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Surface photovoltage investigation of GaAs quantum wells

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We have studied GaAs quantum wells (QWs) embedded in $(AlAs)_4/(GaAs)_8$ superlattices (SLs) with graded interfaces by means of surface photovoltage (SPV) spectroscopy, taking advantage of its high sensitivity and contactless measurements. The metal-insulator-semiconductor operation mode of the SPV method is applied. SPV spectral dependencies are measured at room temperature in samples containing one GaAs QW (5 nm) embedded between 20 and 26 periods of SL. The SPV amplitude spectrum, recorded at a light modulation frequency of 94 Hz, reveals peak structures, related to electron-to-heavy hole and electron-to-light hole exciton transitions in the GaAs QW and a step-like structure related to the optical transitions between the electron and hole SL mini-bands. Their energy positions correspond well to our electronic structure calculations performed by means of the envelope function approximation, considering a model Al concentration profile very close to the experimental one, as well as to photoluminescence data measured on similar samples. This investigation shows some of the SPV spectroscopy interesting abilities for characterization of complicated nanostructures.

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1. Introduction

The SPV method is a powerful non-destructive and contactless characterization technique, which has been used to study the electronic properties of a wide range of semiconductor bulk materials and multilayers [1]. Recently, SPV spectroscopy (SPS) has been successfully applied to study quantum wells (QWs) [2,3], quantum dots [4,5] and more complicated nanostructures, e.g. vertical cavity surface emitting lasers (VCSELs) [6]. It is considered as an alternative for the optical absorption spectroscopy of nanostructures [1,4,7]. This is due to its high sensitivity, which allows obtaining the desired information at room temperature. Moreover the SPS set-up is easily assembled and the measurements are relatively simple to perform. In the metal-insulator-semiconductor (MIS) operation mode of the SPV method, the sample is illuminated through a fixed semi-transparent electrode by periodic light and the variations of the photovoltage are measured, usually by means of a lock-in technique [1]. In this work, we apply the MIS operation mode of the SPV method in order to study GaAs QWs embedded in short-period AlAs/GaAs superlattices (SL). Such structures are interesting because of their novel physical properties as well as some advantages in optoelectronic device fabrication compared to GaAs QWs with homogeneous AlGaAs barriers [8]. SPV spectra, recorded at low light modulation frequencies, clearly reveal spectral features corresponding to free exciton transitions in the GaAs embedded QW (EQW) and in the SL.

2. Experimental

2.1. Samples

The samples are grown in Ecole Polytechnique Federale de Lausanne, Switzerland by molecular beam epitaxy at 600°C on (001) Si doped GaAs substrates ($1x10^{18}$ cm^{-3}). They represent one GaAs QW of 5 nm. [18 monolayers (ML), 1ML = 0.283nm] embedded between 20 (on top) and 26 (on bottom) periods of $(AlAs)_4/(GaAs)_8$ SL (4 and 8 are the number of MLs of AlAs and GaAs, respectively). There is a 50 nm cap layer of $Al_xGa_{1-x}As$ ($x = 0.33$, which is the mean Al content in the SL).

2.2. Experimental set-up

The set-up is schematically shown in Fig. 1. The sample is mounted on a grounded copper platform positioned in a continuous flow optical cryostat. The semi-transparent electrode (probe) is a SnO_2 film deposited on quartz glass mounted on a metallic holder. The opposite end of the probe holder is tightly fixed on an insulating support. By means of an arch with a vertical screw, the holder can be bent. In this way, the probe moves down to press the sample against the copper platform.

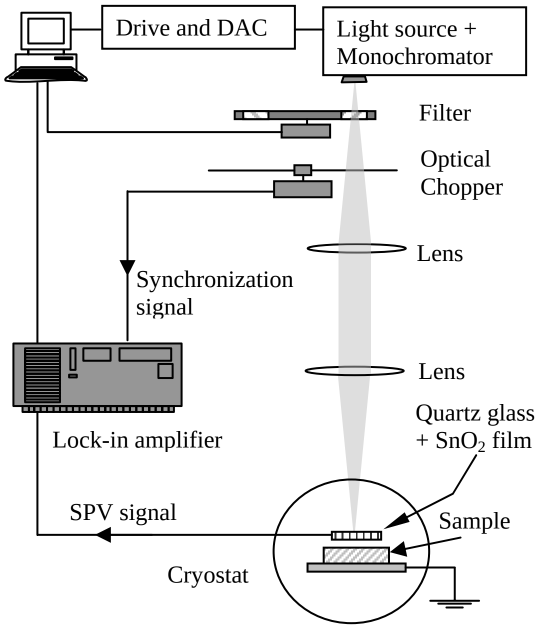

Fig. 1. Experimental set-up for SPV measurements.

The sample surface is illuminated by means of a 100 W halogen tungsten lamp along with a SPEX grating monochromator (f=0.22 m), a filter to cut off the high-order diffraction and a PTI OC4000 optical chopper. The lamp voltage is previously calibrated in order to achieve a constant photon flux density (~$3x10^{13}cm^{-2}s^{-1}$ ± 2%), incident on the sample at each wavelength. The probe signal with respect to ground is fed to a high-impedance unity gain buffer (UGB) and then measured by an EG&G 5207 lock-in amplifier. More details concerning the set-up and the measurement procedure can be found in [7].

The measurements were performed at room temperature with normal incident light, chopped at 94 Hz. The light wavelength was scanned from high toward low values.

In the photoluminescence (PL) measurements the sample was excited by the 488 nm line of an Ar ion laser with an intensity of 3000 $W.cm^{-2}$. The PL spectra were detected by a GaAs photomultiplier along with a double SPEX monochromator (f = 0.85m).

3. Electronic structure calculations

In the calculations of the electronic structure we consider a 5 nm (18 ML) GaAs EQW positioned between 20 and 26 periods of SL, with a semi-infinite $Al_{0.33}Ga_{0.67}As$ cap layer and GaAs substrate. The interface grading is taken into account by considering a diffused Al concentration profile similar to our previous works [8-10]. The diffusion length L_D is a parameter which determines the degree of interface grading. PL data of similar samples, also grown at 600°C, have been satisfactorily explained when assuming an interface grading corresponding to L_D = 4.6 ML (1.30 nm) [10]. Thus, this value is used in the present envelope function approximation (EFA) calculations, together with the material parameters taken from [11]. The structure considered in the calculations is equivalent to the experimental one except the semi-infinite cap layer and substrate.

The one-band EFA equation is solved numerically by the finite difference method. The used concentration profile in the EQW region and its vicinity is represented in Fig. 2 by the solid line, where x is the Al content in the ternary compound $Al_xGa_{1-x}As$. As in our previous works [8], we use as a first approximation the EQW exciton binding energies E_{exc} calculated in [12] for a GaAs/AlAs/AlGaAs QW with a double barrier. The exciton correction for the SL transitions is taken to be 4 meV [13].

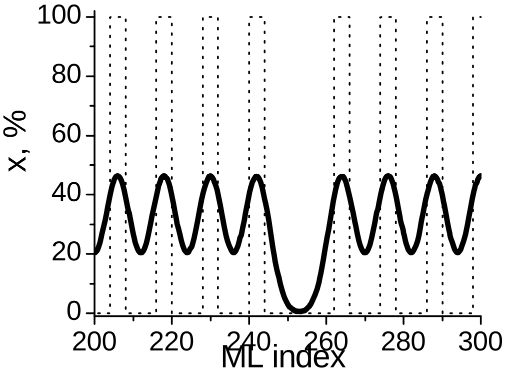

Fig. 2. Al concentration profile in the EQW region and a few periods of the SL around it, in the case of abrupt (dotted line) and graded (solid line) interfaces corresponding to L_D = 4.6 ML.

4. Results and discussions

The calculated transition energies are shown in Table 1, together with the experimental results and the exciton binding energies. The calculated energies corrected for excitonic effects are given in the last column of Table 1, and are to be compared with the experimental ones. It should be noted that the theoretical results presented here are more relevant compared to the ones of our previous electronic structure calculations [8-10], which include model structures consisting of one EQW and only 5 SL periods on both sides.

Table 1. Experimental and calculated optical transition energies.

Transition	SPV	PL	EFA calculations (L_D=1.3 nm)		
	E (eV)	E (eV)	E (eV)	E_{exc} (meV)	$E - E_{exc}$ (eV)
E1-HH1	1.597	1.599	1.605	12	1.593
E1-LH1	1.635	1.625	1.636	13	1.623
E-HH (SL)	1.822	1.838	1.828	4	1.824

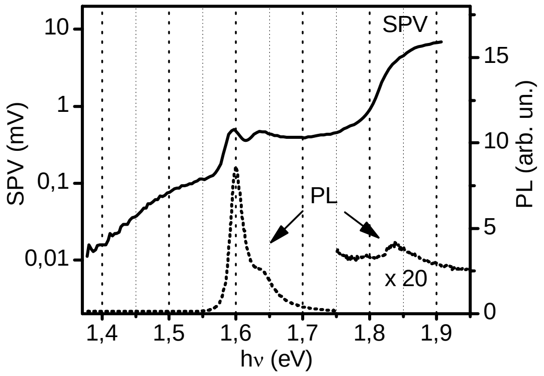

Fig. 3. Typical SPV (solid line) and PL (doted line) spectra measured at 300K. The PL spectrum for energies higher than 1.75 eV is multiplied by a factor of 20 for clarity.

Because the substrate is highly n-type doped and the rest of the structure is nominally undoped, the energy bands in the structure are bent upwards with respect to the bulk and a space charge region (SCR) develops in the structure. Thus, the SL, the EQW and the AlGaAs cap layer are situated in a region with a built-in electric field. The photocarriers, generated in the EQW, escape via thermal emission and field-assisted tunnelling towards the SL minibands, where they are separated by the SCR electric field, thus giving rise to SPV signal generation.

A typical SPV spectrum is presented in Fig. 3, in a semi-logarithmic scale. The step in the range 1.40 – 1.55 eV originates from transitions in the GaAs substrate (E_g=1.424 eV). It is followed by a second step in the range 1.55 – 1.75 eV, which is preceded by two peaks at 1.597 eV and 1.635 eV. This step reveals the two-dimensional joint density of states in the EQW, while the peaks are ascribed to the E1-HH1 and E1-LH1 free exciton transitions in the EQW. This interpretation is based on the fact that their energy positions correspond well to our EFA calculations (see Table 1).

The last feature in the SPV spectrum is the step in the range 1.75 – 1.90 eV with an inflection point at 1.822 eV. According to the calculations (see Table 1) it originates from transitions between the electron and hole mini-bands of the SL. We have also found a strong overlap between the HH and LH SL mini-bands. Therefore more sophisticated multi-band EFA models are necessary in order to explain the fine structure observed in the SL step. The $Al_{0.33}Ga_{0.67}As$ cap layer could also contribute to this step, because its bandgap energy (1.829 eV) is close to the SL one.

It should be noted that the SPV signal corresponding to the first step, which originates from the GaAs substrate, is considerably lower than the one of the EQW HH and LH exciton peaks (1.597 and 1.635 eV) as well as the one from the SL (note the logarithmic scale in Fig. 3). This is due to the high Si doping of the substrate (1×10^{18} cm^{-3}), which effectively screens the electric field and leads to a very narrow SCR in it. Thus, the SPV effect takes place mainly in the SL and the embedded well, but because of their volume ratio (~30 times) the SL related step dominates the spectrum. It should be noted that in similar samples with an undoped GaAs substrate, a well expressed step originating from the substrate is present in the SPV spectrum, in the same energy range (around 1.42 eV).

Fig. 3 also displays a PL spectrum of a similar sample measured at room temperature. It reveals a peak at 1.599 eV, a shoulder at 1.625 eV and a weak peak at 1.838 eV. These energies are in good correspondence with the calculated ones as well as with the SPV results. This is a further confirmation of the presented interpretation of the SPV spectrum.

We note that the LH exciton transition is better resolved in the SPV spectrum than in the PL one. Also, the SL peak in the PL spectrum is much weaker than the signal from the EQW, contrary to the situation in the SPV spectrum (see Fig.3). These advantages of the SPV are due to the fact that it reflects the absorption spectrum [1,4,7], while the PL reveals the emission properties, which are dominated by the lowest energy levels.

5. Conclusion

We have investigated a GaAs QW embedded in an AlAs/GaAs SL, using SPS. Comparison with EFA calculations for an equivalent model structure has shown that the observed features in the SPV spectrum can be ascribed to E-HH, E-LH and SL mini-band transitions. This has been confirmed further by the PL measurements performed on the samples.

This study shows some novel applications of the SPS for investigation of complicated device nanostructures.

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