Experimental and theoretical investigation of the spectral Stark shift in quantum dots-in-a-well infrared photodetectors

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***Abstract*— We report on the bias-dependent spectral shift of the photoresponse in InAs/$In_xGa_{1-x}As$ quantum-dots-in-a-well structures. Experimental results show that the wavelength response of the transition from the quantum dot ground state to quantum well states can be Stark-shifted by ~15% by changing the applied bias between -1V and +1V. A theoretical model based on 8-band k•p method fits our experimental data well using realistic dot parameters. We also demonstrate an increase in the operating wavelength and a reduced bias-dependent spectral shift for samples containing dots formed by depositing less InAs during growth.**

***Index Terms*— dots-in-a-well, k•p theory, quantum dot infrared photodetectors, Stark shift**

I. Introduction

Recently, intraband quantum dot infrared photodetectors (QDIPs) have attracted considerable attention due to the potentially beneficial characteristics which arise from the three-dimensional confinement provided by the quantum dots (QDs). These include the intrinsic capability of normal incidence detection, and longer excited state carrier lifetimes [1], [2]. The development of QDIPs with a detection wavelength which can be Stark-shifted with an external bias would offer further benefits such as the ability to tune the peak wavelength of the photoresponse within one infrared (IR) atmospheric window or between two IR atmospheric windows, as previously demonstrated for QWIP devices [3], [4].

Mid-infrared intraband absorption transitions involving higher energy states (which contribute to the photoresponse) are strongest for radiation polarized in the growth direction (z) as a consequence of the much larger dimensions in the lateral direction than in the growth direction of self-assembled QDs. Transitions take place between the ground state and excited states which arise due to confinement predominantly in the growth direction. A significant Stark effect for these transitions is possible if there is a large z-component of the dipole moment, i.e. if there is a difference of the z-coordinate of the centroids of the two states. As QD heights are small (a few nanometers), this difference becomes small as well. In order to increase the difference between the centroids of the two states, one can displace the excited state by embedding the dot in a well. In order for this effect to be efficient the excited state should be above the quantum well confinement potential. This makes dots-in-a-well (DWELL) structures more suitable for observing the Stark shift than conventional quantum dot structures.

II. Results

In the present study, two colour spectral behaviour has been observed, exhibiting two main photocurrent peaks at energies ~130meV (~9µm) and ~230meV (~5µm) corresponding to transitions from the QD ground state to states in the QW (EQW) and GaAs continuum (Econt), respectively. Experimental results show that the wavelength response of the EQW transition can be Stark-shifted by ~15% by changing the applied bias between -1V and +1V. The theoretical model used to calculate the electronic structure in the conduction band and consequently the intraband absorption spectrum is based on the 8 band k•p method, with the effects of strain and electric field taken into account. The calculation was performed assuming dots of truncated shape with base diameter *D*, height if the dot were not truncated *H*, actual height *h*, and indium content in the dot *x*. In our simulations, these parameters were varied in the range where the calculated absorption spectrum exhibits a maximum in the same spectral region as the experimental spectrum. The best fit for the experimentally observed dependence of the transition energy on bias was obtained when *h*=4nm, x=0.7, *D*=17nm, as shown in Fig. 2 (dashed line).
We also observe an increase in the operating wavelength and a reduced bias-dependent spectral shift of ~10% for samples containing dots formed by depositing less InAs during growth, resulting from the electron wavefunction becoming more localized towards the apex of the dot, thus reducing the separation between the QD and QW wavefunction centroids.

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Using the same theoretical approach we propose as an explanation for this effect, an increased In content in the dot for more InAs deposited during growth, leading to an increased transition energy and either a change in the indium compositional profile or a decrease in dot height leading to an increased Stark shift, and find a good fit between experimental and theoretical results.

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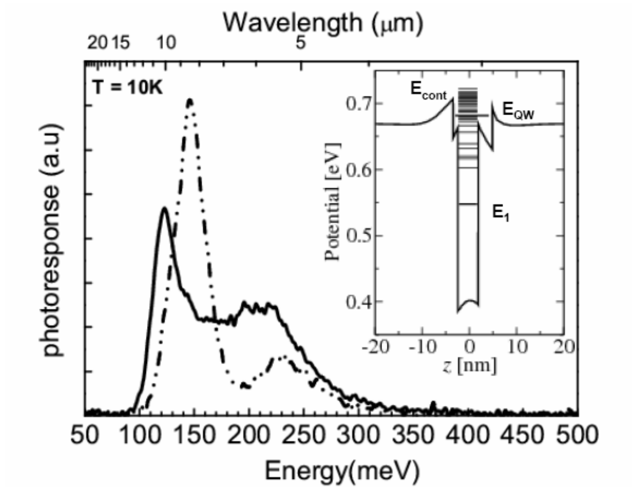

Fig. 1. P-polarized photoresponse for QDIP at 10K at +1V (solid line) and –1V (dashed line). Inset: Calculated potential profile of DWELL conduction band for zero bias for 2.9ML sample. All the states to which absorption from the ground state is allowed by selection rules are shown, with the one mostly contributing to the absorption marked by longer line.

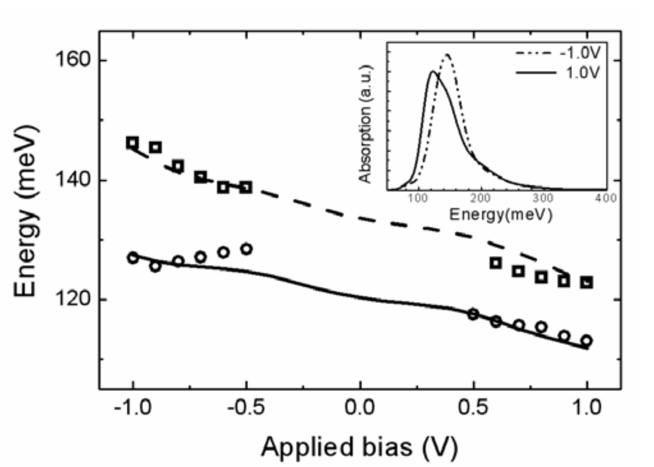

Fig. 3. Photocurrent transition energy dependence on applied bias: for 2.9ML sample experimental (open squares) and calculated (dashed line)., and for2.2ML sample experimental (open circles) and calculated (solid line). Inset: Calculated absorption spectra for 2.9ML at -1.0V and 1.0V.

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