Transient photoconductivity measurements of carrier lifetimes in a InAs/$In_{0.15}Ga_{0.85}As$ Dots-in-a-well detector.

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Abstract— **A pulsed mid-infrared photoconductivity study of electron recapture in dot-in-a-well infrared photodetectors yields bias-dependent electron-capture lifetimes in the range of 3–600ns and photoconductive gain factors of ~10^4–10^5 [1]. The dependence of the lifetimes on temperature and electric field indicates that these surprisingly long values are due to electron intervalley transfer. Under normal device operating conditions, photoexcited electrons transfer efficiently out of the central GaAs Γ minimum into the high energy *L* and *X* valleys, where they couple only weakly to the Γ-like confined states in the InAs dots.**

***Index Terms*— Semiconductor devices, Intersubband Transitions, Quantum Dots-in-a-Well, infrared photodetector**

I. INTRODUCTION

Infrared detection is vital to a range of applications, from biomedical imaging to night vision and communications technologies. There is a high demand for faster, more responsive and multi-spectral infrared detectors. Quantum Well Infrared Photodetectors (QWIPs) are an established commercial technology, and similar quantum dot devices have recently been developed. The dot devices are aimed at overcoming the lack of normal incidence detection in QWIPs and to provide multiple broadband detection spectra. A hybrid technology, a dot-in-a-well (DWELL) device, has also emerged. The addition of a well to the structure ensures specific energy levels can be reliably reproduced, by varying well width, through MBE growth techniques. These also deliver broadband detection, lower dark current and their long carrier lifetimes contribute to high photoconductive gains. Specific detectivities of D*=2.6 x 10^{10} $Hz^{1/2}W^{-1}$ at 77K[2] and high performance array detectors have been demonstrated[3].

We report direct measurements of carrier lifetimes in a DWELL infrared photodetector using a high speed, pulsed mid-infrared photoconductivity technique[1]. The detector is described in detail in Ref. [1], (Sample 1299). The sample wafer consists of 10 DWELL periods on a n+ GaAs substrate, capped with a GaAs contacting layer. A DWELL comprises a 90Å $In_{0.15}Ga_{0.85}As$ quantum wells, with 500Å GaAs barriers. InAs dots are epitaxially grown 10Å from the QW edge (Fig. 1(a)). A 300μm photodector, constructed from the wafer, was biased through 1k Ω and 50Ω resistors in series. The device was illuminated with a 100ps mid-IR pulsed laser, tunable between 4 μm-5 μm and 6.3μm-8.6μm[4]. These tuning ranges corresponded to the peaks in the responsivity curve (Fig.1(b)).

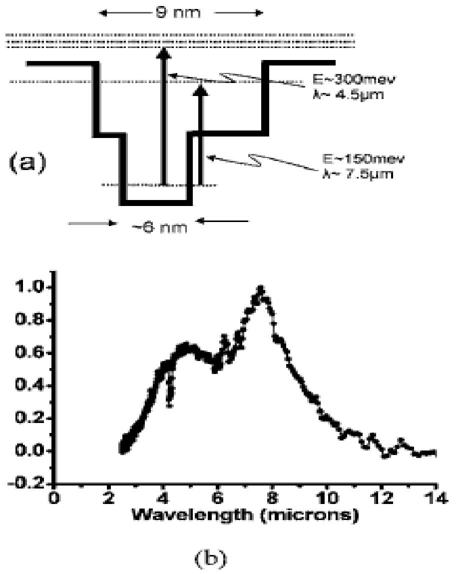

FIG. 1. (a) Schematic band structure for the dot-in-a-well (DWELL) detector[3]. The InAs dots are ~6 nm high and are deposited asymmetrically in a 9 nm wide $In_{0.15}Ga_{0.85}As$ quantum well, giving dot-to-continuum and dot-to-well transitions at ~4.5 and~7.5μm, respectively. (b) Normalised spectral response at 56 K and −1.1 V bias[3].

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The photocurrent pulses generated a decay transient with an initial spike corresponding to carrier heating and thermalisation processes. This was followed by a second, slower decay process, corresponding to the time taken for the excited electrons to be recaptured by the dots, τ_{cap}. Only this slower decay was sensitive to temperature, voltage, and wavelength.

II. RESULTS

The measuered τ_{cap} values range from 3 to ~600ns and show interesting trends. Temperature data for all bias and wavelengths peak at 40K, (Fig 2). The bias dependence also shows a general trend, peaking at -0.5V bias (Fig 3). Finally, exciting at shorter wavelength radiation (4-5μm) consistently results in longer lifetimes. These are typically 2-3 times longer than for long wavelength excitation.

The bias and temperature dependence is attributed to the fact that at fields above 4 x 10^5 V/m (a device bias of ~-0.8V) electrons in n –GaAs transfer to higher energy satellite valleys in the *L* and *X* points of the crystal band structure[5]. Tehse valleys occupy outlying parts of momentum space which are only weakly coupled (via ineffective high-q phonon scattering events) to the *Γ*-like confined states of the quantum dots. Following intervalley transfer the electrons have a reduced cross section for capture into the dots and this is seen in a dramatic increase in the carrier lifetime.

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The proportion of carriers transferring to the satellite valleys increases with the *Γ*-point electron mobility for a given field and explains why the temperature dependence of the lifetime closely follows the n-GaAs mobility curve (Fig. 2).

The intervalley picture however cannot account for the observed discrepancy in lifetimes between long and short wavelength excitation. It is expected that after the typically fast thermalisation, process (~1ps) the electron “forgets” the optical transition responsible for its excitation.

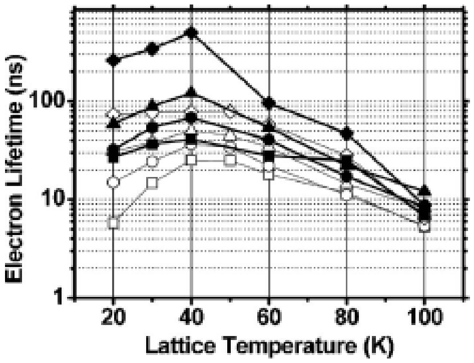

Fig. 2. Carrier lifetime dependence on electric field measured at 100 K (squares), 40K (diamonds), 30K (circles), and 20 K (triangles). Solid/open symbols denote device illumination at the higher/lower energy peaks in the device response at energies of ~270 meV ~170 meV, respectively[1]

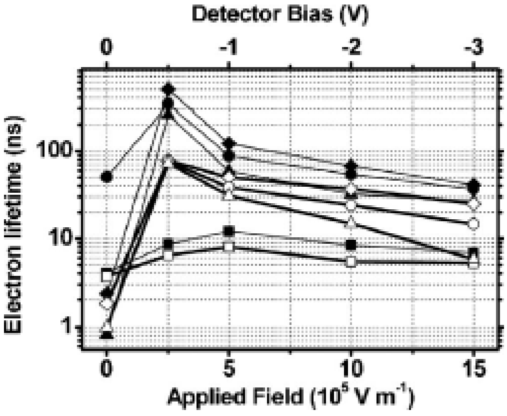

Fig. 3. Temperature variation of carrier lifetime at a device bias of −3 V (circles), −2 V (squares), −1 V (triangles), and −0.5 V (diamonds). The solid/*open* symbols denote device illumination at the higher/*lower* energy peaks in the device response at photon energies of ~270/~170 meV, respectively[1].

It is possible that the two peaks of the spectral response (Fig. 1(b)) correspond to a bimodal distribution of dots, with different electron occupations. Dots with, on average, 2 electrons would sit closer to 2 ionized donors. If the sub ensembles of dots sit within different electrostatic environments, which produce differing optical transitions, the same environment may produce a potential barrier to electron recapture.

III. CONCLUSION

In conclusion we have measured extremely long carrier lifetimes for a DWELL IR photodetector, which correlate with the transfer of photoexcited carriers to regions of the band structure where coupling to the dot states is very weak. Assuming a typical GaAs saturation drift velocity[6] of ~2 x 10^5 m/s gives a $\tau_{transit}$~6.5ps for the carrier transit time in this device. This corresponds to photoconductive gain factors of 10^4-10^5 in the temperature range between 20 and 100K.

REFERENCES

[1] Mary R. Matthews, Robert M. Steed, Mark Frogley, Ram S Attaluri, Sanjay Krishna, Christopher Phillips, Appl. Phys. Lett. 90, 10 (2007).

[2] P. Rotella, G. von Winckel, S. Raghavan, A. Stinz, Y. Jiang, and S. Krishna, J. Vac. Sci. Technol. B 22, 1512 (2004).

[3] S. Krishna, D. Forman, S. Annamalai, P. Dowd, P. Varangis, T.Tumolillo Jr., A. Grey, J. Zilko, K. Sun, M. Liu, J. Campbell and D. Carothers, Appl. Phys. Lett. 86, 193501 (2005).

[4] K. L. Vodopyanov and V. G. Voevodin, Opt. Commun. 117, 277 (1995).

[5] M. A. Littlejohn, J. R. Hauser, and T. H. Glisson, J. Appl. Phys. 48, 110 (1977).

[6] J. S. Blakemore, J. Appl. Phys. 53, R123 (1982)