

## Normal-Incidence Quantum Dot Infrared Photodetectors

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Epitaxial semiconductor three-dimensional nanoscale islands formed via stress-driven self-organization in lattice-mismatched epitaxy, when covered with appropriate capping layers, provide quantum dots (QDs). Such QDs are particularly attractive candidates for mid and long wavelength (3-14  $\mu\text{m}$ ) infrared photodetectors due to their nearly discrete electron density of states which enables normal incidence detection, a greatly suppressed electron-phonon scattering which gives significantly enhanced lifetime of excited electrons, and reduced dark current. In this talk we report on normal-incidence single- and dual-wavelength intraband infrared photodetectors (with contacts in the vertical configuration) based on epitaxial InAs/InAlGaAs quantum dots. Exploiting innovative QD growth protocols, current blocking layers, and manipulation of the capping layers, we have realized (at 77K): i) unimodal quantum dot infrared photodetectors (QDIPs) with detectivity up to  $10^{10}\text{cmHz}^{1/2}/\text{W}$ , ii) very narrow photoresponse with full-width-at-half-maximum down to 6.0meV ( $\Delta\lambda/\lambda=4.6\%$ ,  $\lambda=9.72\mu\text{m}$ ), and iii) bias-controlled, tunable, two-color (middle and long wavelength) QDIPs.

The QDIP samples were grown on GaAs(001) $\pm 0.1^\circ$  substrates via solid-source molecular beam epitaxy. The InAs/InGaAlAs QD density, size distribution, as well as the structure and defect density of QDIPs were characterized using atomic force microscopy and cross-sectional transmission electron microscopy. The InAs QDs were undoped and embedded between highly Si-doped top and bottom GaAs contact layers, i.e., in n-i(QDs)-n structures[1][2]. Typical photoluminescence (PL) full-width-at-half-maximum of the QDs is  $\sim 25$  meV, reflecting high uniformity of the QD size. The InAs QDs based QDIPs have been comprehensively characterized via PL, PL excitation, and Fourier transform infrared (FTIR) based inter- and intra-band photocurrent spectroscopy, and measurements of dark current, noise current, and blackbody based responsivity.

A class of unimodal QDIP is based on five layers of GaAs capped 3ML InAs QDs formed via the innovative punctuated island growth (PIG) approach [3][4]. In Al-free GaAs capped InAs QDs based QDIPs, we demonstrated a peak detectivity of  $1.5 \times 10^9 \text{cmHz}^{1/2}/\text{W}$  and responsivity of 25mA/W at 7.2 $\mu\text{m}$  ( $\Delta\lambda/\lambda \approx 14\%$ ) at a bias of 0.15V. Thin AlGaAs current blocking layers were strategically inserted besides the InAs QDs in the GaAs capping layer to achieve low dark current [5] and lead to a higher 77K peak detectivity of  $10^{10} \text{cmHz}^{1/2}/\text{W}$  and responsivity of 14mA/W at 6.2  $\mu\text{m}$  ( $\Delta\lambda/\lambda \approx 7.4\%$ ) at a bias of -0.7V (see Fig.1). In order to tailor the peak photoresponse in the mid infrared (3-6 $\mu\text{m}$ ) and long infrared (8-14 $\mu\text{m}$ ) wavelength regions, we utilize InGaAs alloy capping layers, in conjunction with control on the average size and shape of the InAs QDs, to manipulate the band offset through the strain relieving and chemical effects of the alloy composition. For smaller and shallower InAs/InGaAs QDs we have realized unimodal intraband photoresponse [6] at 8.3 $\mu\text{m}$  with 77K peak detectivity of  $3.2 \times 10^9 \text{cmHz}^{1/2}/\text{W}$  (see Fig.2) and responsivity of 22mA/W ( $\Delta\lambda/\lambda \approx 11\%$ ). For larger and steeper dots we find a photoresponse [7][8] at 5.9 $\mu\text{m}$  with 77K peak detectivity of  $5.8 \times 10^9 \text{cmHz}^{1/2}/\text{W}$  and responsivity of 3.5mA/W [9].

Utilizing for the first time vertically integrated layers comprising sets of larger and smaller QDs we also demonstrate normal-incidence, bias-controlled, tunable, two-color [mid ( $\sim 6\mu\text{m}$ ) and long ( $\sim 10\text{-}12\mu\text{m}$ )] infrared QDIPs based on InGaAs capped InAs QDs [7][8]. Figure 3 shows that the relative photoresponse in this dual wavelength structure is tunable close to two orders of magnitude with bias. The dual wavelength photoresponse is due to bound-to-bound intraband transitions of the two types of QDs in the active region. Note that in Fig. 3(a), at a bias of -2.400V, the photoresponse at 9.72 $\mu\text{m}$  has a very narrow full-width-at-half-maximum of 6.0meV ( $\Delta\lambda/\lambda=4.6\%$ ). Approaches to enhancing the device figures-of-merit of such multi-color QDIPs are under examination and will be discussed.

This work was supported by the DoD Multidisciplinary University Research Initiative (MURI) program administrated by AFOSR under Grant No. F49620-98-1-0474.

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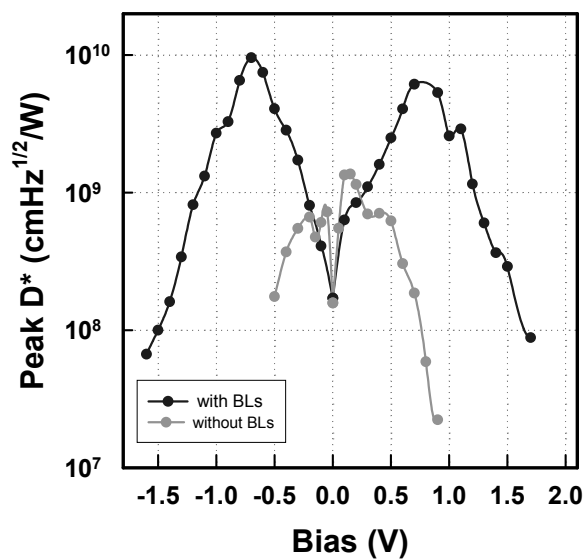


Fig.1 Comparison of the detectivities of QDIPs with and without AlGaAs blocking layers at T=77K.

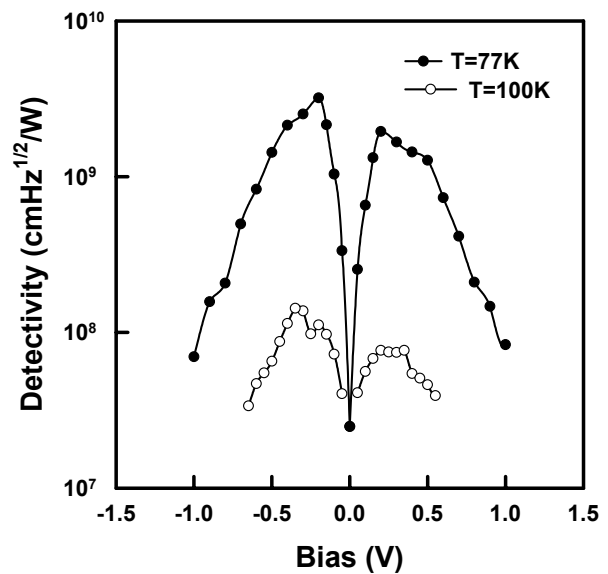


Fig. 2 Peak detectivity of the 8-9μm unimodal QDIP.

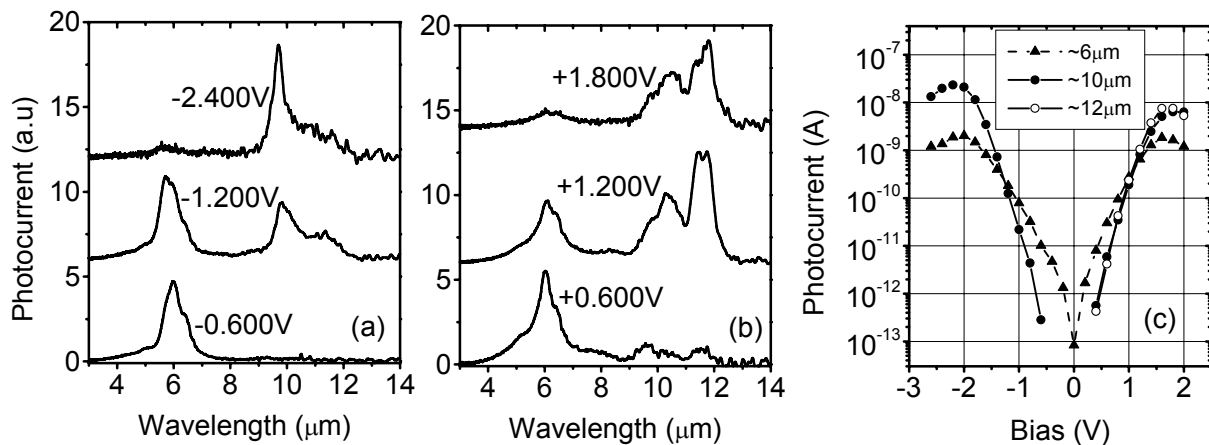


Fig. 3 77K intraband photocurrent spectra of the bias-tunable 2-color QDIP at negative [panel (a)] and positive bias [panel (b)]. Panel (c): Bias dependence of the peak photocurrent at mid (~6μm) and long (~10-12 μm) infrared wavelengths.