Optical and Terahertz Characterization of Be-Doped GaAs/AlAs Multiple Quantum Wells

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We report on optical, photoreflectance and surface photovoltage, as well as terahertz photocurrent investigation of Be-doped GaAs/AlAs multiple quantum wells at room and liquid helium temperatures, respectively. From the Franz–Keldysh oscillations observed in photoreflectance spectra we determine built-in electric fields within the structure. Interband transition energies calculated by the transfer matrix method are in qualitative agreement with experimentally determined values for the samples having various, from 2×10^{10} up to 2.5×10^{12} cm^{-2}, Be doping densities. The photocurrent observed in the range of 5.4–7.3 THz we associate with photoionization of Be-acceptor states.

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1. Introduction

Rapid evolution of THz electronics has stimulated a search for new solutions to realize terahertz devices. The engineering of shallow impurities levels by varying the width of a confining quantum well (QW) provides the possibility to use such

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structures for THz detectors/emitters [1]. The control of their energy level position and knowledge concerning the presence of internal electric fields and imperfections is therefore of particular importance in the design of such devices.

In this communication, we report both, optical and terahertz studies of Be δ-doped GaAs/AlAs multiple QW structures. The GaAs/AlAs QW system is of special interest since it represents the maximum possible confinement for the acceptor states.

2. Samples and experimental techniques

The structures consist of GaAs QWs with different width L_{w} separated by AlAs barriers of thickness 5 nm grown by MBE on a semi-insulating GaAs substrate. The δ-doped Be-layers were placed in the center of the wells. Parameters of the samples are given in the Table. The band diagram of δ-doped multiple QW structures is shown in Fig. 1.

TABLE

Parameters of QWs: repeated period, QW width — L_{w}, doping concentration — P.

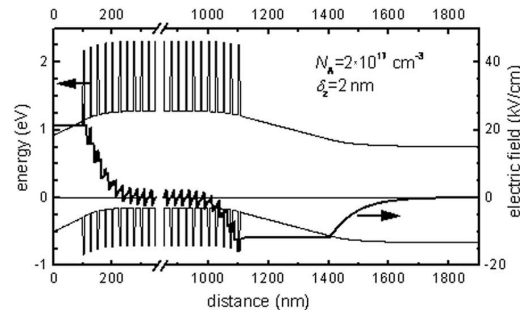| Samples	Periods	L_{w} (nm)	P (cm^{-2})
1795	400	3	2×10^{10}
1794	200	10	5×10^{10}
1392	40	20	2.5×10^{12}
1796	a single 5 μm thick epilayer (GaAs:Be)		2×10^{16}

Fig. 1. Band diagram of Be δ-doped multiple QW structures calculated by solving Schrödinger−Poisson equations.

We applied photoreflectance (PR) and surface photovoltage (SPV) spectroscopies as well as the terahertz photocurrent technique to characterize the structures. The PR measurements were performed using a He–Ne (wavelength is 632.8 nm) laser or light emitting diode (wavelength is 470 nm) light beams as the

modulation sources keeping pumping intensities below 2 mW·cm^{-2}. In the tera-hertz photocurrent experiment we have used several lines of an optically pumped molecular THz laser in the spectral region of interest corresponding to the Be acceptor binding energy (28 meV in bulk GaAs). The photocurrent measurements were performed in planar geometry in closed-cycle helium cryostat at 4 K.

3. Optical spectra

Figure 2 shows the PR spectra in the range of 1.3–1.7 eV for GaAs/AlAs QW samples with various well widths and doping concentrations. The PR spectrum from epitaxial p-GaAs layer is also shown for comparison. The characteristic
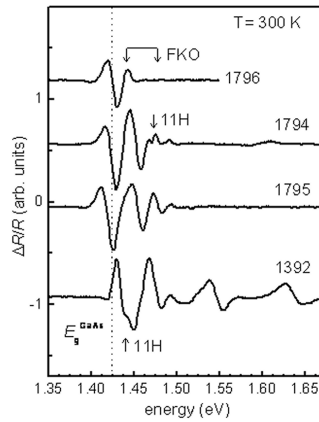

Fig. 2.   PR spectra of GaAs/AlAs QW structures with different well widths at 300 K. The main characteristic features are market by arrows. Data of Be-doped GaAs epilayer are given for comparison.

Franz–Keldysh oscillations (FKOs) are clearly seen above of the GaAs fundamental gap E_g (1.424 eV) for QW samples 1794, 1795, and the GaAs epilayer 1796, too. These spectral features indicate that internal electric field exists in the samples. The values of the built-in electric field in the GaAs buffer/cap layers estimated from the FKOs are within the range of 13–20 kV/cm. For deeper understanding, we measured SPV spectra [2]. The results are given in Fig. 3. The SPV spectra, measured under the same conditions, exhibit features related to GaAs cap and/or buffer layers and QW structure itself. More specifically, the kink at about 1.42 eV is related to the bulk GaAs band edge. At higher energies, characteristic discrete dips associated with excitonic transitions in QWs are clearly visible. The experimentally determined values of the interband transition energies were found to be in reasonable agreement with the calculated ones by the transfer matrix method. Also, it was observed that the broadening of spectral features depends on the doping level. Further, one must note that the spectra show the n-type behavior (positive sign) in spite of the presence of p-type band bending near the surface.
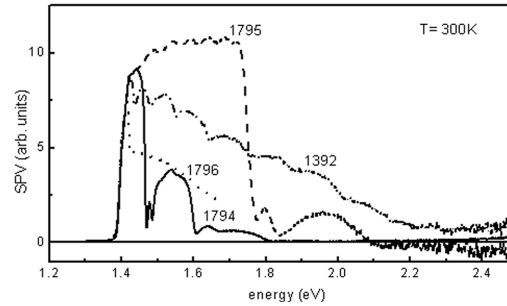
Fig. 3. Experimental SPV spectra of GaAs/AlAs multiple QW structures at 300 K. Data of Be-doped GaAs epilayer are given for comparison.

These results can be explained in the following way: in the structures there are two oppositely directed electric fields, one is in the cap layer while the other one is located in the buffer layer (see Fig. 1). Therefore, the SPV signals from these structure regions should be of opposite signs [3]. As the total SPV is positive, it means that the SPV signal from the interface region of GaAs buffer layer is very strong, and that it conceals the signal from the surface region.

4. Terahertz characterization

Further, we have investigated experimentally GaAs/AlAs structures as THz detectors by spectral photocurrent measurements. The data are given in Fig. 4. It is seen that with the increase of the radiation wavelength the photocurrent decreases. The mechanism responsible for the photocurrent signal is believed to be photothermal ionization of Be acceptors as all spectral curves correspond to the responsivity falling edge at photon energies below the acceptor binding energy. The observed responsivity edge extends to long wavelengths probably due to contribution of excited acceptor states $2P_{3/2}$ and $2P_{5/2}$ having transition energies several meV lower than the binding energy [4]. It should be noted that the absorption lines due to transitions to excited Be acceptor states were observed in [5]
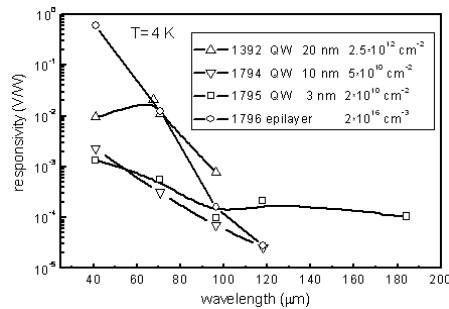

Fig. 4. Responsivity of the QW structures as a function of radiation wavelength at 4 K. For comparison, data of Be-doped GaAs epilayer are depicted.

on the same δ-doped GaAs/AlAs QW structures as studied here. A spectral shift of responsivity to short wavelengths in sample 1794 is in good agreement with the influence of quantum confinement to the acceptor binding energy. Despite sample 1795 having the highest activation energy and similar doping, it shows extension of the photoresponse tail to longer wavelengths. We think that some additional photoconductivity may arise from photoexcitation of holes at crystal imperfections and centers capable to trap holes with low binding energies. In contrast, sample 1392 has about two orders of magnitude higher doping density, therefore, higher responsivity can be related to increased THz absorption. Furthermore, its high doping density may also induce a hopping effect observed in this spectral range between optically excited acceptor states [6] giving thus rise to an additional photosignal with smaller activation energies. As it is seen from Fig. 4, the experimental data supports the previous discussion. Finally, we show that PR, SPV, and terahertz photocurrent methods can give valuable information about internal electric fields and electronic structure of δ-doped multiple QW structures.

Acknowledgments

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