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Quantum dot infrared photodetectors in new material systems

E. Finkman^{a,*}, S. Maimon^a, V. Immer^a, G. Bahir^a, S.E. Schacham^b, O. Gauthier-Lafaye^c,
S. Herriot^c, F.H. Julien^c, M. Gendry^d, J. Brault^d

^aDepartment of Electrical Engineering and Solid State Institute, Israel Institute of Technology, Technion, Haifa 32000, Israel

^bDepartment of Electrical and Electronic Engineering, College of Judea and Samaria, Ariel 44837, Israel

^cInstitut d'Electronique Fondamentale, CNRS, Univervite Paris-XI, 91405 Orsay, France

^dLaboratoire d'Electronique-LEOM, UMR CNRS 5512, Ecole Centrale de Lyon, 69131 Ecully, France

Abstract

Infrared detectors were implemented on InAs self-assembled quantum dots fabricated using Stranski–Krastanov growth mode on InAlAs matrix, lattice matched to InP (001) substrates. These dots grow with a shape of small elongated boxes, with their long axis along the $[110]$ direction, and with a high concentration of $7 \times 10^{10} \text{ cm}^{-2}$. Photoconductive measurements were performed in all three polarizations. Rich spectra in the range of 50–500 meV, with different polarization selection rules were observed. The bias dependence of peak intensity of the intraband transitions serves as an additional tool to identify their origin. Some of the peaks, which increase linearly with bias, are attributed to bound-to-continuum transitions. Others, which appear only at larger biases, and increase superlinearly, are due to bound-to-bound transitions. The magnitude of detector responsivity at normal-incidence is similar to that obtained for polarization normal to the layers, and is comparable to that achieved in QWIPs. BLIP conditions prevail at 77 K for integral photocurrent response at $F\#1$. The effect of unintentional doping is discussed. It is shown that this doping can be destructive for detector operation unless the density of dots is large. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Quantum dots; Intraband transitions; Infrared detectors

1. Introduction

Recent studies have shown the potential advantages in using quantum dot infrared photodetectors (QDIPs) rather than quantum well infrared photodetectors (QWIPs) to implement detectors [1–5]. There

are two major potential advantages of quantum dots over quantum wells as photodetectors, namely:

1. Intersubband absorption may be allowed at normal incidence. In QWIPs only transitions polarized perpendicular to the growth direction are allowed, due to absorption selection rules. The selection rules in QDIPs are inherently different, and normal incidence absorption is, indeed, observed.

2. Thermal generation of electrons is significantly reduced due to the energy quantization in all three

* Corresponding author. Tel.: +972-4-294-686; fax: 972-4-832-3041.

E-mail address: finkman@ee.technion.ac.il (E. Finkman)

dimensions. Generation by LO phonons is prohibited unless the gap between the discrete energy levels equals exactly to that of the phonon. This prohibition does not apply to quantum wells, since the levels are quantized only in the growth direction and a continuum exists in the other two. Hence thermal-generation or recombination by LO phonons results, with a capture time of few picoseconds. Thus, it is expected that S/N ratio in QDIPs will be significantly larger than that of QWIPs.

In this paper we present a study on two material systems of QDIPs. We first present a study on a promising structure for this application, based on InAs/InAlAs/InP material system [6]. In the second study, the more traditional system of InAs/GaAs dots is used to demonstrate the significance of the residual, unintentional, doping in affecting the performance of detectors based on intraband transitions.

2. InAs/ InAlAs/ InP QDIPs

2.1. Experimental set-up

In this work, we investigate InAs self-assembled quantum dots. These structures were grown using Stranski–Krastanov growth mode in an MBE Riber 2300 reactor. They were composed of ten layers of self-assembled InAs dots, separated by 400 Å InAlAs barrier layers, lattice matched to semi-insulating (0 0 1) InP substrate [6]. The layer combination resulted in a high concentration of elongated QDs with a unique shape. These dots grow with a shape of a flattened ellipsoids, around 500 Å long, 300 Å wide and 20 Å high, with their long axis along the $[\bar{1}10]$ direction, and with a high dot concentration of $7 \times 10^{10} \text{ cm}^{-2}$ (see Fig. 1). The barriers were delta-doped in their center by Si at a sheet concentration of $5 \times 10^{11} \text{ cm}^{-2}$. InGaAs contact layers, 5000 Å thick, n-doped with Si at a concentration of $1 \times 10^{18} \text{ cm}^{-3}$ and $8 \times 10^{18} \text{ cm}^{-3}$, were grown on the top and the bottom of the structure, respectively. The dots seem rather flat, but their exact shape is not accurately yet determined from the AFM image, as the AFM images were taken on uncapped dot layers, grown under the same conditions. It is reasonable to assume that the dots shapes and sizes are only slightly modified after the deposition of the $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$

Fig. 1. Typical ex situ surface morphology of the InAs/InAlAs/InP dots.

Fig. 2. Schematic view of MBE grown layer structure and photoconductive intersubband mesa detector.

cap layers, due to a low interdiffusion of the element III atoms, since the As concentration is the same in the dots and in the cap layers.

Photoluminescence (PL) and normal-incidence infrared absorption measurements were previously studied on similar dots [7]. A structured broad PL peak was interpreted as an evidence to a distribution of dot size in the sample. A single strong in-plane intraband absorption in such dots, peaked around 90 meV was observed, with a remarkably large oscillator strength ($f = 10$). This peak is polarized perpendicular to the dot length.

Mesa structure detectors were fabricated with an area of $200 \times 200 \mu\text{m}^2$. $50 \times 50 \mu\text{m}^2$ Ti/Au contacts were evaporated on the InGaAs contact layers (see

Fig. 2). Two illumination geometries were used. In the first, normal incidence (front illumination) photoconductive spectra were taken. Light is polarized either in the $[110]$ direction, defined as the x -axis, in which the electric field is along the width of the dot, or in the $[\bar{1}10]$ direction, the y -axis, where the electric field is along the length of the dot. It must be emphasized that, due to the elongated shape of the dots, absorption of radiation polarized in the x -axis could differ from that at the y -axis.

In the second configuration, the samples were cleaved along the $[110]$ and the $[\bar{1}10]$ directions, and were illuminated through a 45° -wedge, polished along the $[110]$ direction. In this configuration, two polarizations of the incoming IR beam are possible. In the s-polarization (TE), the electric field is parallel to the width of the dots, the x -axis. In p-polarization (TM), due to the 45° wedge, 50% of the component of the electric field is along the growth $[001]$ direction, z -axis, and 50% is in-plane. Thus, the observed transitions are polarized both in the y and z directions. Here we record spectra for polarization along the height of the dot, which is not available in the front illumination.

Fig. 3. QDIP spectra for front illumination: (a) x -axis polarization; (b) y -axis polarization.

2.2. Experimental results

Photoconductive spectra at 24 K were measured using a Mattson Cygnus 25 FTIR. Spectra were taken at various biases and polarizations. Front illumination spectra are shown in Fig. 3a and b for both possible polarizations. At low bias voltages, the dominant photoconductive peaks appear at about 250 and 340 meV, denoted as (c) and (d), respectively. At low biases these peaks are hardly affected by polarization. The relative intensity of the peak (c) with respect to that of (d) is reduced as the bias is increased, and both seem to merge into one.

With increasing bias, two additional peaks emerge. The first, marked as (a), at 100 meV. The other, denoted as (b), varied in position for different detectors on the same wafer at the range of 150–165 meV. The 100 meV line, (a), is strongly polarized along the width of the dot (along the x -axis). The second peak, (b), is present at both polarizations. While the dependence of the low-energy peak (a) on bias is superlinear throughout, the responsivity of the second,

(b), changes from superlinear to linear at larger biases.

The spectra obtained with wedge illumination are presented in Fig. 4a and b. Again the measurements were taken at various bias voltages. The strong voltage dependence of the polarized peak (a) present at front illumination is more pronounced in this configuration. While at low biases it is practically absent, it becomes by far the dominant at the largest bias. Once again, when the radiation is polarized along the length of the dots (y -axis), this peak is absent. Here, peak (b) is absent at lower bias, while at larger biases it increases linearly. In the p-polarization the dominant peak at larger energies is peak (c), and its shape hardly depends on bias.

The detector dark current, as a function of bias voltage, for various temperatures in the range of 50–110 K, is presented in Fig. 5. Also shown is the current due to background radiation at $F\#1$, at front illumination, with the detector at $T = 40$ K. By comparing the background curve to the dark curves, it is possible to conclude that background limited in performance

Fig. 4. QDIP spectra for wedge illumination: (a) x -axis polarization; (b) $y + z$ -axes polarization.

Fig. 5. Dark currents and background current characteristics.

(BLIP) conditions prevail up to 77 K for integral response at $F\#1$ illumination.

2.3. Analysis and discussion

All the confined energy levels in the dots are not degenerated, as a result of their non-symmetric shape.

Thus, two electrons at the most may populate each. The number of electrons per dot can be estimated from the ratio of the doping concentration in the barrier to the dot concentration, assuming all free electrons reside in the dots. Accordingly for the structure analyzed in this work the average number of electrons per dot is about 7. Thus, the 3–4 lowest levels are occupied at low temperatures. The highest of them may be partially populated, due to the variation in dot size. In the most basic approach it is possible to assign three quantum numbers to each level, n_x , n_y , n_z , associated with the x , y and z directions. Assuming, to a first approximation, that separation of variables applies, and that the dots have the shape of parallelepiped boxes, one may create a schematic representation of the confined energy levels in the conduction band of the dots. This scheme is presented in Fig. 6, together with the allowed transitions that result from this simplistic approach. This diagram gives a plausible interpretation to the origin of the observed peaks. Qualitatively, this scheme resembles the results of Dekel et al. [8], which are based on an eight-band model.

All photoconductive signals are due to carriers escaping the dots into the continuum and swept by the bias. The various peaks can be divided into two groups. The first group is generated by bound to continuum transitions. Its peaks increase linearly with bias. The second group consists of peaks, which appear only at larger biases, and their amplitude shows a superlinear dependence. This group should be associated with bound to bound transitions, followed by tunneling.

Peak (a) arises undoubtedly from the same transition as the one reported by Weber et al. [7]. It is strongly polarized along the width of the dots, the x -axis, and shows a super linear dependence on the bias. Thus it is reasonable to associate it with a bound to bound $e2-e5$ transition, that agrees with the observed polarization. Its energy is almost unchanged in all samples under all experimental conditions. In contrast, the other peaks have slightly different energies for different detector elements, which is interpreted as a difference in average dot sizes along the wafer. Dot dimensions should less affect the positions of deep levels in the dots than those of the shallow levels, a further verification of this interpretation.

The interpretation of line (b) is less obvious. The bias dependence turns linear, it is broader, and is

Fig. 6. Simplified schematic representations of the first possible energy levels in the QD. Arrows represent allowed transitions with appropriate polarizations. Only transitions from occupied to unoccupied transitions are indicated. Peaks are polarized in the directions in which the arrows appear. Tentative assignment of arrows corresponds to peaks described in text.

asymmetric. Thus it is probably associated with more than one transition from deep to a shallow bound state. Tentative transitions, e3–e6 and e4–e7 are *x*-polarized, and e3–e7 and e4–e9 are *y*-polarized, as marked in Fig. 6.

Both lines (c) and (d) are assigned to bound-to-continuum transitions, since they are basically linearly dependent on the bias, and their polarization selection rules are not as strict. Peak (d) is associated with electrons excited from the ground state e1, while peak (c) is due to transitions from the partially populated e3, e4, and possibly e5 states. The effects of polarization and bias on the structured spectra in the higher-energy range of peaks (c) and (d) are not completely understood yet. Model calculations are in the working.

3. Residual doping in QDIPs

3.1. Sample structure

An experimental structure of InAs/GaAs self-assembled QD was prepared. The sample was not rotated during the QD growth, thus a gradient in the

dot density was formed across the surface. Samples were grown with 10 layers of InAs QDs separated by 50 nm GaAs barriers. GaAs contact layers were grown on the bottom and the top of the quantum structure. There was no intentional doping in the entire quantum structure, except for the contact layers.

$200 \times 200 \mu\text{m}^2$ mesa detectors, similar in structure to those described in Section 2.1 were implemented on three different sites on the wafer. The concentration of dots varies between the groups: high density (HD, $2\text{--}4 \times 10^{10} \text{ cm}^{-2}$), medium density (MD, $\sim 10^9 \text{ cm}^{-2}$), and low density (LD, $\sim 10^8 \text{ cm}^{-2}$). Alloyed AuGe/Ni/Au $100 \times 100 \mu\text{m}^2$ contacts were formed on top and bottom of the structure.

3.2. Experimental results

Photoluminescence spectra of the HD sample taken at 77 K show a strong peak at 1.32 eV due to inter-band transition in the dots, and a weaker one 1.44 eV, attributed to recombination in the wetting layer. The GaAs luminescence line appears at 1.51 eV. Similar peak transition energies, but with narrower linewidths, were found for samples MD and LD, showing that average dot sizes are similar in all samples.

Fig. 7. I – V characteristics, and differential resistance of high density (HD, $\sim \times 10^{10} \text{ cm}^{-2}$), medium density (MD, $\sim 10^9 \text{ cm}^{-2}$), and low density (LD, $\sim 10^8 \text{ cm}^{-2}$) InAs/GaAs QDs.

The resistance of the three detectors varies greatly with dot density. The HD group shows, at 77 K, a uniform resistance of about 300 M Ω at zero bias. For MD samples the measured resistances is much lower, and much more dispersed, in the range of 50 k Ω to 50 M Ω , mostly in the lower end. The resistance of the LD samples is again lower by several orders of magnitude and it is in the range of 100 Ω to 100 k Ω .

Current and differential resistance as a function of voltage are shown in Fig. 7 for three detectors, one from each group. The HD sample, shows a clear back-to-back diode characteristic, while the LD detector shows almost ohmic behavior.

Spectral response measurements at 77 K were taken both for front and wedge illuminations. Typical spectra for the HD and MD samples are shown in Fig. 8. The spectra of the MD samples consist of a single peak, centered at about 0.2 eV, while those of the HD samples show a double peak. The first peak is identical to that of the MD sample, and the second is located at about 0.22 eV. This indicates that while the dot size in the MD samples is quite uniform, there is double distribution of dot size in the HD samples. The spectra are completely unpolarized, with the same waveform obtained in all configurations. No signal could be observed for the LD sample. The low resistivity generated a large noise current, prohibiting observation of a signal.

Fig. 8. Spectral response of HD and MD samples with front (F) and wedge (W) illuminations.

3.3. Discussion

This set of experiments is aimed at emphasizing the importance of unintentional background doping on device performance. It is shown that in samples with low dot density, the presence of unintentional doping can be destructive and prevent the use of the device. Optimization of doping and dot concentration is essential in order to achieve the desired performance.

4. Conclusions

Intraband transitions in quantum dots were studied by implementing infrared detectors and studying their photoconductivity as a function of applied bias and polarization. Both perpendicular and wedge illuminations were investigated. Complex spectra show different types of lines, attributed to both bound-to-continuum, and bound-to-bound followed by tunneling, transitions.

The present results are compared to absorption measurements performed on similar structures, in which only one bound-to-bound polarized transition was observed. The combination of photoconductivity and photo-induced absorption gives complementary information. It is easier to identify bound-to-bound transitions and estimate their oscillator strengths using IR transmission. On the other hand, photoconductivity spectrum is usually richer, giving easier access to bound-to-continuum transitions as well.

A tentative assignment of the transitions is based on a simplified model based on separation of wavefunctions. A more thorough analysis has to be completed, using a more comprehensive eight-band $\mathbf{k} \cdot \mathbf{p}$ model. Unlike QWIPs, it is obvious that infrared detectors based on quantum dots can perform well with front illumination.

The effect of residual doping must be taken into consideration when designing QDIPs. In epitaxial layers in GaAs/AlAs systems the unintentional doping is frequently in the range of 10^{15} cm^{-3} or higher. Under such conditions, it is possible that the concentration of carriers, which remains in the barrier, due to saturation of the dots, is large enough to effectively shorten the device. Hence, the dark current increases to the extent that the signal cannot be observed. Moreover, filling lower levels in the dots changes the observable transitions and the spectral response of the detectors. All these must be taken into account when designing QDIPs.

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