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Picosecond acoustics in semiconductor optoelectronic nanostructures

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ABSTRACT

We overview the results of three recently performed experiments, where the picosecond acoustic technique was applied to semiconductor devices with quantum wells or quantum dots embedded in an optical microcavity. In these experiments, high amplitude picosecond strain pulses are injected into such a device and the resulting changes in the response of the optical resonance are monitored. First, in quantum well devices we observe the generation of THz sidebands in optical reflectivity near the polariton resonance. Second, for certain conditions we detect the destruction and recurrence of excitons by acoustic shock waves on picosecond time scales. Third, in a vertical cavity surface emitting laser with a quantum dot layer the injection of the picosecond strain pulses induces the giant increase of the laser output. All these effects are governed by nonadiabatic processes in the interaction between a strain pulse and the electronic quantum confined states. Their observation became possible due to the possibility of generating very short strain pulses with sufficiently high amplitude.

1. Introduction

Nowadays picosecond acoustics, pioneered by Thomsen et al. [1] in 1984, has become a powerful tool for studying the properties of various solid objects. The technique operates with acoustic wave packets with spectra spreading up to several Terahertz (THz) and corresponding wavelengths down to several nanometers. Such high frequencies and small wavelengths of the elastic waves allow applying ultrasonic methods, like imaging and defecting probing, on the nanometer scale [2,3]. Besides achievements related to extending the traditional MHz ultrasonic techniques to the THz range, picosecond acoustics resulted in studies of qualitatively new phenomena, like observation of acoustic solitons [4–6].

Since the end of the 1990s picosecond acoustic techniques are also used to probe semiconductor nanostructures containing quantum wells (QWs) [7–9] and quantum dots (QDs) [10]. These studies were aimed mainly on obtaining information about the electron–phonon interaction in the case of electrons (holes) being quantum-confined. In this case the dynamic strain $\eta(t)$ produced by the acoustic wave in the semiconductor nanostructure may be considered as perturbation, which changes in time. The dynamic strain modulates the energies of the electron (hole) states (e.g. the band gap) in the nanostructure, which results in modulation of the optical outputs governed by these quantum states. In particular, the dynamic strain modulates the optical frequency ω of the electron–hole (exciton) transition. This effect may be called *ultrafast piezospectroscopic effect* in analogy with the stationary piezospectroscopic effect, which governs the dependence of the electron energy on uniaxial strain [11,12].

Traditional MHz and GHz acoustics allow efficient modulation of ω such that the modulation amplitude $\Delta\Omega$ is large enough to be seen in the spectrum of the optical signal [13,14]. In this case the modulation occurs on a timescale τ_a (the time that it takes the optical frequency to shift by $\Delta\Omega$) that is much longer than any other transient times (coherence, relaxation etc.). Therefore, the modulation occurs adiabatically and it is easily possible to follow the time dependence of the modulated optical frequency $\omega(t)$ from the light intensity and the optical spectrum. In picosecond acoustics, which operates in the sub-THz and THz frequency ranges, this simple adiabatic approximation may be not valid anymore because τ_a becomes comparable or even shorter than the transient time, which governs the corresponding optical phenomenon. The typical example is the chirping of the optical transition in reflectivity spectra of QWs, when τ_a is comparable to the coherence time of the excitons τ_c [15].

In the present paper, we describe three recent experiments, where picosecond acoustic techniques were applied to semiconductor optoelectronic nanostructures [16–18]. In these experiments it is essential that the modulation of the electron energies

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occurs on a picosecond time scale and the amplitude of this modulation is higher than the spectral width of the corresponding optical transition. The GaAs-based nanostructures used in the experiments contain a single semiconductor layer (QW or QD) where the electrons and holes possess quantum confinement, and this layer is embedded into an optical microcavity (MC) with high finesse. The MC photonic resonance overlaps spectrally with the electron–hole (exciton) optical transition in the semiconductor layer. The effects studied in the three presented experiments have a common basis through the nonadiabatic modulation of ω. However, there is a significant difference between the three experiments: in the first one (Section 2) the nonadiabatic character is related to the long coherence time $\tau_c > \tau_a$ of the modulated optical resonance; in the second experiment (Section 3) the amplitude of the picosecond strain pulses is so high that the exciton state in the QW becomes destroyed which results in the ultrafast transition from the strong to the weak coupling regime for a QW-microcavity; in the last experiment (Section 4) we show how nonadiabatic processes in an active optical microcavity result in a giant modulation of the emission output for a vertical cavity surface emitting laser (VCSEL) with QDs.

2. Terahertz polariton sidebands generated by picosecond acoustics in an optical microcavity with a quantum well

All experiments reported in this paper were carried out in helium cryostat at temperatures $T = 1.8 \div 5$ K. The basic scheme of the first experiment is shown in Fig. 1, and the details of the studied structure may be found in Ref. [16]. The high finesse ($Q \sim 10^4$) optical MC structure (Fig. 1(a)) contains an 8-nm-wide $In_{0.04}Ga_{0.96}As$ QW in the middle of a GaAs barrier layer. This λ-cavity layer is surrounded by distributed Bragg reflectors. The high finesse is large enough to reach the strong coupling (polariton) regime between the QW exciton state and the confined photon mode [19,20]. Fig. 1(b) shows the stationary optical reflectivity spectrum $R(E)$ of the MC, in which two narrow resonances corresponding to the lower polariton (LP) and upper polariton (UP) are seen. The photon-like LP resonance is slightly broadened compared to the cavity mode due to the mixing with the inhomogeneously broadened exciton state and has a spectral width $\Delta\omega = 0.18$ meV.

In the ultrafast coherent experiments the polariton resonances were excited by 150 fs white light pulses from a laser system with a repetition rate of 100 kHz. As a result of the broadband excitation the LP and UP states emit coherent light into the specular direction relative to the excitation beam (Fig. 1(a)). This coherent emission decaying with time τ_c and reflection spectrum therefore comprises the information contained in this time interval [21]. The value of τ_c is connected with the spectral width $\Delta\omega$ of the resonance and for photon-like LP $\tau_c = 7.2$ ps.

In our experiments, the THz frequency modulation is achieved using picosecond strain pulses injected into the sample by ultrafast acoustics methods [1,22]. A 800-nm wavelength femtosecond laser pulse, which is split from the same laser source used also for the generation of the white light pulses, excites an opto-acoustic transducer (100-nm thick aluminum film) deposited on the back side of the substrate opposite to the MC structure (Fig. 1(a)). As a result of ultrafast optical excitation, the bipolar strain pulse shown in Fig. 1(c) is injected into the substrate. The energy density of the

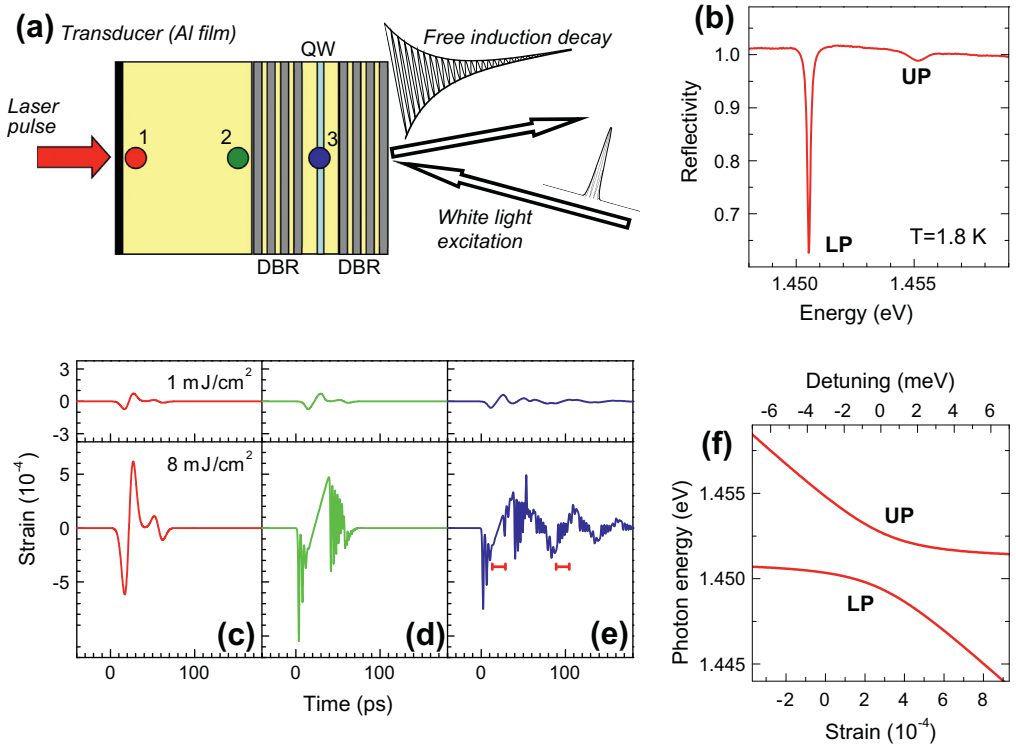

Fig. 1. (a) Scheme of the experiments on a GaAs/AlAs microcavity formed by two distributed Bragg reflector mirrors with an $In_{0.04}Ga_{0.96}As$ quantum well embedded in between [16]. The strain pulses are generated by a laser pulse, shown by the red arrow, focused onto an Al film. (b) Reflectivity spectrum from the MC without applied modulation. LP and UP correspond to the spectral resonances of the lower and upper polaritons, respectively. (c–e) Strain pulses $\eta(t)$ simulated for low (upper panels) and high (lower panels) excitation densities W at various distances [indicated by the spots 1–3 in panel (a)] from the Al opto-acoustic transducer. The propagation time from the transducer to the corresponding points was subtracted for clarity. The red horizontal bars in panel (e) indicate the time intervals when the strain variation is considered as linear in time. (f) The UP and LP energies in the MC as function of static strain (lower scale) and detuning between the energies of the uncoupled photon mode and exciton state (upper scale).

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