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Stark shift of the spectral response in quantum dots-in-a-well infrared photodetectors

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Abstract

We present experimental and theoretical investigations of 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 -1 V and +1 V. A theoretical model based on the 8-band $\mathbf{k} \cdot \mathbf{p}$ 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.

1. 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 [1, 2] and longer excited state carrier lifetimes [3–6]. The latter property in turn leads to high photoresponse. It has also been predicted that QDIPs should have reduced dark currents relative to quantum well infrared photodetectors (QWIPs) which is also a result of the three-dimensional confinement provided by the QDs [7, 8]. Recent reports [8–11] demonstrate that QDIP performance is beginning to approach that of the more mature QWIP technology. Additionally, it has been shown that the spectral response of a QDIP can vary from single to potentially three colour behaviour [12–16]. 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 [17–19]. Stark shifts of ~10 meV for *interband* transitions in QDs have previously been reported [20]; however, relatively large fields of ~300 kV cm⁻¹ were necessary to observe these effects. For typical QDIP structures one order of magnitude smaller electric fields are typically used which makes it difficult to observe and utilize the *intraband* Stark shift.

Self-assembled QDs typically have much larger dimensions in the lateral direction than in the growth direction. As a consequence, it is well known that the mid-IR intraband absorption transitions involving higher energy states (which contribute to the photoresponse) are strongest for radiation polarized in the growth direction (z). Transitions take place between the ground state and the 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 nanometres), 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 QD structures.

In this work we show both experimentally and theoretically that it is possible to obtain a significant amount of Stark shift ($>10\%$ of the transition energy) in DWELL structures. We report the bias dependent spectral behaviour of two-colour QDIPs incorporating InAs/In_xGa_{1-x}As DWELL, with the main peak at the energy ~ 130 meV ($\lambda \sim 9 \mu\text{m}$) and a weaker one at ~ 230 meV ($\lambda \sim 5 \mu\text{m}$). We show that the voltage dependence of the photocurrent transition energy arises from the intraband Stark effect and find good agreement with our experimental data using an 8-band $k \cdot p$ model.

2. Experimental details

The DWELL sample was grown by molecular beam epitaxy (MBE) upon a semi-insulating GaAs substrate. GaAs barrier layers were grown at 580°C at a rate of 0.7 ML s^{-1} , whereas the In_{0.15}Ga_{0.85}As well and the InAs QDs were grown at 510°C at a rate of 0.1 ML s^{-1} . 2.9 monolayers of InAs were deposited during QD growth. The overall growth method is the same as previously used for the optimized growth of similar DWELL QD devices, resulting in high quality structures with very low defect densities [21, 22]. The device structure incorporates a bottom contact layer of 4000 \AA $n+$ Si doped GaAs, an undoped layer containing 5 periods of DWELL absorbing region, separated by 500 \AA of undoped GaAs and a final 4000 \AA $n+$ Si doped GaAs contact layer.

The DWELL absorbing region consists of InAs dots placed within an 80 \AA In_{0.15}Ga_{0.85}As quantum well, with 10 \AA of the well below the dots and 70 \AA above. The calculated conduction band profile of a typical DWELL structure under a zero applied electric field is shown in the inset of figure 1. The active region is Si δ -doped in the GaAs barrier layers, to a concentration of $6 \times 10^{10} \text{ cm}^{-2}$ corresponding to approximately 1 electron per dot. Therefore, only the QD ground state is occupied, thus the initial state of the intraband transitions is the QD electron ground state. Spectral measurements were carried out using a vacuum Bruker IFS-66 V s^{-1} Fourier-transform IR spectrometer with a broad-band globar mid-IR light source. Peak responsivity measurements were carried out using a calibrated black body source at 1005 K modulated using a chopper frequency of 230 Hz . A Ge filter was used to cut off any influence of near-IR radiation.

3. Results and discussion

The spectral photoresponse at 10 K for two different applied voltages is presented in figure 1. For -1 V we observe two photocurrent peaks centred at $\sim 145 \text{ meV}$ ($\lambda \sim 8.5 \mu\text{m}$) and $\sim 230 \text{ meV}$ ($\lambda \sim 5 \mu\text{m}$), which we attribute to electron transitions from the InAs QD ground state E_1 to quasi-bound states in the In_{0.15}Ga_{0.85}As QW, E_{QW} and GaAs continuum states, E_{cont} respectively, as illustrated in the inset of figure 1. This study is mainly concerned with the characteristics of the $E_1 \rightarrow E_{\text{QW}}$ transition. A larger photocurrent signal ($\sim 5\times$) was measured for p-polarized incident radiation, coupled

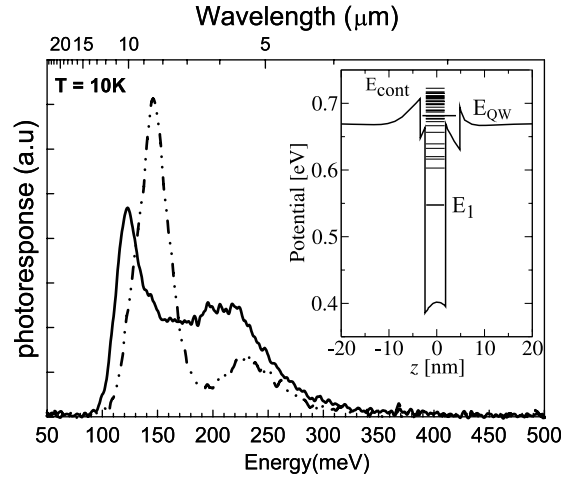


Figure 1. p-polarized photoresponse for QDIP at 10 K at $+1 \text{ V}$ (—) and -1 V (— · —). Inset: calculated potential profile of DWELL conduction band for zero bias for the 2.9 ML sample. All the states to which absorption from the ground state is allowed by selection rules are shown, with the one mostly contributing to the absorption marked by longer line.

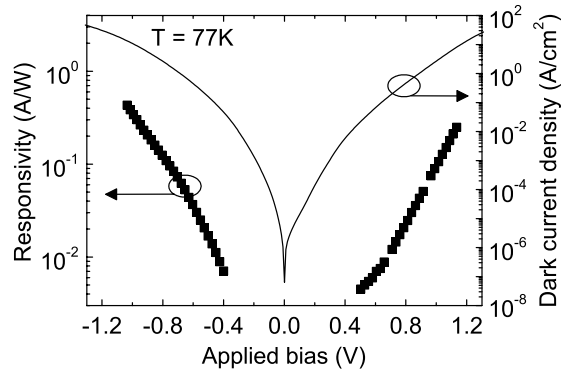


Figure 2. Peak responsivity (■) at p-polarized 45° incidence and dark current density (—) curves at 77 K for $N_{\text{ML}} = 2.9$. Responsivity shows how the peak intensity varies with bias.

into the sample via the substrate polished to 45° , relative to s-polarized radiation. This is expected as the $E_1 \rightarrow E_{\text{QW}}$ transition arises due to confinement in the growth direction. The magnitude of the $E_1 \rightarrow E_{\text{QW}}$ and $E_1 \rightarrow E_{\text{cont}}$ peaks increase with applied bias. However, the intensity of the $E_1 \rightarrow E_{\text{QW}}$ photoresponse increases more rapidly and becomes dominant at biases of $\pm 1 \text{ V}$. In addition, as shown in figure 1, the $E_1 \rightarrow E_{\text{QW}}$ peak is tuneable with applied bias. The photocurrent spectrum at $+1 \text{ V}$ (solid line) is red-shifted with respect to that at -1 V (dot-dashed line), thus indicating an asymmetric dependence with applied bias due to the off-centre position of the QD layer in the well as shown in the conduction band profile in the inset of figure 1.

We performed peak responsivity measurements using p-polarized incident radiation at 77 K . Figure 2 shows the bias dependence of the peak intensity of $E_1 \rightarrow E_{\text{QW}}$, along with the dark current density versus voltage characteristics. The responsivity was measured at the biases where the $E_1 \rightarrow E_{\text{QW}}$ was apparent, and the asymmetry in the intensity for negative and positive bias correlates with the spectral results.

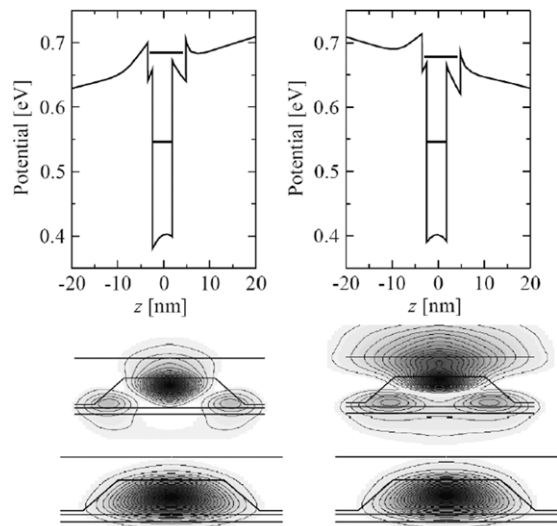


Figure 3. Calculated potential profile along the z -axis (top) and contour plots of wave function moduli of the ground state (bottom) and the state to which absorption is maximal (middle) in the case of dot dimensions that best fit the 2.9 ML sample for -0.6 V (left) and $+0.6$ V (right).

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 $k \cdot p$ method, with the effects of strain and electric field taken into account. The lineshape of the transitions was taken to be Gaussian with the standard deviation equal to 10% of the transition energy in accordance with the experimental value. The Hamiltonian eigenvalue problem was solved by embedding the dot in a large cylinder and using the orthonormal wave function expansion with the basis consisting of Bessel functions in the radial direction and plane waves in the growth direction. More details of the theoretical method have been previously published [23, 24].

The peaks originating from bound to bound transitions, present in the absorption spectrum, will appear in the photocurrent spectrum only if the carriers have a sufficiently high probability to escape from the bound excited state to the continuum and contribute to the photocurrent. However, it is important to note that when a peak appears in the photocurrent spectrum, it is expected that it appears at the same energy of incident photons as in the absorption spectrum. This fact has been confirmed by recent detailed simulations of photocurrent spectrum in QDIP structures [25]. In this study, the main interest is in the positions of the peaks in the photocurrent spectrum and their shift with bias. Since the computational effort for calculating the intraband absorption spectrum is much smaller than for the case of the photocurrent spectrum, and the peak positions in both spectra correspond very closely, theoretical modelling was restricted to the calculation of the intraband absorption spectrum.

In figure 3 we show the wavefunctions of the ground and the excited state to which the absorption is maximal when the bias is equal to -0.6 V and $+0.6$ V, as well as the on-axis potential profile with the energies of the states that mostly contribute to the absorption. The quasi-continuum density of states is represented by a discrete set of states which is a

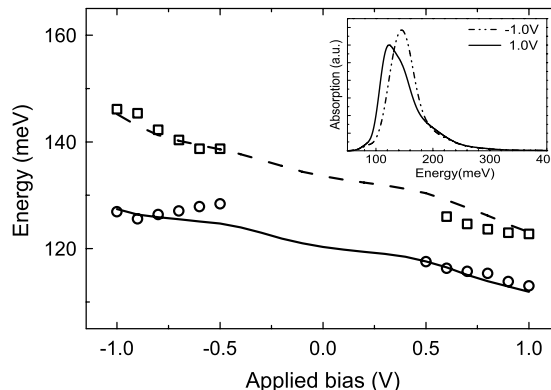


Figure 4. Photocurrent peak transition energy dependence on applied bias: for 2.9 ML sample experimental (\square) and calculated (absorption) (----), and for 2.2 ML sample experimental (\circ) and calculated (absorption) (—). Inset: calculated absorption spectra for 2.9 ML at -1.0 V and 1.0 V.

consequence of embedding the dot in a cylinder of finite size. It has been checked that the embedding cylinder is large enough so that the calculated absorption spectrum and the position of its maximum have converged. One can see from the wave functions shown in figure 3 that the ground state wavefunction is weakly influenced by the electric field, while the influence of the electric field on the wavefunction of higher energy quasi-bound states which mostly contribute to the absorption is much stronger. Negative bias shifts the wavefunction towards the region of low potential and decreases the distance between the centroids and the dipole moment of the transition.

The calculation was performed assuming dots of truncated shape with base diameter D , height h 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: h was varied in the interval 4–7 nm; x from 0.6 to 0.75, D in the range 15–22 nm and H was set to 10 nm. In figure 4, we plot the experimental (open squares) bias dependence of the $E_1 \rightarrow E_{QW}$ transition over the range of biases for which the photocurrent peak is observable. The absorption $E_1 \rightarrow E_{QW}$ does not contribute significantly to the photocurrent at zero and low (≤ 0.4 V) negative or positive biases because of low electron escape probability from the quantum well states. A shift of $\sim 15\%$ of the $E_1 \rightarrow E_{QW}$ transition energy is measured between $+1$ V and -1 V. The best fit for the dependence of transition energy on bias was obtained when $h = 4$ nm, $x = 0.7$, $D = 17$ nm, as shown in figure 4 (dashed line). Calculated absorption spectra showing the bias dependent shift between -1.0 V and 1.0 V can be seen in the inset of figure 4.

It is known that for the transition between two truly discrete states one obtains the following dependence of the transition energy on the electric field (including the terms up to second order of perturbation theory) $E = E_0 + pF + \beta F^2$, where E_0 is the energy at $F = 0$, the second term arises from the nonzero dipole moment p at $F = 0$, and the third term arises from polarization of the dots in the applied field (the quantum confined Stark effect). However, in our case the transition takes place between a truly discrete bound state

and a quasi-continuum density of states. The maximum of the absorption spectrum is then determined by complex changes in the density of states and does not follow a simple quadratic trend, as shown in figure 4. In our calculations the position of the absorption maximum is determined by the interplay of the bias dependences of the energies of several states, as well as by the relative contribution to the absorption spectrum of each of these states.

A further sample (S2) was grown using otherwise identical conditions except with 2.2 monolayers of InAs deposited during QD growth. We observed a similar photoresponse for this sample with the $E_1 \rightarrow E_{QW}$ transition occurring at a lower energy due to the shallower confinement potential. Of note is that a smaller bias dependent shift of the photoresponse ($\sim 11\%$) is also observed for this sample relative to the previous sample (S1) as shown in figure 4 (open circles). This indicates that S2 has a smaller separation between the centroids of the QD ground state and QW wavefunctions (i.e. is *more* symmetric). It is well known that the indium composition in QDs is non-uniform [26, 27], therefore one possible explanation of our results is that the indium composition at the base of S1 is larger than for S2. This leads to the electron wavefunction for S2 becoming more localized towards the apex of the QD, thus reducing the separation between the QD and QW wavefunction centroids. Detailed information about the QDs structure would be necessary to introduce a non-uniform indium profile in our simulation; however, we can still obtain satisfactory agreement with our experimental results using a significantly larger QD height ($h = 6$ nm). The dots are then placed in the middle part of the well and the asymmetry of the system is smaller. The best fit to the experimental results (figure 4, solid line) is obtained when $h = 6$ nm, $x = 0.66$, $D = 17$ nm. Therefore the most probable explanation for the observed differences in the photoresponse of the two samples is an increased In content in the dot for S1, leading to an increased transition energy and either a change in the indium compositional profile or a decrease of the dot height leading to an increased Stark shift. Additional structural investigations would be necessary to unambiguously identify the origin of the increased Stark shift, by using cross sectional scanning tunnelling microscopy (X-STM), or transmission electron microscopy (TEM). However, our results clearly show that the bias dependent spectral shift of the photoresponse is sensitive to QD growth parameters and may be controlled by varying the asymmetry of the DWELL system. The understanding of the bias dependence in DWELL detectors could provide the ability to maximize the Stark effect for applications where a considerable tunability over the IR spectrum is required.

4. Conclusions

In conclusion, we have reported the observation of the intraband Stark shift in DWELL structures and find good agreement with a theoretical model based on the 8-band $k \cdot p$ method. We observe a non-quadratic behaviour of the Stark shift since the transition takes place between a truly discrete dot bound state and a quasi-continuum density of states whereby complex changes in the density of states determine

the maximum of the absorption spectrum. An increase in the transition energy and the amount of Stark shift with increasing number of monolayers deposited during the QD growth was also observed.

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