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Investigation of the optical properties of InAs/InGaAs/GaAs quantum dot in quantum well multilayer structures for infrared photodetectors

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Abstract. A detailed study of InAs/InGaAs quantum dots in quantum well (DWELL) structures grown on GaAs substrates for infrared photodetectors was performed using surface photovoltage (SPV) spectroscopy. Three types of samples were investigated: as-grown, and annealed with dielectric coating SiO₂ or SiN. The annealing resulted in intermixing of the material components. The amplitude and phase SPV spectra were measured at room temperature under various experimental conditions. The comparison of the SPV with the photoluminescence (PL) spectra allows one to conclude that the spectral features are due to optical transitions in the DWELL structure. The blueshift observed of these features in the intermixed samples implies that the energy levels responsible for the transitions change correspondingly due to the intermixing process. The interface band-bending in the samples and the mechanisms of the carrier dynamics were determined by a comparative analysis of the SPV amplitude and phase spectra, using our vector model for representation of the SPV signal.

1. Introduction

The infrared photodetectors (IRPD) based on quantum dots in quantum well (DWELL) structures have several advantages compared to other architectures, for example, higher operating temperature [1, 2], multicolour detection [3] and better optical quality of the QDs due to strain relaxation [4]. They also allow tuning of the detection wavelength by changing the parameters of the QW (composition, thickness), thus changing the position of the excited state, without modifying the bound state in the QD. An alternative post-growth approach is interdiffusion of the material components, by performing a rapid thermal annealing [5, 6].

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The SPV spectroscopy is an advanced semiconductor characterization technique, successfully applied in the study of complex nanostructures in recent years [7, 8]. It is contactless, nondestructive, and provides information for the optical properties of the samples even at room temperature. Compared to the commonly used PL, the SPV spectroscopy gives information for the electronic transitions between ground and excited states. In this work we used the SPV and PL spectroscopy to investigate the optical properties of multi-layer self-assembled InAs/InGaAs/GaAs DWELL structures for IRPD, annealed with SiO₂ and SiN dielectric coatings.

2. Experimental

The samples are grown by MBE technique on semi-insulating GaAs substrate and start with an n⁺ GaAs (2×10¹⁸ cm⁻³) contact layer [figure 1(a)]. After a GaAs buffer layer (49 nm), a Si delta doping plane is introduced. The active region consists of 5 periods, each containing an InAs quantum dot (QD) layers (0.7 nm) embedded in an In_{0.15}Ga_{0.85}As quantum well (QW) (1 nm – bottom, 7 nm – top) and a GaAs (1 nm) barrier layers. The top two layers are a GaAs (50 nm) and an n⁺ GaAs (2×10¹⁸ cm⁻³, 400 nm) contact. During the growth process, a slight n-type residual doping is introduced. The QD density is approximately 6×10¹⁰ cm⁻². The samples coated by SiO₂ or SiN are processed by rapid thermal annealing at 800°C for 2 minutes under N₂ ambient for material intermixing.

The SPV measurements were performed at room temperature using the metal-insulator-semiconductor operation mode of the SPV technique [9]. A 250 W halogen lamp along with a SPEX grating monochromator (f = 0.25 m, 600 gr/mm) and an optical chopper (353 Hz) were used to illuminate the sample. The probe signal with respect to the ground was fed to a high-impedance unity gain buffer and then measured by an SR830 lock-in amplifier. The photon flux was kept constant (≈1.5×10¹⁴ cm⁻²s⁻¹) within ± 0.5 %

for all the wavelengths, by positioning a neutral density filter with variable optical density. The reference signal from the optical chopper defined the zero value of the SPV phase [10]. More details about the SPV experimental set-up and measurement procedure can be found in [11]. The PL measurements were performed at 77 K by a 532-nm diode-pumped laser as the excitation source, and an InGaAs detector was used for signal detection.

3. Results and discussion

Figure 2 presents typical SPV amplitude and phase spectra of the three samples in the range 0.95 – 1.35 eV. For comparison purposes, the corresponding PL spectra are also shown. They are shifted to the lower energies by 55 meV to account for the temperature dependence of the InAs bandgap between 77 K and 300 K.

The SPV amplitude spectrum of the as-grown sample reveals a broad bump in the range 1.0 - 1.25 eV. In the same range, a broad PL peak is observed centered at 1.086 eV with a shoulder at ~ 1.17 eV [figure 2(a)]. These spectral structures are ascribed to optical transitions in the QDs. Their broad shape indicates a relatively large inhomogeneity in the QD sizes.

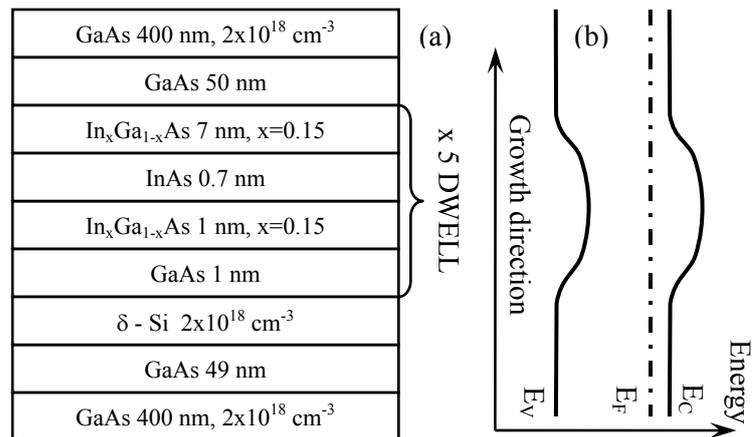


Figure 1. a) Layer sequence in the samples; b) Band diagram of the DWELL structure.

The alignment of the Fermi levels in the layers with different doping level implies that the energy bands in the nominally undoped DWELL structure and the 50 nm thick GaAs layers are bent upward with respect to the surrounding highly-doped 400 nm thick GaAs layers, as represented schematically in figure 1(b). The SPV signal from the QDs is due to photocarriers, which thermally escape from the InAs potential wells of the DWELL structure into the surrounding 50 nm thick GaAs layers, where they are separated by the built-in electric field of the space charge regions (SCR). It is important to note that the SCRs at the top and the bottom interfaces of the DWELL structure have directions opposite to the built-in electric field [figure 1(b)]. Therefore, their contributions to the SPV signal have (nearly) opposite phases [10] and are, consequently, subtracted. The SPV phase for this sample is in the IInd quadrant [see figure 2(a)]. This indicates that for some reasons the contribution of the top DWELL interface, where the electrons (holes) move towards the surface (the bulk), dominates. A simple reason for this could be the exponential decrease of the photon flux in depth of the sample.

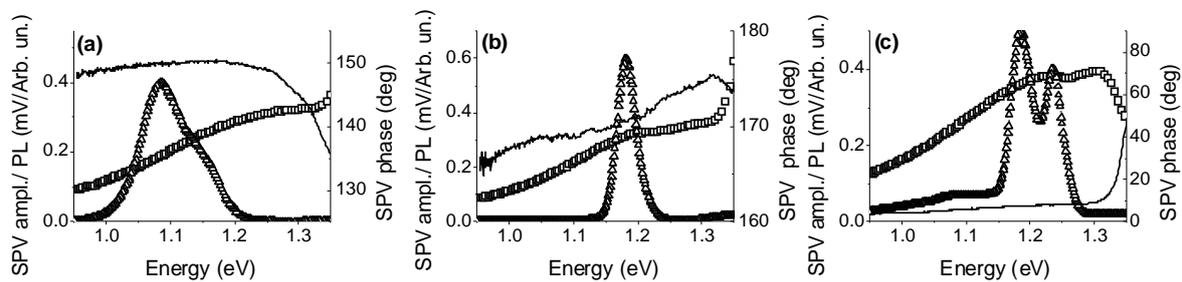


Figure 2. SPV amplitude (open squares) and phase (solid line) spectra of the a) As-grown, b) SiN and c) SiO₂ samples. The PL spectra (triangles), redshifted by 55 meV, are shown for comparison.

In the SPV amplitude spectrum of the SiN annealed sample [figure 2(b)], the bump mentioned above is also present, but it is seen as a well-resolved step at 1.20 eV. The corresponding PL peak is sharp and positioned at 1.182 eV in agreement with the SPV step. Therefore, the annealing has improved the QD size homogeneity and resulted in a blueshift of the optical transition energy. The latter is due to the blueshift of the QD electron and hole levels as a result of the material intermixing. To assess the magnitude of the blueshift it is easier to employ the PL results - from the PL peak positions one obtains 96 meV.

A smaller step is observed at ~1.27 eV in the SPV spectrum [see figure 2(b)]. This energy is slightly above the band-gap of bulk In_{0.15}Ga_{0.85}As (1.21 eV) [12] and, therefore, the step is ascribed to optical transitions in the In_{0.15}Ga_{0.85}As QW of the DWELL structure. A similar, although much weaker, step can be seen at ~1.26 eV in the SPV spectrum of the as-grown sample [figure 2(a)] upon a careful look after magnification. These results show that the transition energy of the QW is less influenced by the intermixing, which is explained by its lower surface-to-volume ratio. It is to be noted that the PL spectra do not reveal any particular structures in this energy range. Thus, the SPV spectra complement the information obtained by PL, where the lowest energy transition is predominantly observed. The SPV phase behavior [figure 2(b)] of the SiN annealed sample is similar to that of the as-grown sample [figure 2(a)] and can be explained in a similar way.

In the SPV amplitude spectrum of the SiO₂ annealed sample [figure 2(c)], the QD related step is clearly resolved at 1.22 eV. As compared to the SiN annealed sample, it is at a higher energy and is slightly broader. This may be understood with the help of the PL spectrum, which shows a sharp doublet of peaks situated at 1.184 and 1.234 eV implying two types of optical transitions, which are not resolved in the SPV spectrum. These observations could be explained assuming a non-uniform intermixing in the structure, e.g. two different planes of QDs blueshifted by different degrees. However, the sharp PL peaks indicate an improvement of the QD homogeneity inside each QD plane similar to that in the SiN annealed sample.

The SPV phase spectrum of this sample is different from those of the other two samples. In the QD spectral range, the phase remains in the Ist quadrant near 0 degrees. According to the vector model [11], such SPV vector results from the addition of two SPV vectors – one in IVth quadrant corresponding to the contribution of the bottom interface of the DWELL structure and one in IInd quadrant corresponding to its top interface. For some reasons, the contribution of the bottom DWELL interface is more pronounced, which pushes the resulting SPV vector closer to 0 degrees.

In the range 1.26-1.30 eV, the SPV amplitude increases, while the phase remains nearly constant. This amplitude step corresponds to the QW transitions in the DWELL structure. However this step is not completed, because above 1.30 eV the phase suddenly changes counter-clockwise towards the IInd quadrant, while the amplitude decreases sharply. Such behavior could be explained by the inclusion and growth of a new SPV generation process with a phase in IInd quadrant. Its SPV vector makes an obtuse angle with the already present vector and, as a result, their addition rotates the overall vector counter-clockwise, while decreasing its magnitude. In view of its phase, the new process should be related to free carrier generation at the top interface of the DWELL structure, but its exact origin is still unknown.

Further, an external voltage was applied to the sample surface in order to change the band bending at dark. Preliminary SPV spectral measurements have confirmed our expectations that with applying a voltage with the correct polarity we can change the direction of the slope of the potential along the structure and thus alter the relative contributions of the top and bottom interfaces to the SPV signal.

Conclusions

This is the first SPV observation of QD optical transitions in InAs/InGaAs/GaAs DWELL structures for IRPD. It is found that the carrier dynamics is governed by the different energy band-bending on the opposite interfaces of the DWELL structure. The RTA has two major effects: a blue shift of the optical transitions and improved size homogeneity of the QDs.

This investigation has a practical aspect since it provides information for the design optimization, growth parameters and post-growth treatment of the structures which is useful for high quality IRPD production. It also has fundamental research aspects, since it gives information for the physical properties of nanosized multilayer structures.

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References

- [1] Lim H, Tsao S, Zhang W and Razeghi M 2007 *Appl. Phys. Lett* **90** 131112
- [2] Barve A V, Montaya J, Sharma Y, Rotter T, Shao J, Jang W-Y, Meesala S, Lee S J and Krishna S 2011 *Infrared Phys. Technol.* **54** 215
- [3] Barve A V and Krishna S 2011 *Semiconductors and Semimetals (Advances in Infrared Photodetectors)* eds S Gunapala, D Rhiger and C Jagadish (San Diego: Elsevier) **84** 153
- [4] Ye Z, Campbell J C, Chen Z, Kim E-T and Madhukar A 2002 *J. Appl. Phys.* **92** 7462
- [5] Krishna S, Raghavan S, Gray A L, Stintz A and Malloy K J 2002 *Appl. Phys. Lett.* **80** 3898
- [6] Gargallo-Caballero R, Miguel-Sanchez J, Guzman A, Hierro A and Munoz E 2008 *J. Phys. D* **41** 065413
- [7] Chan C H, Chen H S, Kao C W, Hsu H P, Huang Y S and Wang J S 2006 *J. Appl. Phys.* **100** 064301
- [8] Ivanov T, Donchev V, Germanova K, Gomes P F, Iikawa F, Brasil M J S P and Cotta M A 2011 *J. Appl. Phys.* **110**
- [9] Kronik L and Shapira Y 1999 *Surf. Sci. Rep.* **37** 1
- [10] Donchev V, Kirilov K, Ivanov T and Germanova K 2006 *Mat. Sci. & Eng. B* **129** 186
- [11] Ivanov T, Donchev V, Germanova K and Kirilov K 2009 *J. Phys.D: App.Phys.* **42** 135302
- [12] <http://www.ioffe.rssi.ru/SVA/>