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Optical Transitions between Confined and Unconfined States in *p*-Type Asymmetric GaAs/InGaAs/AlGaAs QW Structures

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We present contactless surface photovoltage spectroscopy and photoreflectance studies of 10 nm wide, *p*-type doped asymmetric GaAs/InGaAs/AlGaAs quantum well structures. The MBE grown structures differ in spacer thickness between the quantum well and the reservoir of holes. The doping causes that quantum well is placed in electric field. The surface photovoltage spectroscopy measurements gave us detailed information about the optical transitions between confined states and between confined and unconfined states. The comparison of experimental and numerical analysis allows us to identify all features present in the surface photovoltage spectroscopy and photoreflectance spectra. It has been found that spacer layer thickness has significant influence on surface photovoltage spectroscopy spectra.

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1. Introduction

The AlGaAs/InGaAs/GaAs system heavily doped with donors by δ -doping, a heart of electronic devices, i.e. high electron mobility transistors, is well known experimentally and theoretically. This type of devices with two-dimensional electron gas (2DEG) have shown excellent performance in low noise, power microwave, and high-speed digital applications [1–3]. Not so much effort was devoted to the AlGaAs/InGaAs/GaAs system but doped with acceptors. The main reason is much smaller hole concentration of two-dimensional hole gas (2DHG) possible to achieve and consequently considerably smaller mobility of 2DHG in comparison to 2DEG.

In this study, surface photovoltage spectroscopy (SPS) was used to characterize the 10 nm wide, *p*-type doped asymmetric GaAs/InGaAs/AlGaAs quantum well (QW) structures. Two investigated structures differ in spacer thickness between the quantum well and the reservoir of holes. The spacer layer thickness influences 2DHG concentration in the well. This influence has a reflection in SPS spectra. The asymmetry of QW leads to creation of an additional recombination channel between unconfined and confined states. This observation can be essential at designing electronic and optoelectronic devices.

2. Samples and measurement technique

The GaAs/InGaAs/AlGaAs asymmetric QW samples employed in this study were grown on semi-insulating GaAs (100) substrates using a molecular beam epitaxy method. The structures contain a 50 nm undoped GaAs

buffer layer followed by 10 periods of GaAs(5 nm)/AlAs(2.5 nm) superlattice and 600 nm undoped GaAs barrier. In_{0.11}Ga_{0.89}As QW layer is 10 nm thick. Top Al_{0.33}Ga_{0.67}As barrier is 10 nm or 30 nm thick depending on structure. The QW region is followed by 16 periods of GaAs(2 nm)/AlAs(1 nm) superlattice doped with carbon. Additional carbon δ -doping was carried out between GaAs and AlAs layers. The samples were terminated by undoped 117 nm thick Al_{0.33}Ga_{0.67}As and 5 nm thick GaAs layers.

The room temperature hole concentration, measured from transport (quantum Hall effect) is $7.2 \times 10^{11} \text{ cm}^{-2}$ and $3.7 \times 10^{11} \text{ cm}^{-2}$ for sample with 10 nm and 30 nm spacer width, respectively.

The photoreflectance (PR) and SPS measurements were performed at room temperature. In SPS measurement, the contact potential difference between the sample and a reference grid electrode was measured in a capacitive manner as a function of the photon energy of the probe beam [4, 5]. The light from a 250 W tungsten-halogen lamp was passed through a 0.32 m Jobin–Yvon monochromator, chopped at 180 Hz and focused onto the sample. PR measurements were achieved using 5 mW He–Ne laser (632 nm) as the modulating source. The laser intensity was controlled by using neutral density filters. A light from 150 W tungsten-halogen lamp filtered by a 1.1 m monochromator was used as a probe beam. The reflected light was detected by an Si photodetector and the signal was recorded by a lock-in amplifier.

3. Results and discussion

Surface photovoltage spectra of both samples are marked in Fig. 1 with dash-dot lines. To enhance the transitions present in the SPS spectra we numerically computed the normalized first derivative of the

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SPS signals with respect to the photon energy, $\partial(E \times \text{SPS})/\partial E$ [6]. The so-called differential SPS (DSPS) spectra are shown in Fig. 1 with solid lines. In the region below GaAs band gap energy, we can observe well resolved quantum well related features. The lower energy features in both DSPS spectra can be related to the optical transition between the first heavy-hole state in the valence band and the first electronic state in the conduction band. Only for structure with thinner spacer layer we can clearly observe feature originating from optical transition in GaAs. The DSPS spectra of both structures show very strong feature at energy 30–35 meV below GaAs bandgap energy. Intensity of these features is unexpectedly high comparing to other QW related transitions.

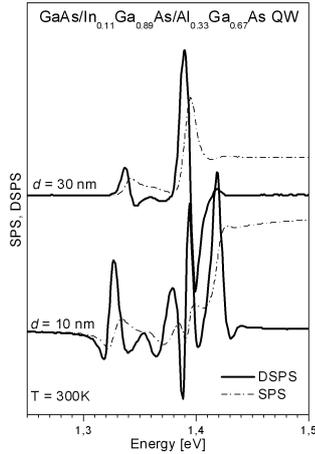


Fig. 1. Room temperature SPS (dot–dash lines) and its derivative — DSPS (solid lines) of structures with different $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$ layer (spacer) thickness.

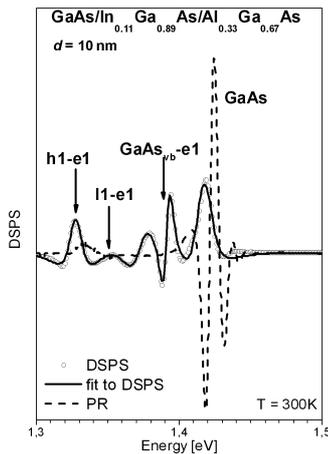


Fig. 2. Comparison of DSPS (circles), fit to DSPS with Eq. (1) (solid line) and PR (dashed line) of structure with 10 nm $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$ spacer layer. Arrows mark the transition energies obtained from fitting to DSPS spectra.

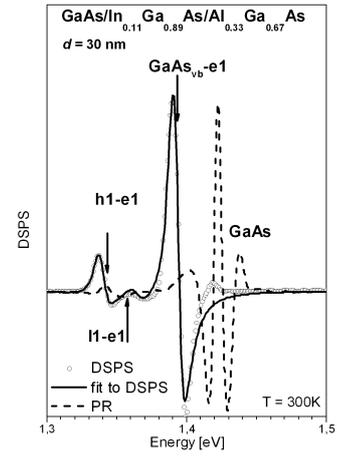


Fig. 3. Comparison of DSPS (circles), fit to DSPS with Eq. (1) (solid line) and PR (dashed line) of structure with 30 nm $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$ spacer layer. Arrows mark the transition energies obtained from fitting to DSPS spectra.

In order to clarify the origin of strong features we performed PR measurements of both structures. Photoreflectance spectra, and for comparison, DSPS spectra are shown in Fig. 2 and Fig. 3 for structures with 10 and 30 nm spacer width, respectively. The intensities of DSPS and PR spectra should not be compared. PR spectrum, for structure with 10 nm spacer layer, presented in Fig. 2 shows strong feature originating from transition in GaAs and very weak feature in the region of fundamental QW transition. Both features have their reflection in DSPS spectrum. The PR spectrum for second structure is very similar to previous one — we can find two features related to GaAs region and QW fundamental transition. But with this case only fundamental QW transition originating feature is present in both, DSPS and PR, spectra. There is no evidence in PR spectra on strong features located 30–35 meV below GaAs bandgap energy in DSPS.

To obtain the QW transition energies we choose the way where such a derivative of SPS spectrum resembles a modulated reflectance spectrum [6], and for fitting to DSPS data we can use well-known Aspnes function, given by [7]:

$$\frac{\partial(E \times \text{SPS})}{\partial E} = \text{Re}\left(Ae^{i\theta}(E - E_0 + i\Gamma)^{-m}\right), \quad (1)$$

where A is an amplitude, θ — a phase angle, E_0 — the critical point energy, Γ — a broadening parameter and m — a parameter which depends on the nature of the critical point transition. To fit the experimental data of excitonic transitions $m = 2$ is used [8]. The fitting curves are shown in Fig. 2 and Fig. 3 as solid lines and the obtained from the fitting procedure optical transition energies are listed in Table.

TABLE

The comparison of transition energies (in [eV]) between confined states and unconfined-confined states obtained from fitting to DSPS data (exp.) and numerical calculations (theory) for two GaAs/In_{0.11}Ga_{0.89}As/Al_{0.33}Ga_{0.67}As QW structures with different Al_{0.33}Ga_{0.67}As layer (spacer) thickness.

Structure	h1-e1		h2-e1/l1-e1		h3-e1	h1-GaAs _{cb}	GaAs _{vb} -e1	
	exp.	theory	exp.	theory	theory	theory	exp.	theory
$d = 10$ nm	1.327(2)	1.323	1.350(10)	1.346/1.341	1.379	1.346	1.390(3)	1.408
$d = 30$ nm	1.337(2)	1.326	1.355(10)	1.348/1.343	1.381	1.349	1.395(3)	1.410

To identify strong features observed in DSPS spectra and absent in PR spectra, we have performed theoretical analysis based on the envelope function approximation, including strain and exciton binding energy. The potential distribution was determined self-consistently by the Schrödinger and Poisson equations [9]. The asymmetric QW transition energies obtained from numerical calculations are listed in Table. From calculations we get that in conduction band QW there is localized only one electronic state. The reason on above is that the indium content in investigated structures is rather low and quantum well in conduction band is shallow.

Analyzing the optical transition energies we have to remember that due to the doping QW is not rectangular and is placed in electric field. Except fundamental h1-e1 transition, well resolved in both DSPS spectra, in the energy region below GaAs bandgap energy there are possible optical transitions to electronic state from higher valence band states, both heavy-hole and light-hole related. We expect that their intensity should be small comparing to h1-e1 transition. Indeed, at energies slightly higher than h1-e1 transitions we can find not well resolved features. Due to the influence of other stronger features it is hard to precisely determine their energies. We can identify that features as originating from l1-e1 transition from first light-hole state to first electronic state. Because of its intensity the strong features located below GaAs bandgap energy cannot be related to states confined in valence band QW. The other possibility is related to transitions between unconfined and confined states [10, 11]. Finally we identify these strong features as originating from optical transitions between GaAs valence band (QW barrier) and electronic state confined in conduction band QW, GaAs_{vb}-e1. Another confirmation of our identification is that there is no evidence of that kind of features in PR spectra. This is because transitions between confined and unconfined states should not be observed in PR [5].

As we noticed earlier, only in the DSPS spectrum of structure with thinner spacer (higher hole concentration) the feature originating from GaAs optical transition was clearly visible. The possible explanation is that for higher hole concentration some carriers cannot recombine through GaAs_{vb}-e1 channel and escape to GaAs. For lower hole concentration the GaAs_{vb}-e1 channel is efficient enough and we cannot observe GaAs related feature.

4. Conclusion

Two 10 nm wide, *p*-type doped GaAs/InGaAs/AlGaAs QW structures were characterized using surface photovoltage spectroscopy. The structures differ in spacer thickness between the QW and superlattice which was the reservoir of holes. The numerical analysis allowed us to identify all the observed in SPS features. Except fundamental h1-e1 optical transition we found another important way for holes to recombine — transition between GaAs valence band and electronic state in conduction QW. For structure with 30 nm spacer width its intensity was considerably higher than h1-e1 transition. The fact that carriers can recombine not only by fundamental transition can be essential at designing electronic and optoelectronic devices.

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References

- [1] J.H. Lee, H.S. Yoon, C.S. Park, H.M. Park, *IEEE Electron Dev. Lett.* **16**, 271 (1995).
- [2] M. Abe, T. Mimura, *IEEE J. Solid-State Circuits* **26**, 1337 (1991).
- [3] A. Kastalsky, J.H. Abeles, R.F. Lejony, *Appl. Phys. Lett.* **50**, 708 (1987).
- [4] B. Adamowicz, J. Szuber, *Surf. Sci.* **247**, 94 (1991).
- [5] P. Sitarek, H.P. Hsu, Y.S. Huang, J.M. Lin, H.H. Lin, K.K. Tiong, *J. Appl. Phys.* **105**, 123523 (2009).
- [6] S. Datta, S. Ghosh, B.M. Arora, *Rev. Sci. Instrum.* **72**, 177 (2001).
- [7] D.E. Aspnes, in: *Handbook on Semiconductors*, Ed. T.S. Moss, Vol. 2, North-Holland, New York 1980, p. 109.
- [8] Y.S. Huang, H. Qiang, F.H. Pollak, J. Lee, B. Elman, *J. Appl. Phys.* **70**, 3808 (1991).
- [9] G. Bastard, *Wave Mechanics Applied to Semiconductor Heterostructures*, Les Editions de Physique, Paris 1988.
- [10] G. Dumitras, H. Riechert, H. Porteanu, F. Koch, *Phys. Rev. B* **66**, 205324 (2002).
- [11] G. Dumitras, H. Riechert, *J. Appl. Phys.* **94**, 3955 (2003).