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In this contribution we present a rate equation model for the simulation of InAs/InP(100) quantum dots which are used as the active material of waveguide photodetectors. Unlike the normal rate equation models in literature which are built for carrier injection and photon emission, our model is modified for the carrier extraction and photon absorption. The simulation results are compared with previous experimental results. Experimental observations are explained in terms of fundamental properties of the quantum dots, e.g. the bias voltage dependent carrier extraction rate and absorption coefficient.

Introduction

In optical coherence tomography (OCT) the wavelength range from 1.6 μm to 1.8 μm is of interest for medical and biological applications. This range lies in between two strong water absorption peaks and due to the longer wavelength compared to what is commonly used in OCT, the imaging depth can be improved since the scattering of light is reduced [1].

The photodetector is one of the key components in an OCT system. It detects the output signal from the Michelson interferometer in the OCT set-up. For application of the 1.6 to 1.8 μm wavelength range in OCT, a photodetector is required to be sufficiently sensitive to these wavelengths. We have used InAs quantum dots (QDs) on InP(100) as the active material for the photodetectors. The average size of the QDs in this material was tuned for a peak optical gain around 1.7 μm. In our previous study [2] these QD photodetectors have shown good performance in the 1.6 μm to 1.8 μm wavelength range.

To interpret and analyze the measurement results a theoretical model based on rate equations was set up. The model is based on a QD optical amplifier model where the current extraction has been included. The responsivities of several real devices have been calculated and compared to the measurement results. The spectral response as well as the absorption behavior of the QDs have also been simulated and will be discussed.

QD rate equation model

Various rate equation models have been proposed for understanding the gain properties of the QD semiconductor optical amplifiers (QD-SOAs) and lasers [3, 4, 5] and such models are used for the analysis of the relation between injected current and gain. In this contribution we present a rate equation model based on a QD-SOA model [3, 5] that has been modified for the simulation of photodetection with current extraction mechanism.

In the previous work, a rate equation model has been applied to the analysis of the gain of the QD-SOAs in the 1.6 μm to 1.8 μm wavelength range [3]. A good match was achieved between the model and the measured small signal gain spectra. Since we used the same QD active material and layer stack for the photodetectors, the QD rate equation model and several of the parameters used in [3] were modified to simulate the behaviour of the photo-absorption of the QDs. The schematic of the energy band diagram is depicted in Fig. 1 where the carrier dynamics in the model are also indicated.

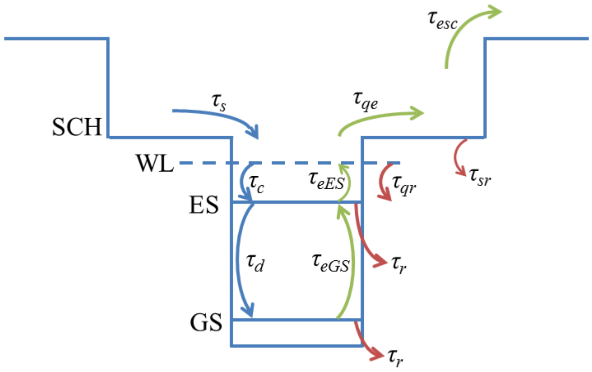


Fig. 1 The schematic of the energy band diagram of the QD active region. The carrier capture and escape rates from the states are indicated.

The model contains a separate confinement structure (SCH) layer where the carriers extracted from the wetting layer (WL) are collected. The excited state (ES) and ground state (GS) are both allocated into N sub-groups to express the inhomogeneous dot size distribution with each group representing a certain average dot size (energy level). The major modification in the model from [3] is the change from current injection to current extraction. We set the current injection in the model to zero, and add an additional carrier escape rate $1/\tau_{esc}$ from the SCH layer out of the diodes. This parameter presents the fast extraction of the photo-generated carriers due to the high electric field and it is assumed to be much faster than other capture and escape rates in the model. In the simulation, the carrier escape rate from the WL to SCH ($1/\tau_{qe}$) is used to represent the different carrier extraction rates due to different reverse-bias voltages. It is adjusted to match the simulation with the measured data for each particular value of the reverse-bias voltage.

Results and Analysis

First the relationship between responsivity, device length and reverse-bias voltage is studied. Simulations of devices with different lengths and for four bias voltages are performed with an optical input at a fixed wavelength and fixed optical power for both TE and TM polarizations. The device length is scanned from 200 μm to 2000 μm which is the range over which the experimental data are available. The simulation results are shown in Fig. 2(a) as the dashed curves. Those match the measured data very well using only the bias voltage dependent τ_{qe} as a fitting parameter. It is clear that as the device length increases, the responsivity increases at the same time since more photons are absorbed in the detector. When the device length increases to a certain value, the increment of the responsivity becomes less and the trend becomes flatter. This indicates that after reaching a certain length, almost all the photons are absorbed. Thus little improvement will be seen using longer devices. The difference in responsivity for the two polarizations is explained by using a lower absorption coefficient for the TM polarization than that of the TE polarization. The relation between $1/\tau_{qe}$ and the reverse-bias voltage resulting from matching the measurements to the simulations is shown in Fig. 2(b). It can be clearly seen that as the reverse-bias voltage increases, the carrier extraction rate increases rapidly. This is mainly due to the enhancement of the electric field in the depletion region of the diode at high reverse-bias voltages. As a result, the carrier extraction rate from the QDs increases.

Simulations for the spectral behavior of the photodetectors have also been performed using the same parameters. The simulation of the response spectrum for a 960 µm-long device for TE polarized input light is shown in Fig. 3(a). The situation is similar for TM polarization. It can be seen in the figure that for wavelengths longer than 1.6 µm, the simulation matches well with the measured spectrum. But for the shorter wavelengths below 1.6 µm, there is a clear deviation between simulations and measurements. The reason for this deviation is that the absorption coefficient of the device in the short wavelength region is underestimated. In Fig. 3(b), the calculated photon absorption coefficient α (cm^{-1}) of the device is presented for TE polarization. It shows that the calculated photon absorption in the short wavelength region is lower than that in the long wavelength region. The small signal absorption parameter has also been measured independently. Here the measured values in the short wavelength region are much higher than those in the long wavelength region (see Fig. 3(c)). It is possible that the photon absorption is underestimated due to the exclusion of the contributions from higher energy states in the QDs. Such states would not show up in the ASE spectra in forward bias, but can play a role in absorption. Also absorption in the wetting layer was not included in our model.

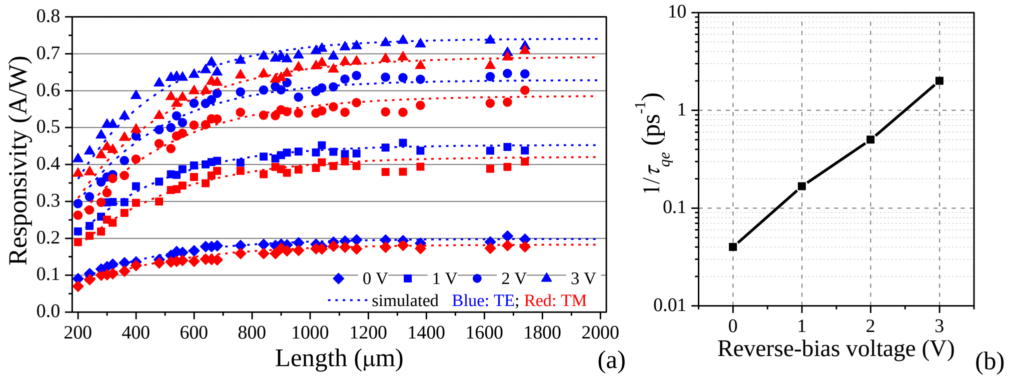
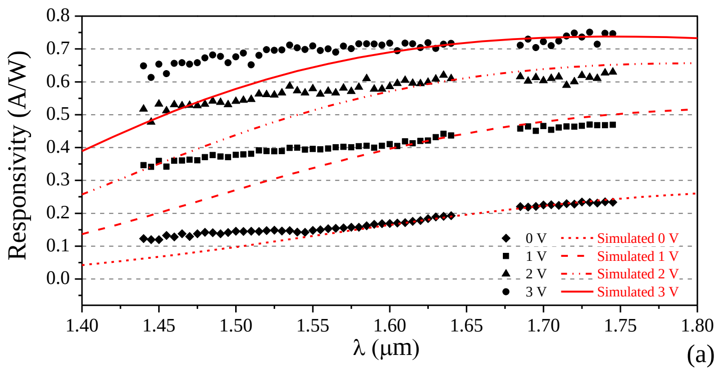


Fig. 2 (a) The measured and simulated responsivities of devices with the lengths ranging from 200 µm to 2000 µm at a wavelength of 1640 nm. The measurements and simulations are done under four different reverse-bias voltages and for both polarizations. (b) The τ_{qe} at different reverse-bias voltages.



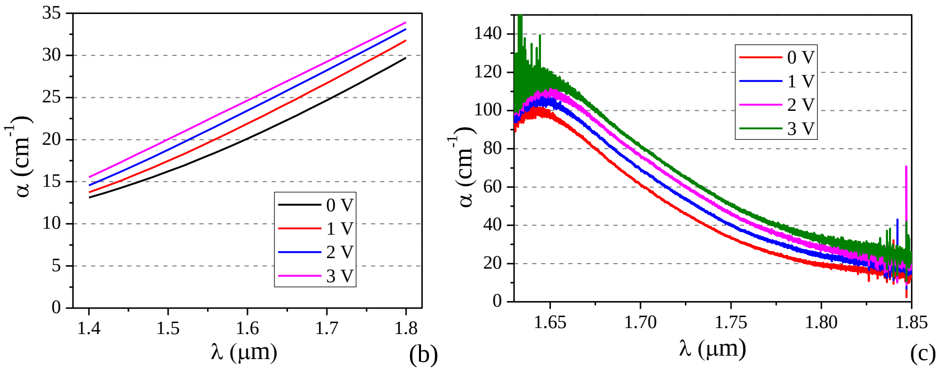


Fig. 3 (a) The spectral simulations of a 960 μm-long device for TE polarization. The measured spectra are also shown for comparison. (b) The total photon absorption of the QDs calculated by the rate equation model (for TE polarization). (c) The measured absorption spectra for different reverse-bias voltages (for TE polarization, including pure propagation loss of the optical mode).

Conclusion

In this paper we have presented the simulation results of QD photodetectors using a modified QD amplifier rate equation model as well as comparison to experimental results. A major modification of this model is the change from carrier injection to the carrier extraction of the dots. The simulations of responsivities with various lengths showed a good match with the measurement results using only one fitting parameter. The relation between carrier extraction rate and reverse-bias voltage was determined. Simulations on the spectral responses were also performed. The model matched well with experiments in the long wavelength region but showed an obvious deviation in short wavelength region. This is attributed to the underestimation of the contributions from higher energy states of the dots and possibly the wetting layer.

Acknowledgements

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References

[1] V. M. Kodach, J. Kalkman, D. J. Faber, and T. G. van Leeuwen, "Quantitative comparison of the OCT imaging depth at 1300 nm and 1600 nm," Biomed. Opt. Express, vol. 1, 176-185, 2010.

[2] Y. Jiao, B.W. Tilma, J. Kotani, R. Notzel, M.K. Smit and E.A.J.M. Bente, "An InAs/InP(100) QD Waveguide Photodetector for OCT application," Proceedings of the European Conference on Lasers and Electro-Optics 2011 and the European Quantum Electronics Conference (CLEO Europe - EQEC 2011), 22-26 May 2011, Munich, Germany.

[3] B. W. Tilma, M. S. Tahvili, J. Kotani, R. Notzel, M. K. Smit, and E. A. J. M. Bente, "Measurement and analysis of optical gain spectra in 1.6 to 1.8 μm InAs/InP (100) quantum-dot amplifiers," Opt. Quant. Electron., vol. 41, 735-749, 2009.

[4] M. Sugawara, K. Mukai, Y. Nakata, H. Ishikawa, and A. Sakamoto, "Effect of homogeneous broadening of optical gain on lasing spectra in self-assembled InxGa1-xAs/GaAs quantum dot lasers," Phys. Rev. B, vol. 61, 7595, 2000.

[5] M. Gioannini, A. Sevega, and I. Montrosset, "Simulations of Differential Gain and Linewidth Enhancement Factor of Quantum Dot Semiconductor Lasers," Opt. Quant. Electron., vol. 38, 381-394, 2006.