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Photoreflectance spectroscopy of semiconductor structures at hydrostatic pressure: A comparison of GaInAs/GaAs and GaInNAs/GaAs single quantum wells

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Abstract

The pressure dependence of optical transitions in $Ga_{0.64}In_{0.36}As$/GaAs and $Ga_{0.64}In_{0.36}N_{0.01}As_{0.99}$/GaAs single quantum well (SQW) structures were studied in photoreflectance (PR) spectroscopy. In order to apply high hydrostatic pressure, up to ~11 kbar, the liquid-filled clamp-pressure cell with a sapphire window for optical access has been adopted in the PR set-up with the so called 'bright configuration'. It has been found that the linear hydrostatic pressure coefficient for the ground state transition are equal to 8.6 and 7.3 meV/kbar for the GaInAs/GaAs and GaInNAs/GaAs SQWs, respectively. This result shows that the incorporation of only 1% of N atoms into GaInAs/GaAs leads to ~15% decrease in the pressure coefficient. In addition, a non-linearity in the pressure dependence of the ground state transition has been resolved for the GaInNAs/GaAs SQW.

Keywords: Photoreflectance; SQW; Hydrostatic pressure; Dilute nitrides

1. Introduction

Photoreflectance (PR) spectroscopy is powerful tool to investigate optical properties of semiconductor systems [1–4]. The derivative nature of this experimental method enables observation of a large number of sharp spectral features including those related to excited state transitions in low-dimensional structures, in contrast to common emission-type experiments such as photoluminescence (PL), which usually probes only the ground state. In addition, this technique can probe different parts of semiconductor structures, i.e. quantum wells, barriers, step-like barriers, quantum dots as well as wetting layers in quantum dot structures. When used in combination with hydrostatic pressure, PR is established as an effective means for revealing information about the pressure coefficients or other phenomena not directly obtained at ambient pressure.

Recently, PR spectroscopy at high hydrostatic pressures has been successfully applied to nitrogen dilute III–V compounds and quantum well (QW) structures [5–12]. The incorporation of only a small amount of nitrogen induces dramatic changes in the electronic properties of the compound [13,14]. The most interesting feature is that the incorporation only few percent of nitrogen into Ga(In)As(Sb) leads to a strong band-gap reduction (about 100–150 meV per 1% of N). Therefore, the nitrogen dilute III–V compounds, such as GaNAs, GaInNAs, GaNAsSb, and GaInNAsSb, are promising materials for the active region of lasers for 1.3 and 1.55 μm. In addition, an unusual pressure behavior of the band gap in III–V–N compounds has been observed. In order to explain the experimental results, Shan et al. [5,9] introduced a two-level model including the lowest conduction band and the localized N resonant state in the host matrix. On the other hand Jones et al. [15] proposed that the repulsion from the X valley in the conduction band is the major cause of the observed nonlinear pressure dependence. Mattila et al. [16] suggested that the lowest conduction band experiences repulsion from two sources: the $\Gamma - L$ interaction at low pressure and $\Gamma - X$ interaction at high pressure. Zhang et al. [17] suggested that the main reason for the unusual pressure behavior might be the formation of an impurity band due to heavy nitrogen doping.

In this paper we report (i) our experimental set-up for PR measurements at 'bright configuration' at hydrostatic pressure and (ii) the results of PR measurements at various hydrostatic pressures for a sample consisting two QWs, i.e. a GaInAs/

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GaAs and GaInNAs/GaAs single QWs (SQWs) with the same width (7 nm). The measurements of QW transitions for the two SQWs and the band gap energy for GaAs at exactly the same hydrostatic pressure give a possibility to investigate the influence of N atoms on the pressure coefficients very carefully. In addition, we show that the applied pressure can be calibrated by means of the shift of GaAs transition usually observed in PR spectra of QW structures grown on GaAs substrate.

2. Experimental set-up and samples

The PR measurements at hydrostatic pressure were performed in the so called 'bright configuration' where the sample was illuminated by white light instead of monochromatic light as it takes place in the standard configuration, i.e. so-called 'dark configuration'. A schematic diagram of the PR set-up is shown in Fig. 1. The sample mounted in a pressure cell is illuminated by light from a halogen lamp (100–250 W) at near normal incidence as it is shown in Fig. 1. The reflected light was dispersed through a 0.55 m focal length single grating monochromator and detected by thermo-electrically cooled InGaAs photodiode. For photo-modulation, the 532 nm line of an Ar^+ laser was used as a pump beam (with the laser power of 10 mW), that was mechanically chopped at a frequency of 280 Hz. The modulated beam was introduced to the pressure cell together with the probing beam (i.e. the white light from halogen lamp) by using a mirror, and a beam splitter, as shown in Fig. 1. In addition, the modulated beam was defocused such as the diameter of the beam on the sample was the same as the diameter of the probing beam, i.e. ~2 mm.

In order to obtain high hydrostatic pressure the sample was mounted in a Be:Cu liquid-filled clamp-pressure cell with a sapphire window for optical access and with a maximum working pressure of ~11 kbar. The pressure is increased by pushing the piston in the hydrostatic cell. The liquid in the cell is methanol–etanol (4:1); it remains hydrostatic and transparent in the 11 kbar range. The pressure in the cell is calibrated with the resistance of an InSb sensor which gives about 0.1 kbar sensitivity in the 15 kbar range.

The sample used to this study was grown on a 500 μm thick (0 0 1)-oriented unintentionally doped GaAs substrate by solid source molecular beam epitaxy (MBE) using an *EIKO 100S* MBE system at Würzburg University. Standard effusion cells were used for As, Ga, and In. An *Applied Epi* UNI-Bulb™ radio frequency (RF) plasma source operating at 13.56 MHz was used to generate nitrogen radicals from high-purity (6 N) N_2 gas. The sample consisted of a 180 nm thick GaAs buffer layer, a 7 nm width $Ga_{0.64}In_{0.36}As$ well layer (reference SQW) separated by a 100 nm GaAs barrier from the second 7 nm-width $Ga_{0.64}In_{0.36}N_{0.01}As_{0.99}$ well layer and a 100 nm thick GaAs cap layer. The GaAs layers were grown at 590 °C and the GaIn(N)As QW at approximately 440 °C. The whole structure was grown without any interruptions.

3. Results and discussion

Fig. 2 shows room temperature PR spectra obtained at various hydrostatic pressures for the sample consisting of the GaInAs/GaAs and GaInNAs/GaAs SQWs. At the atmospheric pressure (0 kbar) PR resonances related to the ground state transition in the QW, i.e. an absorption between the first heavy-hole and the first electron sub-bands, are observed at 0.899 and 1.076 eV for GaInNAs/GaAs and GaInAs/GaAs SQWs, respectively. At 1.42 eV a PR feature related to GaAs buffer and/or cap layer is clearly observed. In addition, weak PR features associated with the optical transitions between the excited states in GaInNAs/GaAs and GaInAs/GaAs SQWs are visible, see the arrows without labels in Fig. 2. All PR transitions blueshift with the rise of the hydrostatic pressure. In order to extract the energy of the optical transitions, PR resonances were analysed using the low-field

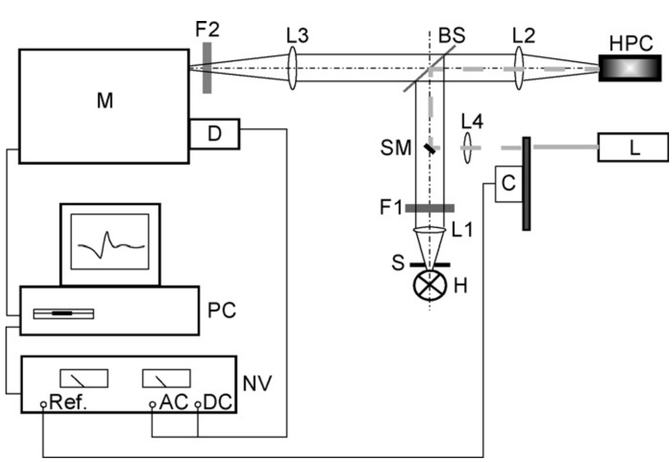

Fig. 1. Experimental set-up for PR measurements in the so-called 'bright configuration' at various hydrostatic pressure. H: halogen lamp; S: slit; L1, L2, L3, L4: lens; F1, F2: filters; SM: small mirror; BS: beam splitter; HPC: high pressure cell; M: monochromator; D: detector; NV: nanovoltmeter (Lock-in); L: laser; C: chopper; PC: personal computer.

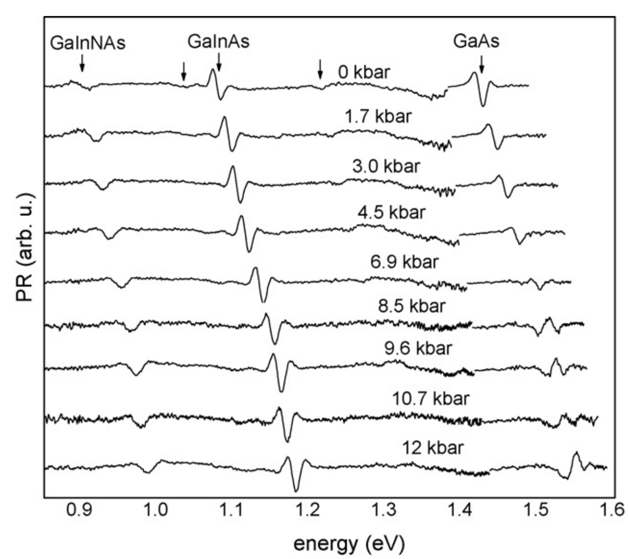

Fig. 2. PR spectra measured at various hydrostatic pressures for the sample consisting of the GaInAs/GaAs and GaInNAs/GaAs SQWs.