Wavelength and polarization selective multi-band tunnelling quantum dot detectors

A.G.U. PERERA*1, G. ARIYAWANSA1, V.M. APALKOV1, S.G. MATSIK1, X.H. SU2, S. CHAKRABARTI2, and P. BHATTACHARYA2

1Department of Physics and Astronomy, Georgia State University, Atlanta, GA 30303, USA
2Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, Michigan 48109-2122, USA

The reduction of the dark current without reducing the photocurrent is a considerable challenge in developing far-infrared (FIR)/terahertz detectors. Since quantum dot (QD) based detectors inherently show low dark current, a QD-based structure is an appropriate choice for terahertz detectors. The work reported here discusses multi-band tunnelling quantum dot infrared photo detector (T-QDIP) structures designed for high temperature operation covering the range from mid- to far-infrared. These structures grown by molecular beam epitaxy consist of a QD (InGaAs or InAlAs) placed in a well (GaAs/AlGaAs) with a double-barrier system (AlGaAs/InGaAs/AlGaAs) adjacent to it. The photocurrent, which can be selectively collected by resonant tunnelling, is generated by a transition of carriers from the ground state in the QD to a state in the well coupled with a state in the double-barrier system. The double-barrier system blocks the majority of carriers contributing to the dark current. Several important properties of T-QDIP detectors such as the multi-colour (multi-band) nature of the photoresponse, the selectivity of the operating wavelength by the applied bias, and the polarization sensitivity of the response peaks, are also discussed.

Keywords: multi band, IR detectors, quantum dot, resonant tunnelling, polarization.

1. Introduction

With the increasing interest in the terahertz region of the spectrum (0.1–3.0 THz) for applications in imaging, communication, security and defence, there is a need for terahertz detectors exhibiting low dark current and high operating temperatures. One of the challenges in developing terahertz detectors is the reduction of the dark current (due to thermal excitations) associated with terahertz detection mechanisms. At the present time, terahertz detectors such as Ge BIB detectors [1], photo conductors triggered by femtosecond laser pulses [2], quantum well detectors [3], hetero junction detectors [4], and thermal detectors, such as bolometers and pyroelectrics all of which operate at low temperatures, are being studied. A typical detector structure, in which the transitions leading to terahertz detection occur between two electronic states with an energy difference of \( \Delta E \) (4.1 meV for 1 THz), would not be suitable for high temperature terahertz detection since the thermal excitations become dominant even at 77 K due to small \( \Delta E \). Quantum dot (QD) based detectors inherently show low dark currents, offering a suitable platform for high operating temperature terahertz detectors. In order to decrease the dark current further, a tunnelling quantum dot infrared photo detector (T-QDIP) structure was studied [5]. Successful results on a two-colour T-QDIP with photoresponse peaks at 6 µm and 17 µm operating at room temperature [5], and a terahertz T-QDIP responding [6] at 6 THz (50 µm) for a temperature of 150 K have been previously reported. In the T-QDIP structure grown by molecular beam epitaxy (MBE), a QD (InGaAs or InAlAs) is placed in a well (GaAs/AlGaAs) with a double-barrier system (AlGaAs/InGaAs/AlGaAs) adjacent to it. The photocurrent generated by a transition from the ground state in the QD to a state in the well (denoted as resonant state as this state is considered for resonance tunnelling) coupled with a state in the double-barrier system, while the double-barrier system blocks the majority of the carriers contributing to the dark current (carriers excited to any state other than the resonant state in the well). Two important properties of the T-QDIP detectors are the selectivity of the operating wavelength and the multi-colour (band) nature of the photoresponse based on different transitions in the structure. Furthermore, the wavelength bands in a dual-band T-QDIP resulting from transitions between the QD ground state and two QD excited states coupled with states in the double-barrier system (i.e., two resonant states) can be tuned by varying the bias voltage due to the dependence of resonance conditions for each resonant state on the applied bias. This allows for sep-
paration of the photo current generated by two response bands, without using external filters. The multi-band nature of T-QDIPs would be useful for applications such as mine detection [7], where scanning in two different wavelength bands greatly enhances detection capabilities and reduces false positives.

2. **Tunnelling quantum dot structures: background**

The low quantum efficiency associated with reduced photo current is a major constraint with conventional terahertz detector structures designed to use above cryogenic temperatures. This is due to the fact that structures normally designed to reduce the dark current could reduce the photo current as well. A T-QDIP structure, which uses resonant tunnelling to selectively collect the photo current generated within the quantum dots, while the tunnelling barriers block the majority of thermally excited carriers contributing to the dark current, would be an appropriate choice for the development of high performance high operating temperature detectors. The schematic diagram of a T-QDIP structure (labelled as MG386) is shown in Fig. 1(a), and the conduction band profiles under zero bias and under an applied reverse bias are shown in Fig. 2(a) and (b), respectively. The structure was grown by molecular beam epitaxy (MBE), with the GaAs and AlGaAs layers grown at 610°C and the InGaAs QD layers grown at 500°C on a GaAs layer. Al0.3Ga0.7As/In0.1Ga0.9As/Al0.3Ga0.7As serves as the double-barrier system. Vertical circular mesas for top illumination were fabricated by standard photolithography, wet chemical etching and contact metallization techniques. The n-type top ring contact and the bottom contact were formed by evaporated Ni/Ge/Au/Ti/Au with thickness of 250/325/650/200/2000 Å. Radius of the optically active area is 300 µm. The structure was designed to include a bound state in the well, which can couple to another state in the double-barrier system. For carriers excited by radiation with energy equal to the quantum dot ground state and the resonant state, the tunnelling probability can be shown to be near unity. Carriers excited into other states (contributing to the dark current) are blocked by the double-barrier system. In this way, a higher barrier for thermal excitations can be introduced, even though the photo excitation energy is very low. As a result, the operating temperature of the detector can be significantly increased. The operating wavelength can be tuned by changing the parameters that are associated with the QD and the well in the structure.

The QD energy levels are calculated by using 8-band k·p model [8]. This model takes into account the strain in the quantum dot calculated from the valence force field [9,10] (VFF) model, which has proven to be successful in calculating the strain tensor in self-assembled quantum dots. QD size and confinement potential should be determined in order to obtain required energy spacing between states in the QD. Energy states in the well, including the presence of the wetting layer and the double-barrier system, are calculated by solving the one-dimensional Schrödinger equation. The transmission probability for the double-barrier system is calculated using the transfer matrix method [11]. The width of the well and parameters of the double-barrier system are determined so the transitions from E0, E1, and E2 states give rise to the expected peak wavelengths.

A comparison of the dark current density between quantum dots-in-a-well (DWELL) [12] and T-QDIP (MG386) detectors at 80 K is shown in Fig. 3. The dark current densities at a bias of –2 V are 3×10⁻¹ and 1.8×10⁻⁵ A/cm² for DWELL and T-QDIP, respectively. The reduction of the dark current of T-QDIP is associated with dark current blocking by the double-barrier system in the structure. The response of MG386 showing two-colour response at wavelengths of ~6 and ~17 µm up to room temperature was recently reported [5]. The spectral response measured at 80 K under different bias values are shown in Fig. 4, and the responsivity at 300 K under –2 V bias is shown in the inset. The peak responsivity and the quantum efficiency of QDs, and the average size of QDs was found to be 140/40 Å (base dimension/height).