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Effects of dissipative electron tunneling manifested in the photocurrent of a GaAs *p-i-n* photodiode with a double InAs quantum dot layer

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Abstract. We report on the results of experimental studies of the photocurrent (PC) of photodiodes based on GaAs *p-i-n* structures with InAs/GaAs(001) double asymmetric quantum dot (DAQD) arrays obtained by self-assembling in the process of low-pressure metal-organic vapor phase epitaxy (LP-MOVPE). Three peaks were observed in the dependence of the PC on the reverse bias, measured under photoexcitation with a photon energy equal to the energy of the interband ground state transition in larger InAs QDs. These peaks were attributed to photoexcitation of electrons from the ground hole states in larger QDs into the ground electron states followed by resonant dissipative (with absorption or emission of optical phonons) and conservative tunneling into the GaAs conduction band via the ground electron states in smaller QDs. The PC dependence on the bias voltage agrees qualitatively with the theoretical field dependence of the probability of 1D dissipative tunneling between the QDs.

1. Introduction

An experimental observation of the theoretically predicted macroscopic effects of dissipative tunneling is one of the major tasks set by Prof. Anthony J. Leggett, 2003 Nobel Prize winner [1-5]. In the last decade, we have been trying to make our modest contribution to solving this problem. The results achieved to date are presented in Table 1. In this work, we experimentally investigated the dependence of photoconductivity (PC) on the reverse bias for a GaAs-based *p-i-n* photodiode with a double-layered asymmetric array of self-assembled InAs quantum dots (DAQDs) upon resonant photoexcitation of the interband optical transitions between the ground electron and hole states in larger QDs.



Table 1. Experimental observations of the dissipative tunnelling effects

1D		2D	
Weak dissipation	Strong dissipation	Weak dissipation	Strong dissipation
A single peak at one of the polarities of tunnel I - V curves for Au(Zr) QDs [5]	Non-equidistant peaks in tunnel I - V curves of InAs/GaAs(001) QDs [5].	2D bifurcations on tunnel I - V curves of Au QD arrays [5]	Expected 2D bifurcations in the field dependence of PL intensity in InAs/GaAs(001) DAQDs

The experimental results were interpreted on the basis of 1D dissipative tunneling taking into account two local optical phonon modes of the GaAs matrix (treated as a heat bath) [4].

2. Experiment

The GaAs-based p - i - n diode structure with a built-in InAs DAQD array was grown on an n^+ -GaAs(001) substrate (MeGa SM[®] company), misoriented by 2° in the (011) direction, by the method of metal organic vapor phase epitaxy (MOVPE) at a reduced pressure (100 mBar) from trimethylgallium, trimethylindium, and arsine using an Aixtron[®] AIX 200RF growth setup. A schematic representation of the p - i - n structure is shown in figure 1., A 300-nm-thick n^+ -Ga buffer layer doped with Si from monosilane has been grown on the surface of an n^+ -GaAs(001) substrate. Then, an approximately 350-nm-thick layer of intentionally undoped i -GaAs (with the background electron concentration $n_0 \sim 5 \cdot 10^{15} \text{ cm}^{-3}$) has been grown.

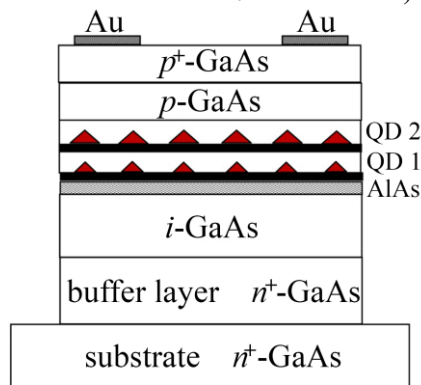


Figure 1. Schematic representation of a mesa photodiode based on a GaAs p - i - n structure with a double-layered array of vertically coupled InAs DAQDs embedded in an i layer.

A double-layered array of InAs DAQDs was formed on the surface of an i -GaAs layer by self-assembling according to the Stranski-Krastanov mechanism [6] at the growth temperature $T_g \approx 490^\circ\text{C}$. First, in order to stimulate self-assembling of InAs QDs, an AlAs sublayer with a thickness of ≈ 0.8 nm was deposited on the surface of the i -GaAs layer. Then, an array of smaller QDs with the height $h \approx 4$ nm and the base lateral size $D = 12 - 14$ nm was formed. The InAs QDs were capped with an i -GaAs spacer layer of 8 nm in thickness, on top of which a second InAs QD layer with $D = 16 - 18$ nm and $h \approx 6$ nm has been formed at growth temperature $T_g \approx 505^\circ\text{C}$. The second QD layer was capped by an approximately 7-nm-thick i -GaAs layer, and then by a p -GaAs layer of about 190 nm in thickness. Finally, a p^+ -GaAs subcontact layer of about 60 nm in thickness was deposited. The calculated room-temperature band diagram the InAs/GaAs(001) DAQD built into the GaAs p - i - n diode is shown in figure 2.

Mesa photodiodes with cylindrical mesas 350 μm in diameter with windows in the top Ohmic contact were fabricated using standard optical lithography with wet chemical etching. The PC spectra of the photodiodes were measured with an Acton[®] Spectra Pro[™] 500i grating monochromator by the standard lock-on technique using a Stanford Research[®] SR-810 digital lock-on detector.

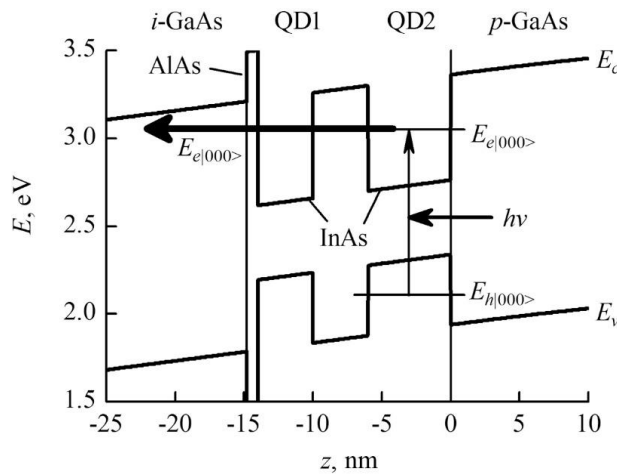


Figure 2. Calculated room-temperature band diagram of the InAs/GaAs(001) DAQD built into a GaAs p - i - n diode. The bias voltage was $V_b = 1.1$ V. The arrows show the interband optical transitions between the ground quantum confined states of holes and electrons (the corresponding energy levels are denoted as $E_{h|000>}$ and $E_{e|000>}$) in the larger QD (QD2) under photoexcitation at the wavelength $\lambda = 1.3$ μm followed by resonant electron tunnelling into the GaAs conduction band via the ground electron state in the smaller QD (QD1).

3. Results and Discussion

Figure 3 shows the room-temperature PC spectrum of a mesa photodiode with a built-in InAs/GaAs(001) DAQD array. The spectrum exhibited a threshold at the photoexcitation photon energy $h\nu \approx 1.41$ eV, which is approximately equal to the value of E_{GaAs} at 300K, associated with the edge of intrinsic photosensitivity of GaAs. In addition, the PC spectrum exhibited three peaks in the spectral range $0.9 \text{ eV} < h\nu < 1.4 \text{ eV}$ associated with interband optical transitions in InAs DAQDs. The peaks with $h\nu_m \approx 1.18$ eV and ≈ 0.95 eV were associated with interband optical transitions between the ground quantum confined hole and electron states in smaller and larger InAs QDs of the 1st and 2nd layers (QD1 and QD2), respectively. The peaks with $h\nu_m \approx 1.05$ and 1.3 eV can be associated with interband optical transitions from the ground quantum confined hole states into some excited electron states in InAs QDs of the 1st and 2nd layers, respectively. The PC band with the edge at $h\nu \approx 1.35$ eV was associated with interband optical transitions between the ground two-dimensional hole and electron quantum confined states in the InAs wetting layer (WL).

Figure 4 shows the dependence of the room-temperature PC signal magnitude of the photodiode on the reverse bias voltage V_b , measured under photoexcitation at the wavelength $\lambda = 1.3$ μm corresponding to the interband optical transition between the ground quantum confined states of holes and electrons in larger QDs (QD2, see figure 2). This dependence has three peaks, the origin of which can be explained as follows.

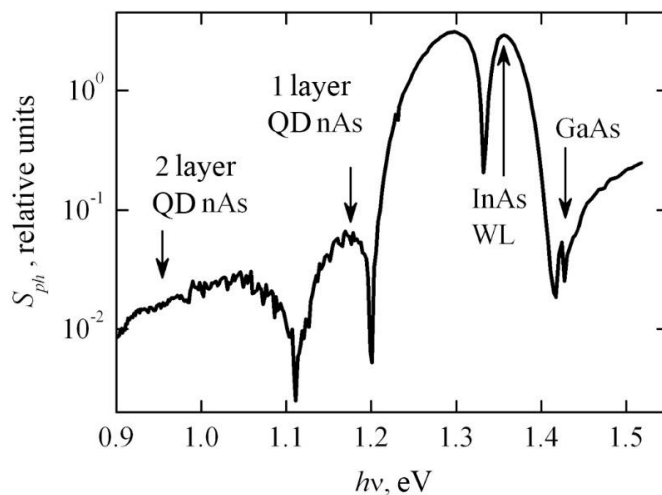


Figure 3. Room-temperature PC spectrum of a mesa photodiode based on a p - i - n structure with an InAs/GaAs(001) DAQD array built into the i -layer.

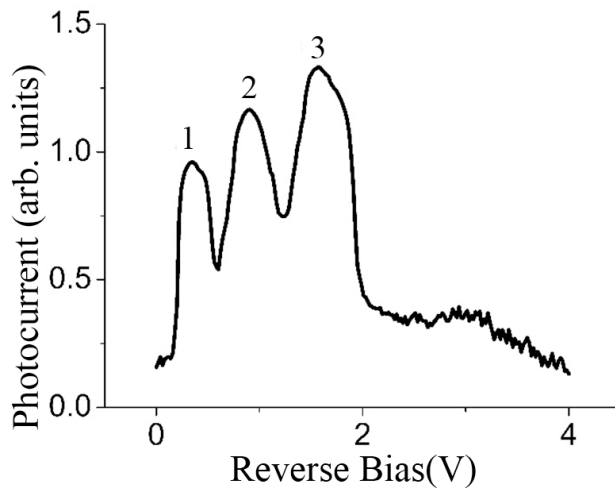


Figure 4. Dependence of the room-temperature PC of the photodiode based on a $p-i-n$ structure with an InAs/GaAs(001) DAQD array built into the i -layer on the reverse bias voltage. The photoexcitation wavelength $\lambda = 1.3 \mu\text{m}$. 1, 3 correspond to the tunneling interband optical transitions with absorption and emission of optical phonons, respectively; 2 corresponds to no-phonon interband optical tunneling transition.

The mechanism of photoelectric effects in heterostructures with QDs under interband photoexcitation of QDs includes, as a necessary and essential element, the emission of photoexcited charge carriers from QDs into the surrounding matrix [7]. In this regard, the maximum 2 of PC in figure 4 can be associated with the excitation of electrons from the ground quantum confined hole states into the ground electron states in larger QDs (QD2) followed by a resonant tunneling transition of photoexcited electrons into the GaAs matrix through the ground electron states in smaller QDs (QD1), see figure 2. Such a process is most probable when the energies of the ground quantum confined electron states in QD1 and QD2 are the same (this particular case is shown in figure 2). This condition is satisfied at a certain value of V_b ($V_b = 1.1 \text{ V}$ in the case shown in figure 2). Note that the peak 2 in figure 4 was observed at $V_b \approx 1.1 \text{ V}$, as expected.

Peaks 1 and 3 in figure 4 can be associated with resonant tunneling of electrons from QD2 to QD1 with absorption and emission of optical phonons, respectively. Note that peaks 1 and 3 in figure 4 are split, which can be ascribed to the tunnel transitions assisted by LO and TO phonons (the energies of TO and LO phonons in GaAs are 38 and 34 meV, respectively [8]). The splitting of the peaks attributed to the phonon-assisted tunnel transitions can be considered as an indirect confirmation of the above interpretation of the phenomena observed in the present work.

Figure 5 shows a qualitative comparison of the experimental dependence of the PC signal magnitude in the investigated photodiodes on the bias voltage, shown in figure 4, with the theoretical field dependence for the probability of 1D dissipative tunneling of a quantum molecule in a dielectric matrix, calculated taking into account two local phonon modes [4, 9, 10]. The oscillations of the theoretical curves are due to the energy exchange of a tunneling electron with two phonons [4]. The qualitative agreement was achieved between the theoretical and experimental curves.

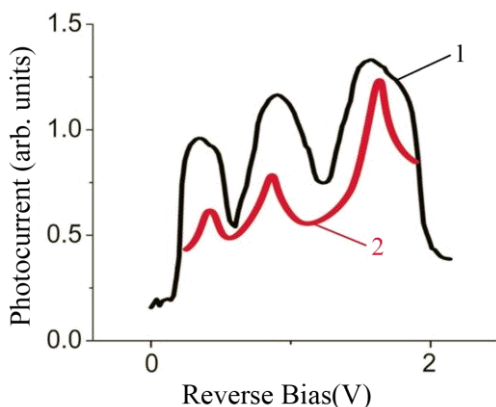


Figure 5. Comparison of the experimental dependence of the PC signal on the bias voltage (1) for the $p-i-n$ photodiode with an embedded InAs/GaAs(001) DAQD array with a theoretical field dependence for the probability of 1D dissipative tunneling (2) [4].

4. Conclusion

The $p-i-n$ structures based on GaAs with arrays of vertically coupled InAs/GaAs(001) DAQDs embedded into the i -GaAs layer were grown by LP-MOVPE. The mesa photodiodes were formed from these structures to study the tunnel interband optical transitions in the coupled InAs/GaAs(001) DAQD by measuring the dependences of the PC of the photodiodes on the bias voltage. The room-temperature PC spectra exhibit the features associated with interband optical transitions between ground and excited quantum confined states in InAs QDs. The energies of the interband optical transitions between the quantum confined electron and hole states in QDs were determined from the PC spectra. Three peaks have been observed in the dependence of the PC signal on the reverse bias under resonant photoexcitation of QDs at the wavelength corresponding to the energy of the optical transition between the ground quantum confined electron and hole states in larger QDs. These peaks were associated with phonon-assisted (with absorption and emission of optical phonons) and no-phonon tunnel optical transitions from the hole ground states into the electron one in larger QDs followed by resonant tunneling of the photoexcited electrons into the GaAs conduction band via the ground electron states in smaller QDs. The qualitative agreement has been found between the experimental dependence of the PC on the bias voltage for the investigated photodiode and the theoretical field dependence for the probability of 1D dissipative tunneling of a quantum molecule in a dielectric matrix, calculated taking into account the effect of two local phonon modes.

Acknowledgements

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