

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

Mary R. Matthews, Robert J. Steed, Mark D. Frogley, and Chris C. Phillips^{a)}
Experimental Solid State Group, Blackett Laboratory, Imperial College London, London SW7 2AX, United Kingdom

Ram S. Attaluri and Sanjay Krishna
Center for High Technology Materials, ECE Department, University of New Mexico, 1313 Goddard Street SE, Albuquerque, New Mexico 87106

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A pulsed midinfrared photoconductivity study of electron recapture in dot-in-a-well infrared photodetectors yields bias-dependent electron-capture lifetimes in the range of 3–600 ns and photoconductive gain factors of $\sim 10^4$ – 10^5 . The dependence of the lifetimes on temperature and electric field argues for these surprisingly long values being 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. © 2007 American Institute of Physics. [DOI: 10.1063/1.2712810]

Quantum well infrared photodetectors¹ (QWIP's) are now an established commercial technology, and large area arrays are available for a wide range of applications including cancer detection² and night vision. More recently, quantum dot (QD)-based devices have been developed, driven by a desire for sensitivity to normally incident radiation (which is only possible with QWIP's after costly surface texturing), and to allow for multiple detection bands in the infrared (IR).

However, the statistical nature of the QD growth mechanism leads to a stochastic variation of the energy levels which, in turn, makes it difficult to produce quantum dot IR detectors targeted for specific wavelengths. Recently though "dots-in-a-well" (DWELL) devices³ have emerged [Fig. 1(a)], where the IR absorption energy is strongly determined by the width of the quantum well (QW), a parameter which can be controllably reproduced by molecular beam epitaxial (MBE) growth. For a given device wavelength the electrons in a DWELL are still more deeply bound than in a QWIP, which lowers the dark currents.⁴ The long carrier lifetimes⁵ in DWELLS lead to significant photocurrent gain, giving good responsivity, even with modest quantum efficiency. DWELL specific detectivities of $D^* = 2.6 \times 10^{10}$ cm Hz^{1/2} W⁻¹ at 77 K and high performance array detectors have both been demonstrated.⁶

As well as their impact on detector performance, the electron-capture dynamics in dot-based structures is important for future information processing and storage devices.⁷ Here we report direct measurements of carrier dynamics in QD-based detectors, using a high-speed mid-IR photoconductivity technique.

The device studied [Fig. 1(a)] is made from a MBE-grown wafer described in detail (as sample No. 1299) in Ref. 8. It consists of a 500 nm, $n \sim 2 \times 10^{18}$ cm⁻³, GaAs contacting layer on a $n+$ GaAs substrate. Onto this are grown ten periods of DWELL and a 200 nm, $n \sim 2 \times 10^{18}$ cm⁻³, GaAs top contacting layer. Each DWELL period comprises a 9 nm In_{0.15}Ga_{0.85}As QW, separated by a 50 nm GaAs barrier, with

the InAs dots epitaxially grown, in the Stranski-Krastanov mode, ~ 1 nm from one of the QW edges [Fig. 1(a)]. This asymmetry is reflected in asymmetric current-voltage characteristics (Fig. 2). Transmission electron microscopy revealed dots of ~ 6 nm high and ~ 14 nm across with areal densities of 10^{11} cm⁻² per well. Doping is such that each dot contains between one and two electrons.⁸

The wafer was patterned into photodetectors with 300 μ m diameter active areas on 410 mm \times 410 mm square mesas which were mounted in a high-speed package, and

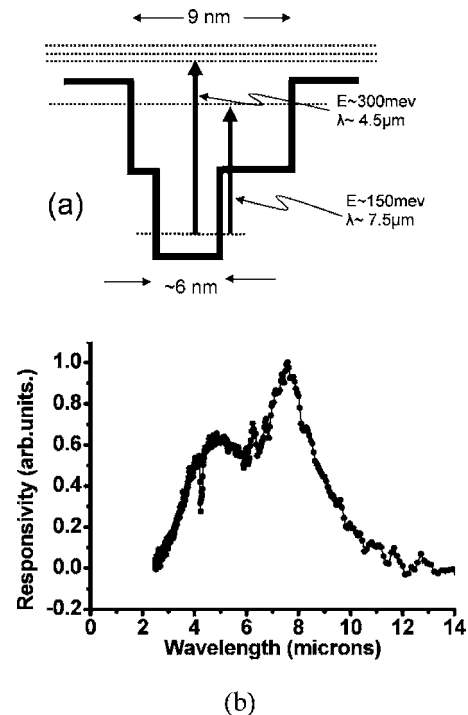


FIG. 1. (a) Schematic band structure for the dot-in-a-well (DWELL) detector. The InAs dots are ~ 6 nm high and are deposited asymmetrically in a 9 nm wide In_{0.15}Ga_{0.85}As quantum well, giving dot-to-continuum and dot-to-well transitions at $\lambda \sim 4.5$ and ~ 7.5 μ m, respectively. (b) Normalised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

^{a)}Electronic mail: chris.phillips@imperial.ac.uk

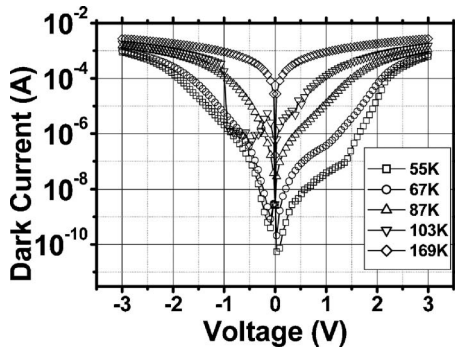


FIG. 2. Dark current-voltage curves for a 300 μm diameter DWELL detector on a 410 mm \times 410 mm square mesa at a range of temperatures.

biased through 1 k Ω and 50 Ω resistors in series. The transient photoconductive signal was taken across the 50 Ω resistor for impedance matching into a digital oscilloscope, and RC time constants were shorter than the ~ 1 ns oscilloscope time resolution.

The devices were illuminated with ~ 100 ps mid-IR pulses from a tuneable optical parametric generator.⁹ This consisted of an amplified $\lambda = 2.8$ μm wavelength pulse, from an erbium laser, which, via a parametric amplification process, simultaneously generated signal (4 $\mu\text{m} < \lambda < 5$ μm) and idler (6.3 $\mu\text{m} < \lambda < 8.6$ μm) pulses, each with ~ 0.2 μm linewidth, from an angle-tuned ZnGeP₂ crystal. These tuning ranges spanned the twin peaks in the responsivity curve, at $\lambda \sim 4.5$ μm and $\lambda \sim 7.2$ μm [Fig. 1(b)], which have previously been assigned to dot-to-continuum and dot-to-well transitions, respectively [Fig. 1(a)].

The signal and idler pulses are orthogonally polarized, so could be selected with a wire grid polarizer. After filtering of the erbium laser radiation, they were focused through a ZnSe cryostat window, onto the cold-finger mounted device, at a fluence of ~ 1 mJ cm⁻² and a repetition rate of ~ 3 Hz. The resulting photocurrent pulses had an initial spikelike transient (limited by our ~ 1 ns time resolution), corresponding to carrier heating and thermalization processes. This was followed by a much slower decay as the excited photocarriers are recaptured by the dots (Fig. 3). Only this slower decay was found to be sensitive to changes in, e.g., bias, temperature and excitation wavelength, and it fitted well to a single exponential function from which capture times τ_{cap} could be deduced.

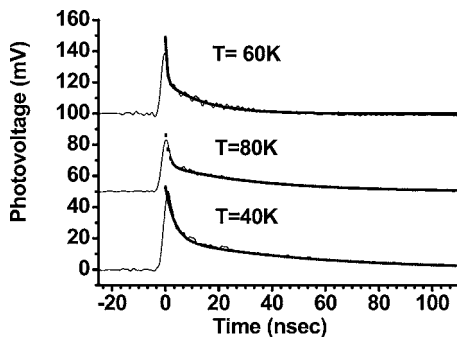


FIG. 3. Photoconductivity transients, measured with $\lambda = 7.3$ μm pulses, at a device bias of -4 V and at a range of temperatures. Traces offset for clarity. Heavy lines: theoretical fits yielding τ_{cap} lifetimes of 35, 14, and 53 ns at 60, 80, and 40 K, respectively.

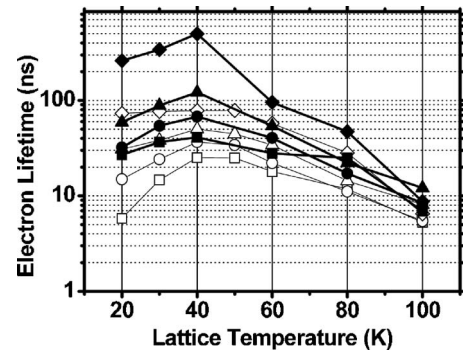


FIG. 4. Temperature variation of carrier lifetime at a device bias of -3 V (circles), -2 V (squares), -1 V (triangles), and -0.5 V (diamonds). The solid/open symbols denote device illumination at the higher/lower energy peaks in the device response at photon energies of $\sim 270/\sim 170$ meV, respectively.

The measured τ_{cap} values range from 3 to ~ 600 ns and show some curious trends. At all biases and excitation wavelengths, the τ_{cap} show a similar temperature dependence (Fig. 4), peaking noticeably at ~ 50 K. The bias dependence (Fig. 5) also shows a generic trend, peaking at ~ -0.5 V bias, largely irrespective of temperature and wavelength, and dropping monotonically as the bias is further increased toward ~ -3 V. Finally, exciting at the higher energy peak in the responsivity curve [Fig. 1(b)] consistently results in a longer lifetime (typically by a factor of 2 or 3) than when exciting at the lower energy responsivity peak (Fig. 5).

The first question is why these lifetimes are so long. Although “persistent photoconductivity” (PPC) effects, associated with the so-called DX centers, are known in this materials system, they occur only when the Fermi energy is high enough (~ 200 meV) above the GaAs band edge to populate the DX levels; PPC is seen only at low fields and temperatures, in either $\text{Al}_x\text{Ga}_{1-x}\text{As}$ alloys¹⁰ with $x > 0.22$ or in δ -doped GaAs samples,¹¹ and it cannot be the origin of our long transients. The bulk of the device is n -GaAs, with dots laterally separated by ~ 31 nm in the QW planes and 60 nm between QW’s in the stack. Taking standard bulk n -GaAs mobility data¹² suggests that, in these high-dot-density samples, electrons could diffuse far enough to find a dot in less than a picosecond, and intersubband capture/energy relaxation processes happen on a similar time scale.⁵

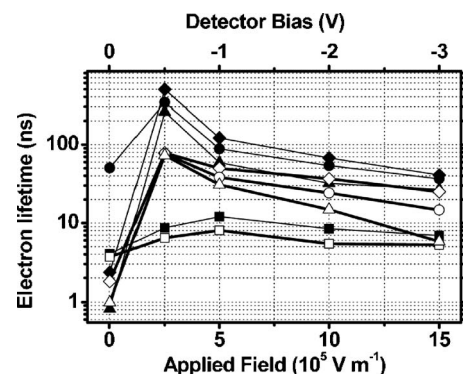


FIG. 5. Carrier lifetime dependence on electric field measured at 100 K (squares), 40 K (diamonds), 30 K (circles), and 20 K (triangles). Solid (open) symbols denote device illumination at the higher (lower) energy peaks in the device response at energies of ~ 270 meV (~ 170 meV), respectively.

However, this analysis ignores the well-known fact¹² that for fields above $\sim 4 \times 10^5 \text{ V m}^{-1}$ (which corresponds to a device bias of only 0.8 V) electrons in *n*-GaAs start to transfer to higher energy satellite valleys in first the *L* and then the *X* points of the crystal bandstructure.¹³ These valleys have high effective masses, and their densities of states and degeneracy factors are so high that, once the field exceeds this threshold, practically the whole electron population transfers into them. Once there they experience progressively increasing phonon-scattering rates and falling drift velocities as the field is further increased. From the point of view of understanding the lifetime data the critical point is that these valleys occupy outlying parts of momentum space which are only weakly coupled (via inefficient, high-*q* phonon-scattering events) to the Γ -like confined states in the QW's and QD's. After this intervalley transfer, an electron experiences a reduced cross section for capture into the dots and a dramatic increase in carrier lifetime.

At a given field the fraction of electrons transferring to the satellite valleys rises monotonically with the Γ -point electron mobility, as the carriers gain more energy from the field. This explains why the form of the τ_{cap} temperature dependences (Fig. 4) closely mirrors *n*-GaAs Hall mobility curves and peaks at similar temperatures.¹²

This intervalley-transfer effect can also explain the bias dependences of Fig. 5. Below $\sim 0.8 \text{ V}$ bias the electrons remain dominantly in the Γ minimum, where the large capture cross sections (for capture into the QD states of the same part of momentum space) combine with fast diffusion rates to give τ_{cap} values close to or below the experimental time resolution. Between ~ 0.8 and 3 V ($\sim 4 \times 10^5$ to $\sim 15 \times 10^5 \text{ V m}^{-1}$) Monte Carlo simulations¹⁴ indicate near-complete intervalley transfer, with an electron mean free path which *drops*, from ~ 30 to $\sim 10 \text{ nm}$, as the field increases. Comparing this with the mean interdot spacing of $\sim 50 \text{ nm}$, one can see how the increasing electron scattering rates at high biases will increase the chances of the electron being scattered into the dot states, causing the drop off in lifetimes evident in Fig. 5.

On its own the intervalley-transfer picture cannot account for the excitation wavelength differences observed. This is because, after a typical intersubband thermalization time ($\sim 1 \text{ ps}$) the QD will have “forgotten” the nature of the optical transition which led to its photoionization. One possibility is that the two peaks in the spectral response actually correspond to subensembles of dots with different electron

occupations. On average, a dot with two electrons will be closer to two ionized donors than would a dot with only one electron. This could produce electrostatic field changes which, at the same time, perturb the optical transition energies and produce a potential barrier to electron recapture.⁵ This would be consistent with the correlation between lifetime and excitation wavelength seen in Figs. 4 and 5. In spite of these complexities, for photoexcitation at these wavelengths, the long-lived tail of the transient can only be determined by the single-time constant process of electron recapture by the dots.

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 quantum dot states is very weak. Assuming a typical saturation GaAs saturation drift velocity¹² of $\sim 2 \times 10^5 \text{ m s}^{-1}$ gives a $\tau_{\text{transit}} \sim 6.5 \text{ ps}$ value for the carrier transit time in this device. This corresponds to photoconductive gain factors $g = \tau_{\text{cap}} / \tau_{\text{transit}}$ of the order of 10^4 – 10^5 in the temperature range between 20 and 100 K, where these devices are most likely to be used.

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