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Rate equation modelling and investigation of quantum cascade detector characteristics

Sumit Saha*, Jitendra Kumar

Department of Electronics Engineering, Indian School of Mines, Dhanbad 826004, Jharkhand, India

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ABSTRACT

A simple precise transport model has been proposed using rate equation approach for the characterization of a quantum cascade detector. The resonant tunneling transport is incorporated in the rate equation model through a resonant tunneling current density term. All the major scattering processes are included in the rate equation model. The effect of temperature on the quantum cascade detector characteristics has been examined considering the temperature dependent band parameters and the carrier scattering processes. Incorporation of the resonant tunneling process in the rate equation model improves the detector performance appreciably and reproduces the detector characteristics within experimental accuracy.

1. Introduction

Quantum cascade detectors (QCDs) [1–4] are semiconductor heterostructure photon detectors [5] that rely on the intersubband cascaded transition of carriers through energy steps in quantum cascade structures (QCSs) [6]. Due to their unique characteristics, QCDs are becoming highly reliable and promising devices for many commercial and military applications. Unlike interband photodetectors where band gap of the semiconductor decides the detection wavelength, it has become possible to design detectors of different wavelengths using the same material system only by changing the active well (AW) width because of its intersubband nature. The device is free from dark current noise thanks to the photovoltaic operation. The problem of the capacitance saturation by dark current in the readout integrated circuit (ROIC) is prohibited due to zero dark current that permits longer integration time and the thermal load of the detector is considerably reduced which makes QCD as a potential device for spatial applications. The detection wavelength of a QCD covers the whole infrared (IR) spectral region [7] starting from the near-IR wavelength (0.75–1.4 μm) [8] to a very long-IR (15–30 μm) wavelength [9–12] and the terahertz (THz) region [13] of the spectrum with an excellent responsivity and detetctivity performance. QCDs in the short-wave-IR (1.4–3 μm) [14–16], mid-wave-IR (3–8 μm) [17–20] and long-wave-IR (8–15) [21,22] spectral range have become very dependable photon detectors with brilliant room temperature performances. A broadband QCD covering spectral region from 4.7 μm to 7.4 μm for room temperature operation with a reliable noise performance is reported by Hofstetter et al. [23] in 2008. Incredibly high speed detection [24,25] is possible using QCD due to the very short intersubband carrier relaxation time which has made it compatible with very high speed photonics technologies. Although QCDs are very

* Corresponding author.
E-mail addresses: sumitahas@gmail.com (S. Saha), jitenkg@rediffmail.com (J. Kumar).

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good and reliable devices for IR and THz detection, they suffer from very low quantum efficiency, hence very low responsivity. One of the important reasons for low quantum efficiency is that at oblique incidence only TM mode gets absorbed as dictated by intersubband selection rules which make quantum wells (QWs) insensitive to surface normal incidence of radiations. However, this condition will not have an impact on the performance of the QCD if it is used with a QCL. In general, the quantum efficiency will be determined by QCD parameters like the number of periods, doping [4]. Recent developments in new device technologies based on surface plasmons [26] and photonic crystal slab resonant cavity [27] enable QCDs to absorb surface normal illuminations and ensure a very high quantum efficiency and enhanced responsivity. A novel QCD design [28,29] based on diagonal carrier transition in the active region provides a better QCD performance in terms of higher responsivity and detectivity compared to vertical transport designs. Most of the studies mentioned here are mainly based on the experimental designs and characterization of QCDs. Only few theoretical models are available in the literature to describe the device physics and predict the device performance characteristics with precision. The “Thermalized Cascade” model [6] explains the transport in a QCD with experimental accuracy for a temperature range of 90–200 K at dark condition and zero bias with doping as an adjustable parameter. The model is based on the assumption of a single quasi-Fermi level for a cascade period of subbands and the carrier transport is calculated based on only longitudinal-optical (LO) phonon Hamiltonian. In 2010 Buffaz et al. [30] have proposed an improved model known as “Thermalized Subbands” model based on the assumption that not only the cascade but also the subbands in a cascade are quasi-thermalized. It describes the transport for a more wide range of temperatures (40–300 K) compared to the previous model. All the models are mainly based on the LO-phonon Hamiltonian for the carrier transport in the structure and neglect all other transport mechanisms. Therefore, an accurate theoretical model of QCD considering all the transport mechanisms is required that can describe the device at any temperature and bias condition under dark and illumination environment without any adjustable parameters.

A QCD comprises of an active QW which is degenerately doped and an extractor of multiple QWs which is usually undoped, together forming a period of the QCD. The extractor region in a period is designed in such a way that the ground state energy levels of the wells in the extractor jointly form a phonon ladder. The photovoltaic operation of a QCD can be described as follows: the incident photons are absorbed by the carriers in the active QW ground energy level and excited to the second energy level in the active QW. The photoexcited carriers then escape from the active QW to the first extractor well through tunneling process and then the carriers move to the AW of the next period by non-radiative phonon scattering through the phonon ladder. The escape tunneling from the active QW to the extractor well can be characterized mainly by two processes: the resonant tunneling process and the scattering tunneling process. A complete resonant tunneling escape is possible when the excited state in the AW and the first extractor state are in energy resonance and separated by a very thin barrier. But at zero bias condition as in our case, complete resonance is not possible between states as the states get degenerated for smaller barriers. In 2008, Terazzi et al. have shown that the resonant tunneling current is high between the states with an effective population that are in resonance or detuned by a very small amount of energy from the resonance as the resonant tunneling process deals with the energy conservation, not the wave vector [31]. The scattering tunneling process is significant when the first excited energy state in the active QW is separated by a considerable amount of energy from the ground energy state of the first well in the extractor. The scattering tunneling process includes transport of carriers by various scattering processes such as electron-phonon (e-phn) scattering, electron-ionized-impurity (e-IIMP) scattering and electron-interface roughness (e-IFR) scattering. Among different e-phn scatterings, electron-LO (e-LO) phonon scattering dominates in device systems of polar semiconductors. Doping in QCD gives ionized impurities and results in IIMP scattering of carriers. Transport of carriers through a QCD is mainly by tunneling transport processes which involves crossing the interface between semiconductor alloys and the structure of the interface strongly depends on the growth processes and growth conditions of the epitaxial layers. A rough interface can strongly affect the transport of carriers through the QCD, even they can cause strong scattering of carriers that involves change in state. Thus, carrier transport modelling in a QCD requires proper knowledge and identification of the scattering processes and their accurate computations.

The responsivity characteristic of a QCD is driven mainly by a very simplified equation given as $R = (\lambda q/hc)\eta g_p$ [32], where λ, q, h, c and η are the wavelength of the signal, elementary charge, Planck's constant, speed of light in vacuum and absorption efficiency, respectively. The photodetector gain is given as $g_p = p_e/N_{QW}p_c$, where p_e is the escape probability of an excited carrier from the AW to the extractor well and is approximated as $p_e \approx \tau_{rel}/(\tau_{rel} + \tau_{esc})$, where τ_{rel}^{-1} is the carrier relaxation rate to the ground energy level from the excited energy level in the AW and τ_{esc}^{-1} is the escape rate from the excited energy level in the AW to the ground energy level in the extractor well. The capture probability p_c is approximated and usually taken as unity [9,13,17] for a QCD structure which is not appropriate because the capture of carriers in the AW is determined by different scattering processes as in the case of escape probability which are strongly temperature dependent. Even at higher temperatures backscattering of carriers increases significantly which affects the capture and escape probability to a considerable extent. Therefore, a more accurate formalization is needed for the characterization of a QCD. Rate equation modelling of QCDs can circumvent the problem, as it deals with the rate of change of subband populations and takes care of all the possible carrier transport mechanisms through different scattering processes inside the QCD structure.

In this paper, first self-consistent solution of the Schrödinger-Poisson equation considering nonparabolicity in conduction band is performed using finite difference method (FDM) for the QCD structure and numerical values of the energies and wave functions are obtained. A rate equation approach is adopted for the carrier transport modelling in an intersubband cascade structure considering all the possible radiative and non-radiative events encountered by the carriers during their transport through the structure. We have assumed that the extraction of carriers from the AW to the first extractor well in a QCD is due to the combined effort of resonant tunneling transport and scattering tunneling transport processes. The resonant tunneling