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An analysis of electrical and optical characteristics of a type II superlattice for optical switching applications

M Rahman, A S M S Rouf and F M Mohammedy

Department of Electrical and Electronic Engineering, *Bangladesh University of Engineering and Technology*, Dhaka -1000, Bangladesh.

E-mail: muktadir@ieee.org

Abstract. The present work demonstrates an analysis of electronic and optical characteristics of InAs/GaSb Type II superlattice based photodetectors. The electronic characteristics are analyzed by developing a model of the Type II superlattice. The 8 band k.p method is implemented to deduce the wavefunctions. The effects of temperature on zero-bias resistance-area product (R_0A) are also included in the model. The newly proposed M-Structure design method is also implemented for our model. Electrical and optical properties of the material such as dark current density and absorption coefficient are calculated. At 50mV reverse bias, the dark current density is found equal to 1.5×10^{-4} A/cm^2. These calculations are done based on the approximation based models of reflectivity. These results were used to demonstrate the variation of optical properties with applied bias voltage to be used as a novel optical switching technique in WDM based communication networks.

1. Introduction

In recent times III-V semiconductor materials have achieved growing interest for potential new device applications. This interest originates from their excellent optical and electronic properties. One particular example is the InAs/GaSb broken gap Type II superlattice (T2SL) which is finding ever increasing applications in lasing operations and as IR photodetectors for larger effective mass and tunability of the energy gap.

Novel engineering techniques have contributed in the significant reduction of Auger Recombination as well. But the greatest advantage is undoubtedly the tunability of cutoff wavelength between 3μm to 20μm, covering almost the entire EM wave spectrum. Currently the development of these materials has entered a phase where cost effectiveness and mass production have become important concerns. As a result, numerous research activities are currently being conducted to counter the problems involved.

In this paper, such a device was modeled with experimentally verified parameters using the 8 band k.p method. These techniques have been employed only for the LWIR and MWIR range until now. Our results were matched with experimental results and found to be consistent. We demonstrated a correlation between the bias voltage and the cutoff wavelength of the absorption coefficient, which has the potential to be used as a novel optical switching technique within the LWIR range.

2. Modeling of the type II superlattice

The wave functions of the superlattice structure were determined using the 8 band k.p method. The appropriate boundary conditions were applied at the interfaces between layers and the Schrodinger's equation was solved. For this purpose, the interactive education tool nextnano™ was used. The miniband approximation for the T2SL based structure was successfully included in the simulation scheme.

The M-structure is constructed by inserting a thin barrier of AlSb in the middle of the GaSb layer of the superlattice[1,3,4] to enhance the carrier effective mass and provide better control over the band edges. The wavefunctions of the M-Structure was determined through the same method.

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3. Characteristics of the T2SL Structure

The diffusion current due to thermally generated minority carriers diffusing into the depletion region is given by

$$J_{diff} = n_i^2 \sqrt{qkT} \left(\frac{D_p}{N_d L_p} + \frac{D}{N_a L_n} \right) \left(e^{qV/kT} - 1 \right) \tag{1}$$

The current due to generation and recombination of electron-hole pairs in the depletion region is approximately

$$J_{GR} = \frac{q n_i d(V)}{\tau_{GR}} \frac{\sinh(-qV/2kT)}{q(V_{bi} - V)/2kT} f(b),$$
$$f(b) = \int_0^\infty \frac{du}{u^2 + 2bu + 1}, \text{ where } b = \exp\left(\frac{-qV}{2kT} \right) \tag{2}$$

The Zener tunneling current is given by

$$J_T = \frac{q^3 F(V) V}{4\pi^2} \sqrt{\frac{2m_T}{E_g}} \exp\left(- \frac{4\sqrt{2m_T} E_g^{3/2}}{3q F(V)} \right) \tag{3}$$

The Trap-assisted Tunneling Current is given by

$$J_{trap} = \frac{q^3 m_T V M^2 N_t}{8\pi^3} \exp\left(- \frac{4\sqrt{2m_T} (E_g - E_t)^{3/2}}{3q F(V)} \right) \tag{4}$$

If the total leakage current is consisted of diffusion, generation- recombination and surface leakage current, it can expressed as,

$$J_T = J_D + J_{gr} + \left(\frac{p}{A} \right) J_S \tag{5}$$

Where p/A is perimeter-to-area ratio of the diode. The surface leakage current J_S can be disregarded due to its very low value.
The curve of Current vs. Reverse Bias for the M-Structure has been displayed in the following figure. The device area was taken to be 300µm×300µm [2].

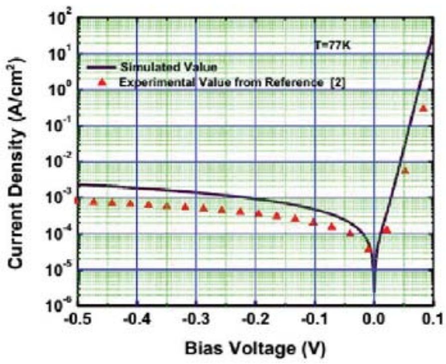

Figure 1. Current Density vs. Bias Voltage Characteristics of M-Structure Design.

5. Novel optical tuning applications in WDM

The cutoff wavelength obtained from the absorption coefficient was plotted against variations of applied bias voltage. As evident from the figure, a negative bias of 0.1 volt displays a variation of almost 50nm. The channel spacing for WDM is 0.8nm [6]. This clearly implies that the T2SL based photodiode has a distinct advantage of tunability over a vast range which may be very effective in WDM networks.

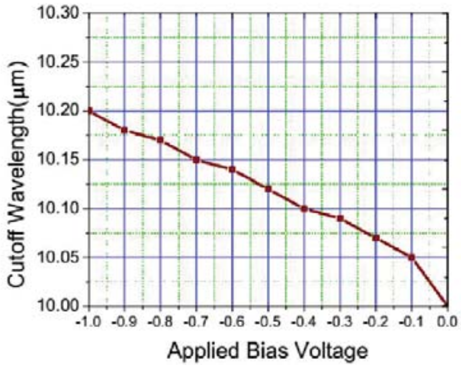

Figure 2. A variation of Cutoff wavelength with Applied Bias Voltage.

Temperature is a very important consideration in any photo detection scheme. A variation of the cutoff wavelength of the basic structure against the temperature was also displayed. This plot also displayed a significant variation in the cutoff wavelength.

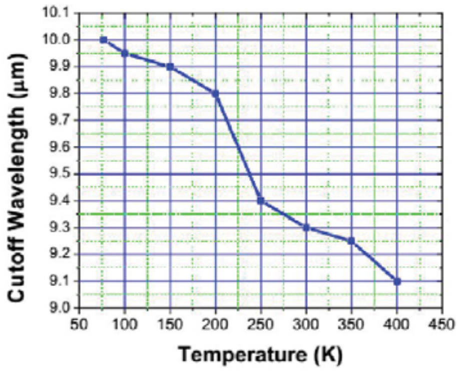

Figure 3. A variation of Cutoff Wavelength with Temperature.

This variation of the cutoff wavelength indicates that the T2SL based InAs/GaSb photodetector may be used in a wide range of temperature scale. As seen from fig. 4, a variation from 400K to 77K displays a change of almost 1 μm in cutoff wavelength.

This discrepancy, that can be seen in some of the simulated curves, can be attributed to the fact that, we did not put in the substrates between the superlattice structure, as a result, the wavefunctions are transmitted instead of reflecting inside the superlattice. This caused a minor disparity in the results of the current density and detectivity simulations when compared with experimental curves.

6. Conclusion

This analysis of the electrical and optical properties effectively demonstrates that the Type-II superlattice is a promising material system, viable for the cost reduction and size expansion of infrared imagers in the third generation. The dark current of 1.5×10^{-4} A/cm^{2}at 50mV reverse bias also displays satisfactory match with experimental values. The M-structure model also displayed promising results. The value of dark current density at 50 mV reverse bias was found to be 5×10^{-4} A/cm^2. A change in temperature also displays change of almost 1µm in cutoff wavelength. The superlattice based photodetector can become the material of choice for the IR camera market. Moreover, WDM promises to be the central technology in the all-optical networks of the future and our research provides the scope for a control parameter of the WDM based network. The modeling and analysis carried out in this thesis work can undoubtedly contribute to the performance enhancement of such photodiodes for the detection of wavelength in the near to mid infrared range.

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