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Quantum Dot Intersubband Devices

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1. Introduction

While quantum dot *interband* devices such as lasers emitting at 1.3 μm and 1.55 μm have shown remarkable improvement in performance characteristics like low threshold current, high differential gain and low chirp, quantum dot *intersubband* mid-infrared ($\Delta E \sim 100$meV, 12μm) devices, until recently, have not been extensively investigated. There is an increasing demand for sources and detectors in the mid infrared (8-20 μm) for applications such as optical IR spectroscopy, point-to-point atmospheric communication, thermal imaging and night vision applications. Mid-infrared detectors, based on intersubband and bound to continuum transitions in quantum dots, have been demonstrated by us and other groups. Unlike quantum wells, quantum dot detectors are sensitive to normal incidence radiation and this makes them highly suitable for focal plane array applications. Moreover they are expected to demonstrate high temperature operation due to their favorable carrier dynamics. We have recently demonstrated reasonable performance of vertical quantum dot detectors upto 150K (λ_p=4μm, D*=1x10^{8}cmHz$^{1/2}$/W). We have also recently reported both far infrared spontaneous emission and stimulated emission, based on intersubband transitions in quantum dots. In this talk, the design, growth, fabrication and characterization of these quantum dot intersubband sources and detectors will be discussed in detail.

2. Quantum Dot Intersubband Sources

Measurement of carrier relaxation times in self-organized InGaAs/GaAs quantum dots, by high frequency electrical impedance measurements and by differential spectroscopy measurements reveals that: (a) the intersubband carrier relaxation time is much longer in quantum dots ($\tau \sim$30-60 ps) than in quantum wells ($\tau \sim$2-5 ps) due to the presence of a phonon bottleneck, (b) the intersubband relaxation time in quantum dots increases with increase in temperature in contrast to the observations made in quantum wells. These two observations suggest that population inversion between the electronic excited states and the ground state could be achieved easily in quantum dots. However there have been very few reports on MIR emission from the dots.

From a simple two-level steady state rate equation model, we have calculated a population inversion and gains upto 170 cm^{-1}, for the modal density of interband photons, N_{ph}=50 and the intersubband relaxation time, τ_{21}=60 ps, in InGaAs-GaAs quantum dots with an intersubband energy spacing of 50 meV (Fig. 1). To achieve population inversion, the lifetime, τ_1, of the electron in the ground state can be made small by providing a high density of coherent photons in the cavity, which can greatly reduce the interband electron-hole recombination time, $\tau_{stim} = \tau_{sp}/N_{ph} = \tau_1$. The intersubband population inversion process, together with the relevant relaxation times, is illustrated in Fig. 2.

Far-infrared measurements of the spectral output intensity were performed on a long-wavelength plasmon-enhanced waveguide designed for 13 μm emission at 283K using a Fourier transform infrared (FTIR) spectrometer and liquid nitrogen cooled HgCdTe detector. The FIR output power under CW biasing is shown in Fig. 3. The threshold current density of 1.1 kA/cm^2, is in fair agreement with theoretical calculations. The output spectrum is shown in the inset to Fig. 3. Since the ridge is very wide (60 mm), the emission is highly multi-mode in nature. The low output power can be enhanced with improved device design. These results will be discussed and presented.

3. Quantum Dot Intersubband Detectors

In the past we have demonstrated normal incidence InAs/GaAs quantum detectors with D*~1e10 cmHz$^{1/2}$/W at T=40K. However the large dark current prevented operation at higher temperatures. Symmetrically and asymmetrically placed current blocking AlGaAs layers were introduced in the active region of the detecor to decrease the dark current and increase the operating temperature of the devices. The dark current curves are shown in Fig. 4. The spectral response of the detector is shown in Fig. 5. Using appropriate heterostructure engineering of the detectors, we have achieved reasonable operation till T=150K, with D*=1e10 cmHz$^{1/2}$/W and R=2mA/W at T=100K with a peak response at l~4μm (V_b=0.1V, T=78K) as shown in Fig. 6. *This is highest reported detectivity in quantum dot detectors and the highest operating temperature for normally incident vertical QDIPs.* The design of these detectors and their performance will be discussed in detail in the talk.

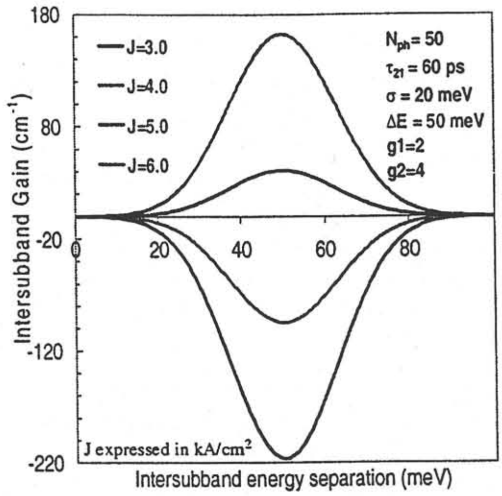

Fig. 1: Calculated intersubband gain in $In_{0.4}Ga_{0.6}As$ quantum dots.

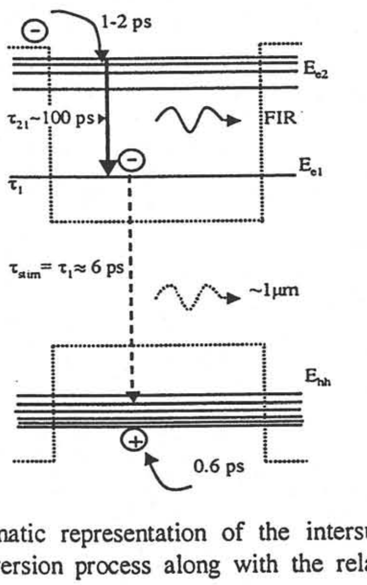

Fig. 2: Schematic representation of the intersubband population inversion process along with the relaxation times

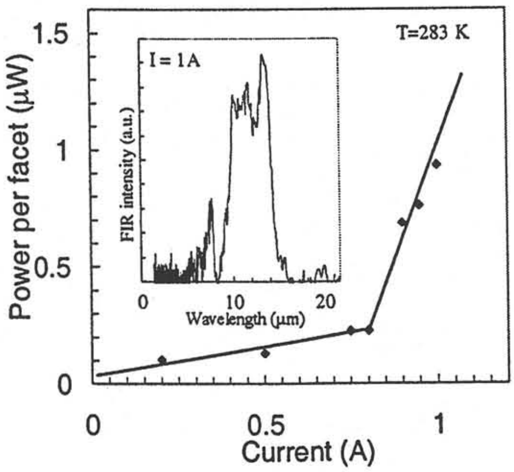

Fig. 3: FIR output power as a function of the injected current (the spectral output is shown in the inset).

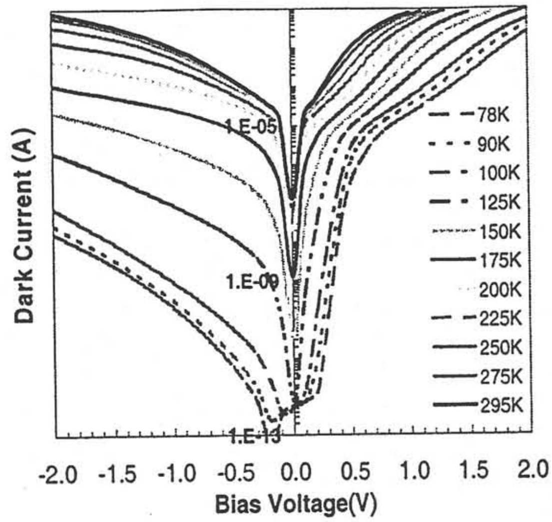

Fig. 4: Temperature dependant dark current of the 10 layer InAs/GaAs quantum dot detector.

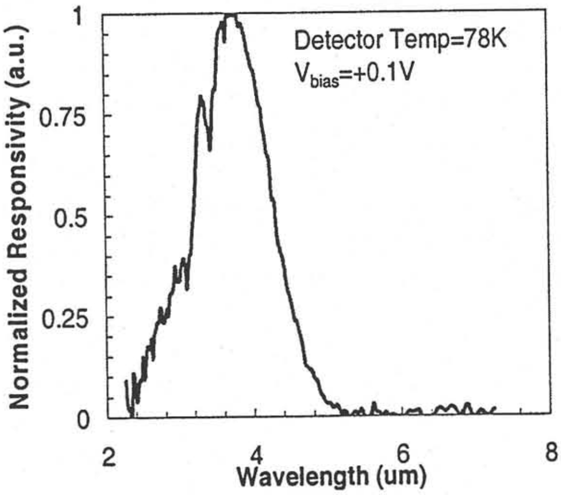

Fig. 5: Mid infrared spectral response of the 10 layer InAs/GaAs quantum dot detector.

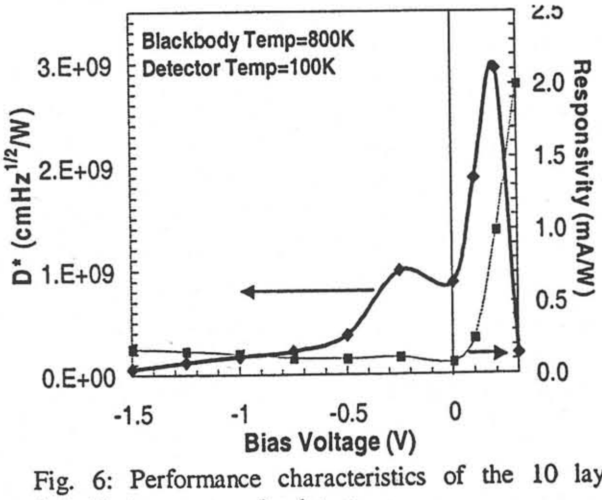

Fig. 6: Performance characteristics of the 10 layer InAs/GaAs quantum dot detector.