FIGURES OF MERIT ESTIMATION OF QUANTUM WELL INFRARED PHOTODETECTORS USING INTERBAND AND INTERSUBBANAD TRANSITIONS

LABORATÓRIO DE GUERRA ELETRÔNICA

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ABSTRACT

Recent commercial and military applications have demanded photodetectors with high sensitivity, high selectivity and multispectral capability for detection and identification of objects. These characteristics have been found in quantum well infrared photodetectors (QWIP). Driven by those applications and aiming to improve the analysis and the design of QWIPs, a technique was developed for numerically estimate their main figures of merit such as *IxV* characteristics, dark current, quantum efficiency, responsivity, etc. The mathematical models of QWIP figures of merit, extracted from the references [1-4], can be adapted according to the semiconductor structure configuration. The main issue in this work was to be able to estimate the QWIPs' quantized energy levels inside the wells, their respective wavefunctions and the transition rates between them. Two kinds of transitions were of special interest: interband and intersubband transitions. In both cases, depending on the QWIP's structure characteristics and the external bias, transitions can occur from a confined state to a continuum one. Interband transitions in non-doped wells and intersubband transitions in n-doped wells were studied and modeled using a computational tool developed to solve self-consistently the Schrödinger-Poisson equation with the help of the shooting method [5]. The shooting method was used due to its ability to handle multilayer structures with any potential profile, making the design more flexible. This approach allowed computing the stark effect caused by the external electric field, and predict quite accurately the figures of merit of devices under bias. A good agreement between our theoretical predictions and the measurements made in several structures [1], [4] shows that this technique is suitable for analysis and design of practical devices.

INTRODUCTION

There is much concerned nowadays with respect to terrorist attacks and this has brought important changes in the aeronautics industry and, mainly, in photonics industry. In this context, recent defense applications have demanded photodetectors with high sensitivity, high selectivity and multispectral capability for detection, identification and imaging of a target. These characteristics have been found in quantum well infrared photodetectors (QWIP). Driven by those applications and aiming to improve the analysis and the design of QWIPs, a technique was developed for numerically estimate their main figures of merit such as *IxV* characteristics, dark current, quantum efficiency, responsivity, etc. In this context, the objective of this paper is to present the results of the mathematical models used to predict some merit figures of the QWIP cited above. But, the main issue in this work was to be able to estimate the QWIPs' quantized energy levels inside the wells, their respective wavefunctions and the transition rates between them.




Mathematical Models

Absorption Spectra

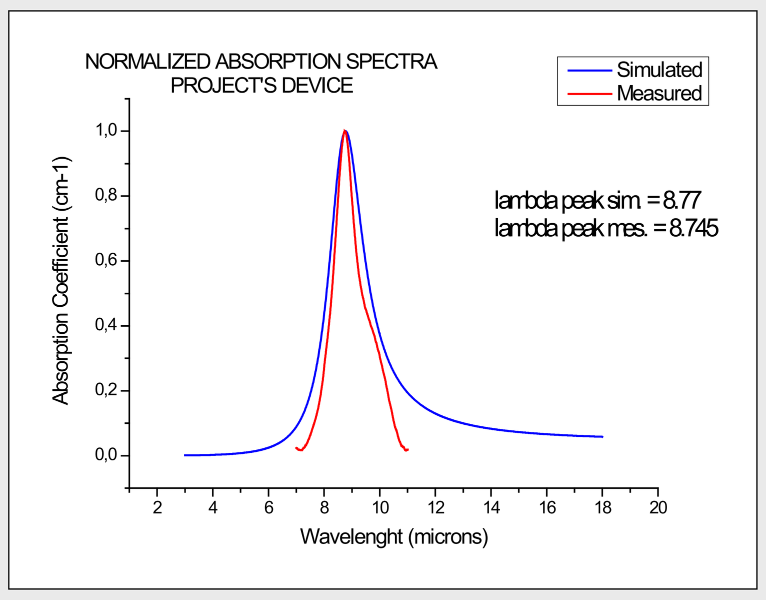
The absorption coefficient is the key parameter used in photodetector design. The crystal heterostructures are optimized for the absorption spectra requirements and the absorption coefficient is normally measured after the sample growth, before the device fabrication. The absorption models in QWIPs are normally complexes and use concepts not employed in this work. Reference [4] gives a detailed model for bound-to-bound and bound-to-continuum electron absorption designed during the research, given by the expression:

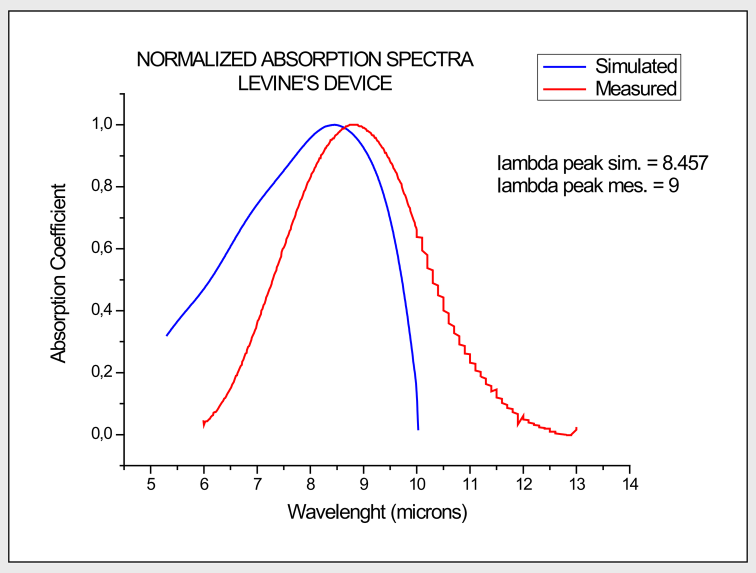
$$\alpha_{CbCb}(\hbar\omega)=\frac{q^2 d}{(m_e^*)^2}\frac{\hbar^3}{\varepsilon_o n_r c(\hbar\omega)}\left|\left\langle\psi_f(z)\left|\frac{\partial}{\partial z}\right|\psi_i(z)\right\rangle\right|^2 X\cos^2(\phi)\frac{\Gamma}{(E_f-E_i-\hbar\omega)^2+(\Gamma/2)^2}$$

where α_{CbCb} is the bound-to-bound absorbtion coefficient, d is the well doping density, E_i and E_f are the ground and excited state energies respectively, q is the electron charge, c is the light velocity, ε_o is the vacuum electric permissivity, G is the broadening parameter, ω is the angular frequency, ħ is the Planck constant divided by 2π , m_e^* is the effective electron mass, ϕ is the angle between the incident flux and the growth axis and Γ is the envelope function superposition of initial and final states. Mathematically,

$$\alpha_p\frac{\Delta\lambda/\lambda}{d}\approx cont.$$

where α_p is the absorption coefficient peak, *Δλ/λ* is the absorption bandwidth and *d* is the well doping density.



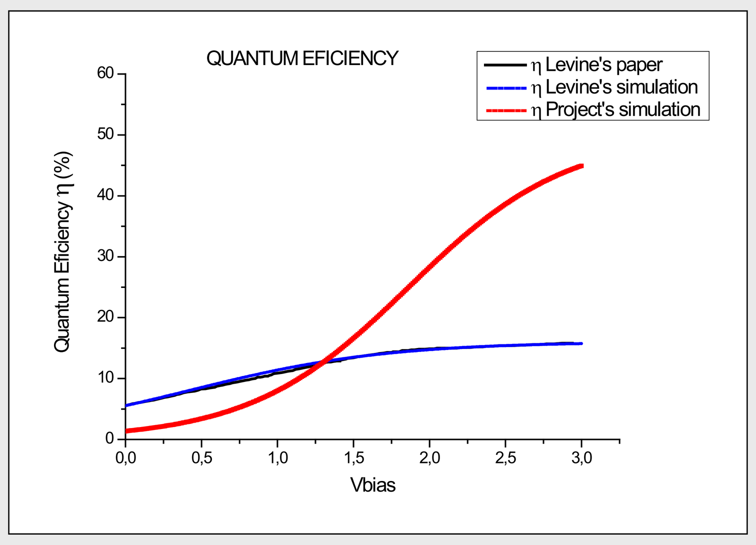


Quantum Efficiency

It was employed the Levine's proposed method [8], which uses the electron recapture probability inside the well as a function of the applied bias.

$$\eta_a=(1-e^{-2\alpha_p.l}) \longrightarrow \boxed{\eta=\eta_a.p_e(V)}$$

$$\frac{\tau_e}{\tau_r}(V)=\left(\frac{\tau_e}{\tau_r}\right)_o e^{-\frac{V}{V_p}} \longrightarrow p_e(V)=\left(1+\frac{\tau_e}{\tau_r}(V)\right)^{-1}$$



Responsivity

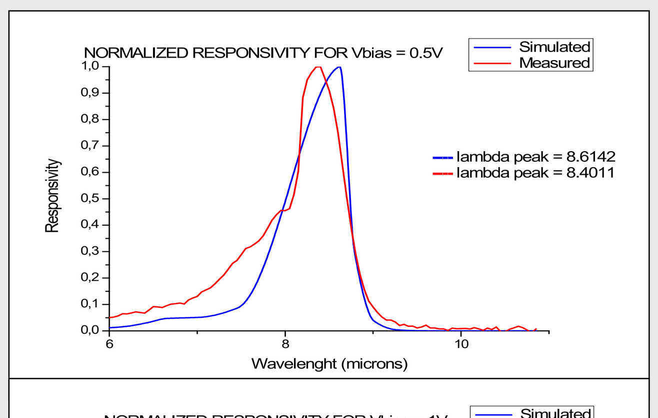
The responsivity figure quantifies the amount of photocurrent generated per watt of incident radiant photon power. It can be expressed mathematically as

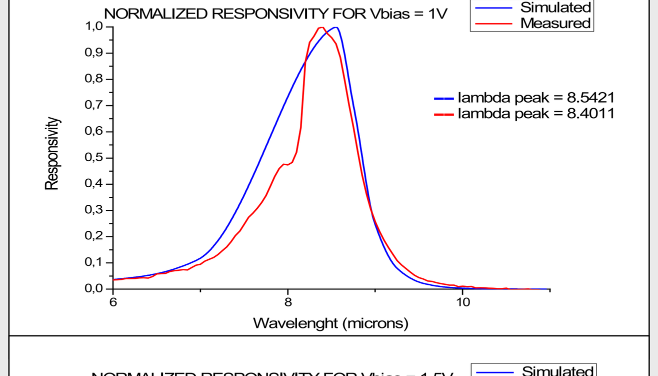
$$R(F)=\frac{I_p(F)}{\Phi_o}$$

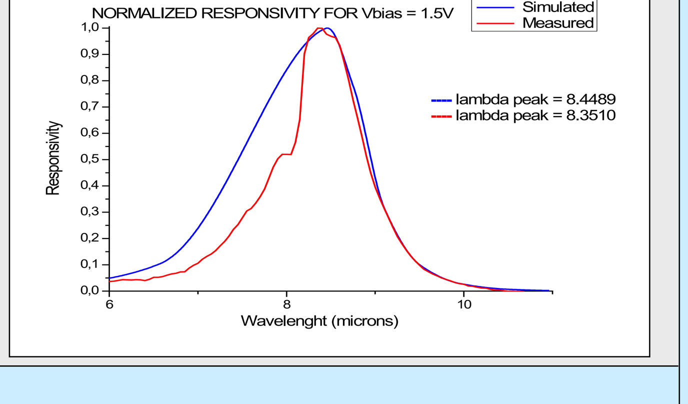
It is important to notice the responsivity dependence on the absorption coefficient and bias, through the drift velocity. The absorption coefficient is responsible for the shape (spectrum) and the electric field for the amplitude. Increasing the availability of carriers (doping concentration), the photocurrent will increase and consequently the responsivity.

$$I_P(F)\approx\frac{2q\Phi_o}{\hbar\omega}\alpha L_W G \qquad G=\sum_{n=1}^{N}e^{-\frac{nL}{\upsilon(F)\tau}}$$

$$I_P(F)\approx\frac{2q\Phi_o}{\hbar\omega}\alpha L_W\left(\sum_{n=1}^{N}e^{-\frac{nL}{\upsilon(F)\tau}}\right) \longrightarrow R_P(F)\approx\frac{2q}{\hbar\omega}\alpha L_W G$$







Dark Current

A biased photodetector, when no light is incident, exhibits dark current. Three dark current generation mechanisms in quantum well devices can be easily identified [38]. First, sequential resonant tunneling can happen, causing electrons to "jump" from well to well, through the barriers. This process is independent of temperature and is the dominant source of dark current at very lower temperatures. It can be reduced if larger barriers are used. The second mechanism is thermally assisted tunneling which involves thermal excitation and tunneling through the tip of the barrier into the transport states. This process is the dominant source at medium temperatures and can be reduced by placing the final state as far as possible to the initial state, reducing the probability of thermoionic transitions. The third mechanism is classical thermoionic emission and it is the dominant source at higher temperatures. To reduce this effect, deeper wells must be considered in combination with reduced available carriers (less doping). Obviously this will reduce the photocurrent as well, and a compromise between both must be established. Mathematically,

$$I_D(F)=\frac{e v_{drift} A m_w^*}{\pi\hbar^2 L}\int_{E_1}^{\infty}f^{FD}(E)T(E,F)dE$$

$$f^{FD}(E)=\frac{1}{1+e^{\frac{E-E_F}{k_B T}}}$$

$$T(E,F)=\exp\left(-\frac{4.L_b}{3eV}\left(\frac{2m^*}{\hbar}\right)^{\frac{1}{2}}\left[(V_o-E)^{\frac{3}{2}}-(V_o-E-eV)^{\frac{3}{2}}\right]\right)$$

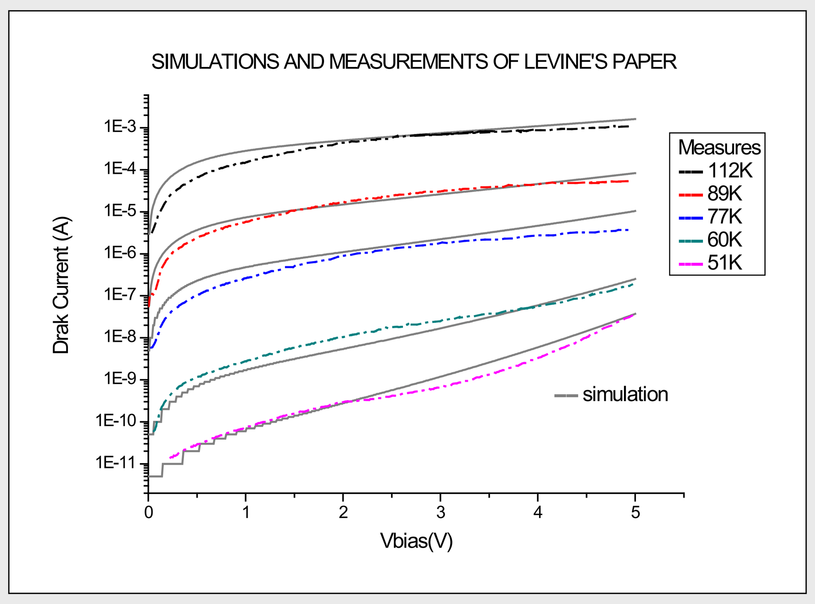
Eo < E < Vo – eV

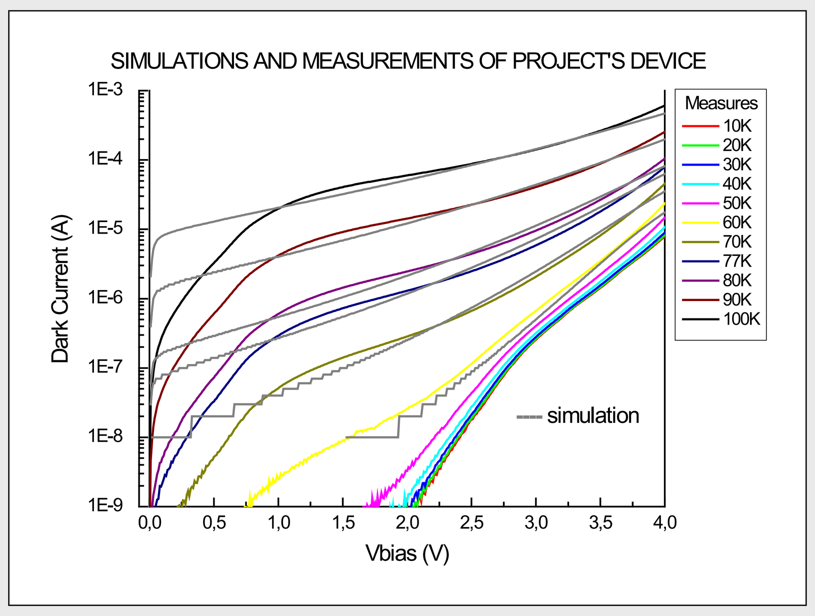
$$T(E,F)=\exp\left(-\frac{4.L_b}{3eV}\left(\frac{2m^*}{\hbar}\right)^{\frac{1}{2}}(V_o-E)^{\frac{3}{2}}\right)$$

Vo – eV < E < Vo

$$T(E,F)=1$$

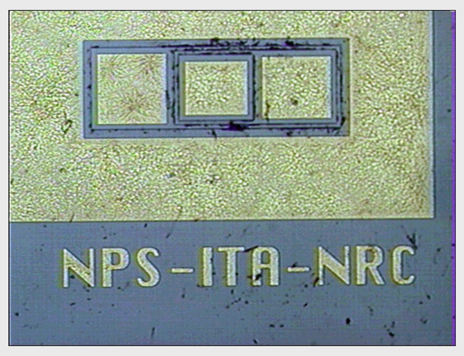
E>Vo

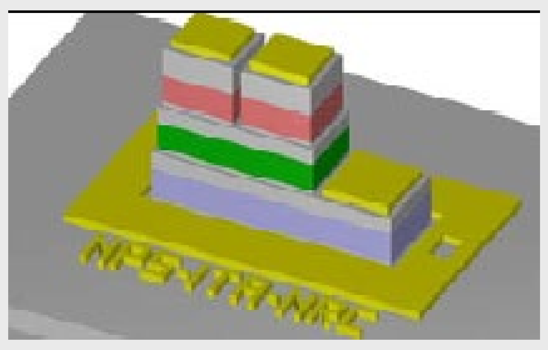
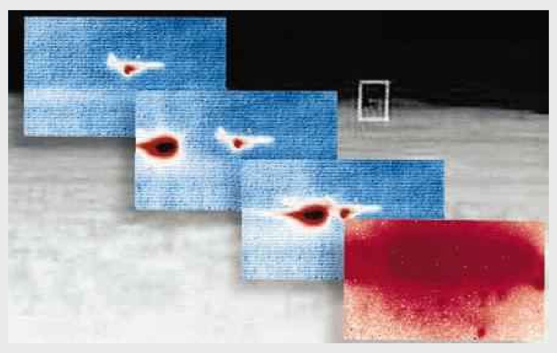




Goals

Driven by defense applications and in continuity of the work conducted at Sensor Research Laboratory (SRL) at the Naval Postgraduate School (NPS), a project to study, model, design and fabricate QWIPs was established, involving collaboration between NPS (USA), National Research Council (Canada), National University of Singapura (NUS) and Instituto Tecnologico de Aeronautica (ITA – Brazil). The first phase, the proof-of-concept of a three color IR detection in a single pixel with separate readouts was the goal. Now, the develop of mathematical models to predict the merit figures of the developed device is the objective and the first results are being presented. The LWIR merit figure was predict mathematically and may be improved. In a few time, will be presented the MWIR and NIR merit figures. Detection broadening to cover the totality of the desired detection spectra and optimization in the responsivity and detectivity were expected to be obtained in third phase. Finally, a prototype of fully operational multispectral array, with desired spectral response, responsivity and detectivity was planned to be working in the fourth and final phase.



Operational Impact

Analysing the present trends in this area, widely discussed in the last International Workshop on Quantum Well Infrared Photodetector, it is quite safe to state that the continuity of this project increases the potentiality to use QWIPs in the IR heads of the next generations of intelligent weapons, military imaging systems and defense systems. The helps consolidate the Brazilian capability to develop photodetectors for these specific applications.