near-infrared radiation were carried out in classic heterolasers on QD and QW [5] and QD [3, 6] in condition of electrical injection.

The present paper is devoted to the investigation of optical phenomena in structures with QDs and QWs directed to the development of bipolar mid-infrared lasers.

Interband and intraband light absorption in quantum dots

Compared to PL studies, spectra of interband absorption enable to obtain more complete information about multilayered structures. The results of the first investigations of interband absorption in QD structures are presented in Fig. 1. Structure consisted of 15 InAs QD (2.5 ML) layers in $In_{0.12}Ga_{0.88}As$ QW (50 Å) divided with 40 nm GaAs barriers. Multipass geometry of the sample was used (see inset in Fig. 1(b)). Light beam passed through QD layers 10 times. The observed absorption peaks can be attributed to carrier transitions between ground states, excited states and between states of wetting layer. Results of the optical matrix element calculations are also presented in Fig. 1. Calculations were carried out in frames of ***kp*** method taking into account strain, band mixing and wetting layer related states using wetting layer thickness of 0.28 nm and QD as truncated pyramid with the base area of 16×16 nm^2, top area of 4×4 nm^2 and a height of 5.5 nm. A resonable agreement between theory and experiment was found.

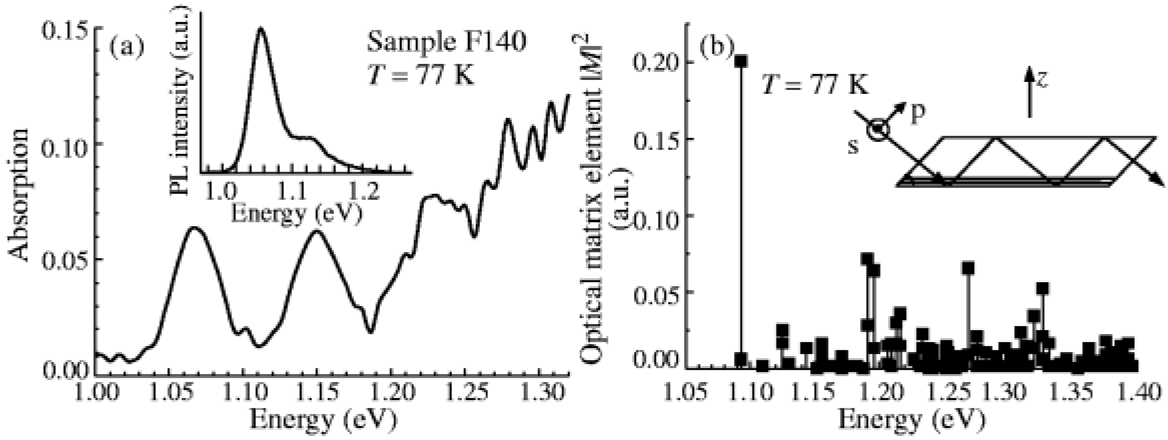

Fig 1. Spectra of interband light absorption in QD structures: experiment (a) and calculation (b). Insets: PL spectrum and geometry of experiment.

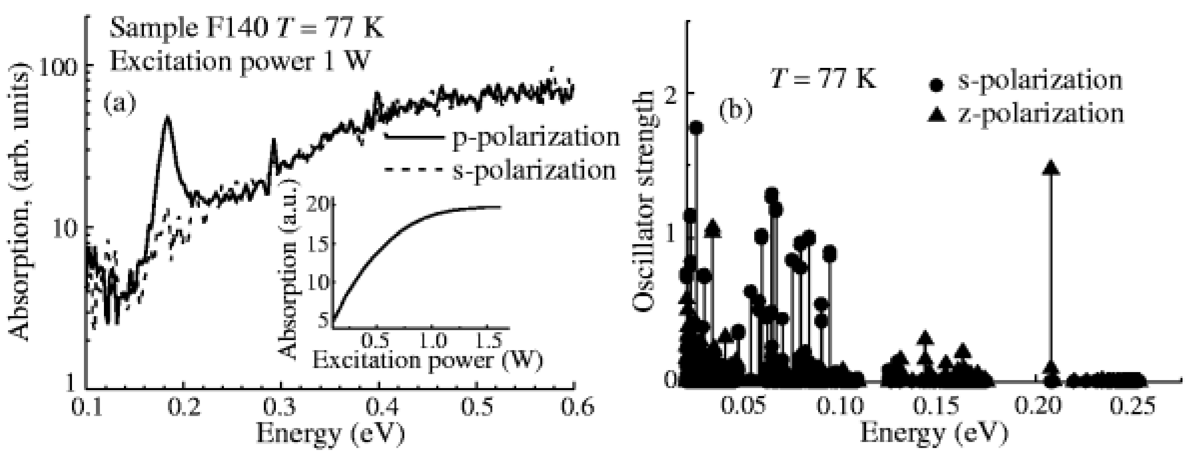

Fig 2. Spectra of absorption (a) and calculated oscillator strength of intraband electron transitions (b). The saturation of absorption is presented in the inset.

Experimental results of photoinduced absorption for *s*- and *p*-polarizations of light are presented in Fig. 2(a). Absorption peak for light of *p*-polarization only was observed in our experiments. Probably, this peak is connected with electron transitions from ground state to excited states $\langle 001 \rangle$ near the wetting layer. Oscillator strength $f = 1.6$ estimated from absorption peak magnitude is in a good agreement with results of calculations (see Fig. 2(b)). Spectral peak position also correlates well with calculations. Filling the excited states and saturation of absorption occur under high intensity of optical pumping (see inset in Fig. 2(a)). According to calculations, absorption peaks for the light of *s*-polarization are located at the photon energies $h\nu<0.1$ eV.

As for interlevel light absorption by holes, it is essential for light of *s*-polarization only. In accordance with calculations this absorption belongs to spectral range $h\nu<0.08$ eV and is one order less in comparison with absorption by electrons.

Photoluminescence and light absorption in funnel shaped QWs

2.1. To find the intraband population inversion under optical pumping the surface photoluminescence was studied in the structure with a single funnel-shaped QW. The design of the structure and the interband electron transitions with the maximal optical matrix element are presented in Fig. 3(a). Experimental PL spectra are presented in Fig. 3(b), the calculated values of the transition energies are shown by the arrows. There are two peaks corresponding to *e*1–*hh*1 and *e*3–*hh*5 transitions. The calculated probabilities for both of them and for *e*2–*hh*2 transitions are equal approximately to 1.4×10^9 s^{-1}. The calculated electron lifetimes on *e*3 and *e*2 levels related to intersubband transitions are equal to 4.3 and 0.5 ps, respectively. The lifetimes on *e*1 and *e*2 levels related to recombination processes are about 1 ns. Due to small electron lifetime on *e*2 level there is no peak connected with *e*2–*hh*2 transitions in PL spectra under low pumping. Analyzing transition probabilities, electron lifetimes and PL peaks intensities one can conclude that there is a significant population inversion between *e*3 and *e*2 levels.

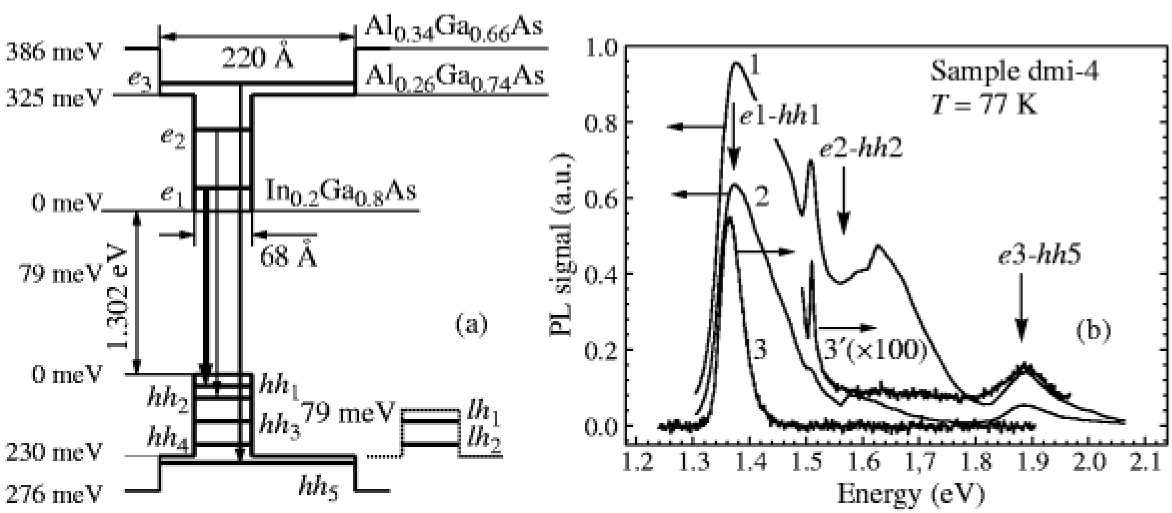

Fig 3. (a) Potential profile, subband-edge energies and the main interband electron transitions in QW. (b) PL spectra for different levels of pulse (1 — 3×10^3 W/cm^2, 2 — 1.8×10^3 W/cm^2) and continuous (3, 3' — 20 W/cm^2) laser pumping.

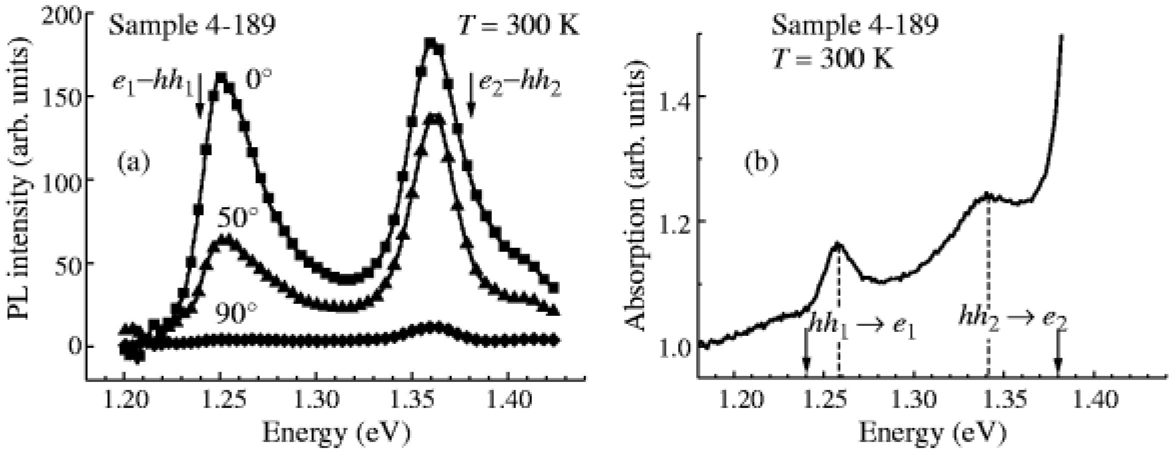

Fig 4. PL spectra for different light polarizations (a) and spectrum of interband absorption in QW (b). The numbers near the curves indicate an angle between PL polarization and plane of QWs.

2.2. Investigation of PL under intense optical pumping with the pulse duration comparable to the time of intersubband transitions with LO phonon emission is a powerful tool for the studies of energy spectrum in QW. The edge PL spectra measured in the structure consisted of $20In_{0.24}Ga_{0.78}As/Al_{0.12}Ga_{0.88}As$ funnel-shaped QWs divided with 15 nm $Al_{0.2}Ga_{0.8}As$ barriers are presented in the Fig. 4(a). Excitation was provided by 4 ps light pulse (λ = 0.523 μm) with energy of 28 μJ. The peaks of PL and absorption spectra (Fig. 4) are in a good correlation. The calculated values of the $e1$–$hh1$ and $e2$–$hh2$ transition energies are shown by the arrows. PL connected with these transitions should be polarized in QW plane, and this was observed experimentally. Under used intensity of laser pumping the nonequilibrium carrier concentration exceeds 10^{14} cm^{-1}. Nevertheless we see sufficiently narrow PL peaks due to use of a very short laser pulse and pulse sampling registration because only a small part of electrons and holes get into $e1$, $e2$ and $hh1$, $hh2$ subbands and occupy the lower states there. In particular, one can see a sharp PL peak corresponding to the electron transitions from $e2$ subband with small lifetime $\tau_2 \approx$ 0.5 ps. Analyzing the peak intensity one can estimate the times of the electron capture into QW levels.

Acknowledgements

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