Dark current modeling of interband cascade infrared photodetectors

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BIOGRAPHY

Robert T Hinkey: Mr. Robert Hinkey was born in Baltimore, Maryland in 1985. He received a Bachelor of Science in Physics in 2007 from Loyola College in Maryland. Since 2008, he has worked in the OU Quantum Devices group under Prof. Rui Yang, conducting research on semiconductor devices based on quantum structures. He received a Master's Degree from the University of Oklahoma in Engineering Physics, and is currently pursuing the Ph.D degree, which he aims to complete in 2013. His doctoral dissertation topic is the design, modeling, and characterization of interband cascade structures for mid-infrared photodetectors and photovoltaic devices for energy conversion. He also collaborates with other members of the group on the development of long-wavelength interband cascade lasers.

TECHNICAL ABSTRACT

Interband cascade infrared photodetectors (ICIPs) [1-3] employ a flexible device architecture designed to overcome short diffusion lengths and achieve high performance in photovoltaic devices based on InAs/GaSb superlattice (SL) absorbers. This is done by substituting the standard long single absorber (typically > 2.0 μm) for a group of shorter discrete absorbers (*e.g.* 0.1-0.2 μm). The conduction and valence bands of adjacent absorbers are connected in series using an interband tunneling heterostructure. This heterostructure consists of an electron barrier formed from GaSb/AlSb quantum wells (QWs) and a hole barrier formed from InAs/AlSb QWs, and is designed to facilitate a preferred carrier transport direction. The absorbers are sandwiched between the interband tunneling heterostructures, and the device exhibits the rectifying behavior required for photovoltaic operation. This architecture is similar to the "stacked multijunction" approach, which has been proposed in the past for realizing uncooled operation in MCT-based photovoltaic detectors [4], but has not received much attention in the literature. In this work, we will present our initial efforts in modeling ICIPs under non-equilibrium conditions. Here, we focus on the case where the dark current is solely due to generation-recombination processes in the absorber. The thermalization of carriers (due to drift-diffusion processes) within the absorber and interband tunneling heterostructure region is assumed to occur on a timescale much faster than the generation-recombination processes. Under this approximation, the holes within the valence band of one absorber are in equilibrium with the electrons in the previous absorber, and thus share a common chemical potential.

This represents the ideal operation condition which we aim to achieve when designing the ICIP structures. The electron and hole carrier density profiles were found using a Schrodinger-Poisson solver. We assumed that for a *p*-type absorber, the generation-recombination rate within an absorber could be written:

$$U = \frac{n(V_{stage}) - n_o}{\tau}, \qquad \text{(Eq. 1)}$$

where V_{stage} is the voltage across the stage, $n(V_{stage})$ is the minority carrier density in the absorber at a given V_{stage}, n_o is the minority carrier density in the absorber at equilibrium, and τ is the characteristic time for minority carrier generation/recombination in the absorber. In this work we assumed τ = 10 ns for the doped p-type absorber [5] at all temperatures since SRH processes are relatively temperature-insensitive.

The structure we considered was an ICIP with 30-period (~ 0.14 μm) *p*-doped InAs/GaSb SL absorbers. The calculated cutoff wavelength for this structure found from the Schrodinger-Poisson solver was ~3.25 μm at 77 K and ~3.9 μm at 300 K. Note this is not exactly same as the experimentally measured cutoff wavelength of ~4.0 μm at 77 K and ~5.0 μm at 300 K. Our calculations indicated that under ideal operation, the driving bias is primarily applied to the interband tunneling heterostructure. This confirms our speculations based on observations of the voltage-dependent

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photocurrent in earlier ICIPs [3]. There is also an "internal" electric field present, even at zero bias. The internal field is caused by a large accumulation of positive and negative charge on either side of the electron and hole barriers. Further simulations indicate this field can be reduced with *p*/*n* doping of the electron/hole barriers, which may aid in creating the desired fast relaxation. Fig. 1 shows the calculated carrier density within the absorber, as well as the current density evaluated from Eq. 1 as a function of bias voltage for a *single* ICIP stage. Under ideal operation, the current is controlled by the exchange of minority carriers between the hole barrier and the absorber. Full depletion of minority carriers, and hence reverse bias saturation occurs at fairly low voltages.

Although our current devices are operating far from the theoretical limit given by the model, the results have provided some insights on the nature of the device transport at low and high temperatures. The calculated generation-recombination currents at low temperature are much lower (many orders of magnitude) lower than any of the values we have measured in our devices. This indicates that that there are additional transport current channels that dominate the low temperature transport. This also shows that even though ICIPs in the 3-5 µm range have demonstrated very low dark current at low temperature ($R_oA \sim 3.6 \times 10^8\ \Omega m^2$ at 80 K [6]), significant improvement is still possible by designing the structure to suppress the leakage through these additional channels. It is not currently clear what the mechanisms for this current are, although we speculate it may be due to defect-assisted tunneling. At higher temperature, the difference between the calculated and measured results is still 2-3 orders of magnitude lower than any of our observed dark currents. Also, even at high temperature, the measured current-voltage characteristics do not show the saturation at high voltages that would be expected for a fully depleted absorber. Thus, even at high temperatures there could be additional leakage current channels, which lead to higher dark current levels. Our current work is concentrated on identifying these additional leakage current channels so that steps may be taken in the device design to suppress them.

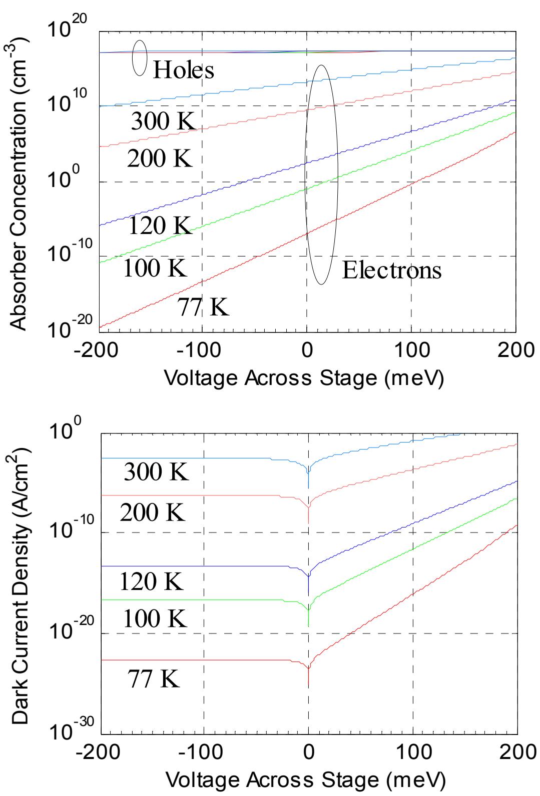

Figure 1: Voltage and temperature behavior for (a) carrier concentration of minority electrons and majority holes in the absorber and (b) generation-recombination current density.

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