Design and Analysis of Quantum Dot Based Avalanche Photodiode with Intersubband Multiplication

Amir Yousefli[1], Mahdi Zavvari[2], Kambiz Abedi[3]
1- Department of Electrical Engineering, Islamic Azad university, Ahar Branch, Ahar, Iran.
Email: amir.yousefli@yahoo.com
2- Department of Electrical Engineering, Islamic Azad university, Urmia Branch, Urmia, Iran.
Email: m.zavvari@iaurmia.ac.ir
3- Department of Electrical Engineering, Shahid Beheshti, University, Tehran, Iran.
Email: k_abedi@sbu.ac.ir

Received: September 2013 Revised: December 2013 Accepted: February 2014

ABSTRACT:
This article presents an avalanche photodiode with quantum dot layers in its active region which operates at 10µm. Performance of this structure is based on intersubband impact ionization phenomenon in quantum dots. The proposed detector requires lower energy threshold for the onset of avalanche phenomenon, hence it can work in lower operating voltages. In this paper, by presenting a theoretical approach for calculation of intersubband transition rate and electron-electron interaction, the photo-generated current is modeled and consequently the responsivity is calculated. Results show that peak responsivity about 1.9 A/W can be obtained at a voltage of 14V. Also the dark current is modeled and calculated at different temperatures and applied voltages.

KEYWORDS: Quantum Dot, Avalanche Photodiode, Intersubband Impact Ionization, Responsivity, Dark current.

1. INTRODUCTION

Mid and long infrared photodetectors have been studied extensively by researchers for their wide applications in the fields of telecommunications, aerospace, and medical in recent years[1]. Achieving a detector with high efficiency and performance has encountered some challenges to researchers in recent years [2]. On the other hand, avalanche detectors at telecommunication wavelength with high efficiency are suggested in which using impact ionization phenomena is used for avalanche multiplication of photo-generated carriers [3-4]. However, to achieve optimal performance in avalanche detectors, absorption and multiplication regions are considered separated from each other. In the bulk multiplication region the type of impact ionization is interband in which a pair of electron- hole generated as a result of high energy carrier impacting to lattice. Regarding the higher required energy threshold for achieving interband impact ionization which leads to higher operating bias, in this article the detector is designed to use intersubband impact ionization. It is obvious that intersubband energy is much smaller than the interband. Therefore, for such device the threshold voltage is expected to be lower than other types. For this purpose, it is needed to have quantum confined structures such as quantum well, quantum wire or dot in active region. Recently, various types of detectors such as quantum well and quantum dot detectors which their performance were based on transitions of intersubband have been studied for mid and long wavelengths [5]. However, by extending the use of quantum dots in electronic devices, these structures are also used because of their unique advantages in photo-detectors. Most of these features arise from three-dimensional confinement of electron in these structures which leads to less temperature dependence and lower dark current in detectors made by these structures [6]. In this paper a p-i-n detector is presented whose active region consists of QD layers. For such detector, intersubband absorption in QD layers results in creation of photo-generated electrons which are moved in the presence of applied electric field. However if the electric field is high enough, the energy of generated electron can be increased and cause an intersubband impact ionization in incidence to next QDs. This leads to increase in photocurrent and hence higher responsivity of detector. To rate how efficient this detector is, we calculate its performance characteristics based on developed models. We obtain the energy levels and wavefunctions for a QD by numerical solution of Schrodinger equation and the intersubband absorption coefficient is then calculated for different incident energies. The intersubband impact ionization for QD layers is calculated based on a closed-form model derived from Fermi's golden rule and finally the responsivity can be calculated. We also study dark current characteristics based on different terms contributing in current geneation.

2. INTERSUBBAND ABSORPTION

It is necessary to calculate the energy levels of quantum dots, so we solve Schrodinger equation for dots with pyramid shapes. Then by obtaining momentum matrix element, absorption coefficient can be calculated from [7].

$$\alpha(\hbar\omega)=\frac{\pi e^2}{\varepsilon_0 n_0 c m_0^2 V_{ac}}\cdot\frac{1}{\hbar\omega}\sum\left|\bar{a}P_{fi}\right|^2 N(\hbar\omega) \qquad (1)$$

where V_{ac} is the average dot volume, $\bar{a}$ is the polarization of the light, e is the electron charge, P_{fi} is the momentum matrix element between states i and f , C is the light velocity, n_0 is the refractive index, ε_0 is the permittivity constant, $N(\hbar\omega)$ is the electron density of states with effects of inhomogeneous and homogeneous broadening mechanisms(IHB and HB). Since quantum dots are formed with different sizes and shapes, we model such variations by inhomogeneous broadening while the homogeneous broadening accounts for phonon scattering mechanisms.

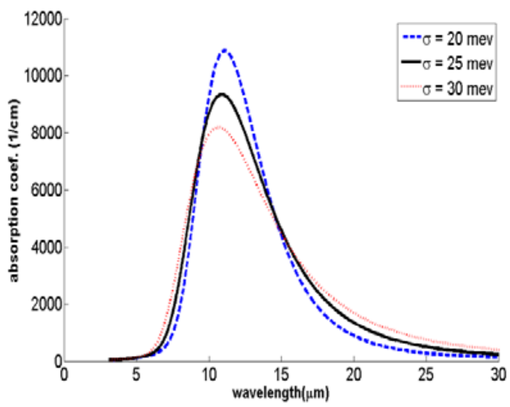

Fig .1. Absorption coefficient against wavelength at different IHB

Fig (1) shows calculated absorption coefficient for different values of IHB with $\gamma=5mev$. The size of dots is assumed $14\times14\times7$nm and the peak absorption is at $\lambda=10\mu m$. Inhomogeneous broadening energy changes from 20mev to 30mev. According to figure increase of IHB leads to decrease in peak absorption, as for the $\sigma=25mev$, absorption coefficient is about $10^4 cm^{-1}$.

3. INTERSUBBAND IMPACT IONIZATION

As the photo generated electron travels in the active region, it can excite the ground state electron of next QD by intersubband impact ionization if its energy is high enough. Because of lower transition energy, it is expected that intersubband impact ionization has lower threshold energy than interband which occurs in bulk materials. Fig (2) illustrates detail of this mechanism from absorption of mid-IR photons to generation of excess carriers by avalanche multiplication.

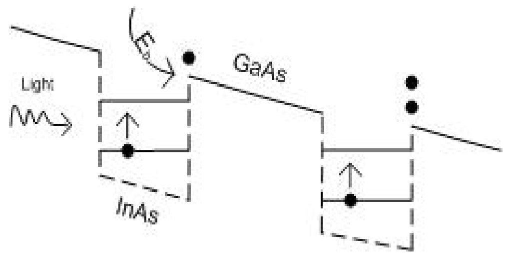

Fig .2. Illustrate tunneling and impact ionization mechanism in quantum dots

From figure the photo-generated electrons of wave vector k and kinetic energy E_k take newer values of the energy and momentum $E_{k'}$ and k' after interaction via coulomb potential.

The corresponding transition rate is given by [8].

$$W=\frac{2\pi}{\hbar}\sum_n\sum_{u'}\sum_{k'}\sum_u\left|\langle n,u',k'|V|1,u,k\rangle\right|^2\delta(E_f-E_i) \qquad (2)$$

Where V is the coulomb potential, 1 and n are ground and excited levels in dot, u and u' are perpendicular momentum of dot before and after scattering. k and k' are electron wave vectors before and after interaction, respectively. After evaluating the interaction matrix element, we convert $\sum_{k'}$ to the integral over the volume element. So we can rewrite transition rate as ($k>>k'$) [9]:

$$\langle k'|V|k\rangle=\int\psi_{k'}^*\frac{e^2}{4\pi\varepsilon(r_1-r_2)}\psi_k \qquad (3)$$

$$W=\int\frac{dq}{q^3}\frac{N_s\left(e^2m_b^*\right)^2J}{2\pi(\varepsilon k)^2\hbar^4} \qquad (4)$$

where N_s the two dimensional electron density and J is the incident flux. Finally, by performing a mathematical operation and setting the limits of integration $q_{\min}=k'-k$ and $q_{\max}=k'+k$, we obtain transition rate which dependent on $E_k=\hbar^2k^2/2m_b^*$ as:

$$W = \frac{N_s J e^4}{4\pi\varepsilon^2 E_k^2}\left(1-\frac{\Delta E}{E_k}\right)^{1/2} \quad (5)$$

4. RESPONSIVITY

Responsivity is the ratio of output signal to the incident power. Hence we need to calculate the photocurrent first. According to transition rate, ionization coefficient is given by $\beta(E_k)=\rho W/J$ where ρ is the tunneling probability. For a distribution of energies, we assume a Gaussian distribution which can be described by a normalized distribution function.

$$f(E_k) = \frac{1}{\sigma\sqrt{2\pi}}\exp[-(E_k - E_p)^2 / 2\sigma^2]$$

where $E_p = (eV_p - E_b)$, E_b is approximately equal to the energy difference between the top of the tunneling barrier and quantum dot excited state E_2. $V_p = V_a/50$ which V_a is the applied voltage.

The average ionization coefficient is then calculated from:

$$\beta = \int \beta(E_k) f(E_k) dE_k \quad (6)$$

In order to obtain the responsivity of photodetector, first we calculate its photocurrent which can be calculated from:

$$I_p = \frac{e}{50}\sum_{x=1}^{50}(50-x)\left[(\alpha f \rho P\lambda/hc)(1+\beta)^x\right] \quad (7)$$

then we use relation $R = I_p/P$ to calculate the responsivity. P is the incident power.

$$R = (\frac{e\lambda}{hc})\alpha f \rho \frac{1}{50}\sum_{x=1}^{50}(50-x)(1+\beta)^x \quad (8)$$

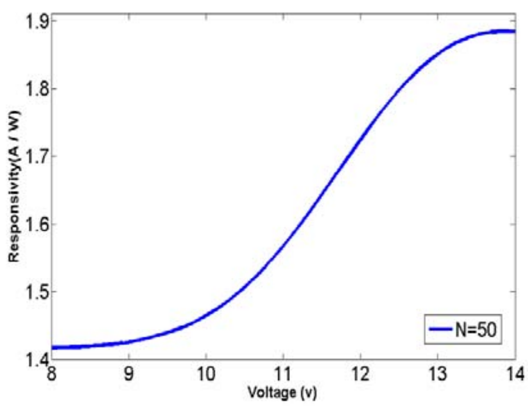

Fig .3. Responsivity against voltage at N=50 period

In the mentioned relations, the number of QD layers is assumed to be 50. Fig (3) shows calculated responsivity as a function of applied bias. According to the figure, increasing the bias results in higher responsivities. The reason arises from the fact that in the presence of higher fields, the photo-generated electron takes higher energy and hence the impact ionization rate increases resulting in avalanche gain. Hence one can expect that higher photocurrent and consequently higher responsivity occurs for increased voltages. Responsivities as high as 1.9 A/W are obtained for such situation.

5. DARK CURRENT

Dark current is the current that flows in the absence of light and is strongly temperature dependent. Because of noisy behavior, lower values for this quantity is desired. For our structure it is assumed that the dark current is originated from different mechanisms as[10]:

$$I_D = I_{D,qd} + I_{D,avalanche} \quad (9)$$

where $I_{D,qd}$ is the thermal current of QD layers which can be calculated from:

$$I_{D,qd} = q\upsilon(V)A\int N(E) f(E) T(E,V) dE \quad (10)$$

where υ is the electron drift velocity in the barrier material, $T(E,V)$ is the tunneling probability across the barrier, $f(E)$ is the Fermi function, $N(E)$ is the density of states considering the contribution of QDs, wetting layer and bulk and can be written as:

$$N(E)=\sum_i \frac{2N_D}{L_p}\frac{1}{\sqrt{2\pi}\sigma}\exp\left(-\frac{(E-E_i)^2}{2\sigma^2}\right)+ \frac{4\pi m*}{L_p \hbar^2}H(E-E_w)+\frac{8\pi\sqrt{2}}{\hbar^3}m^{*3/2}\sqrt{E-E_c}\cdot H(E-E_c) \quad (11)$$

where N_D is the dot density, L_p is the absorption region length, $H(E)$ is the step function. First term in eq. (11) is quantum dot density of states, second term is wetting layer density of state and last term is density of state in bulk barrier material. E_i, E_w, E_c are quantum dot energy levels, wetting layer and conduction band edge respectively.

$I_{D,avalanche}$ is the current of other terms of dark current in multiplication region consisting of generation and leakage currents and is given by [11]:

$$I_{D,avalanch} = \frac{qn_i AW}{\tau_{eff}}\left(1-\exp\left(\frac{-qV}{KT}\right)\right)+\frac{V}{R_s} \quad (12)$$

where n_i is the intrinsic carrier density, τ_{eff} is the carrier lifetime, and R_s is the leakage resistance.

Fig (4) shows calculated dark current as a function of voltage bias for different temperature. According to the figure, higher temperatures considerably increase the dark current. The reason is because of thermally

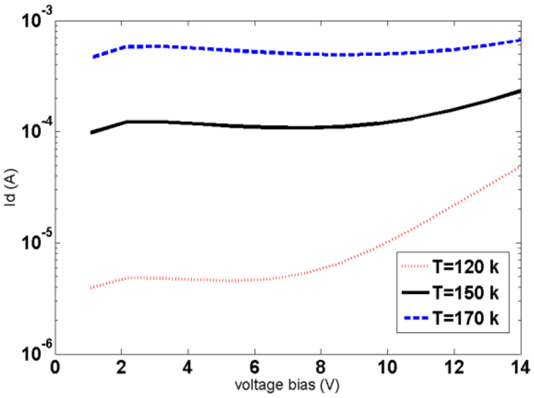

Fig 4. Dark current against bias for different temperature

nature of electrons distributed in energy space. On the other hand applied bias have considerable impact on electron drift velocity and hence result in growing the dark current. Some of parameters used in our calculations are listed in Table 1.

Table 1: Parameters used in our calculations

$R_s\,(\Omega)$	σ (mev)	W(nm)	$N_D\,(cm^{-2})$	Parameter
10^{10}	25	200	5×10^{10}	Values

6. CONCLUSION

In this paper, an avalanche photodiode is presented with quantum dot layers in its active region which is designed for operation at 10µm wavelength. Intersubband impact ionization accounts for avalanche gain in this structure and hence higher responsivity and lower threshold voltage is expected. We calculated the intersubband ionization rate and coefficient from Fermi's golden rule and derived an analytical expression for responsivity. We also calculated the dark current of detector as a function of bias and temperature. Results predict responsivity about 1.9 A/W for this detector.

REFERENCES

1) J., Philips, P., Bhattacharya, S. W., Kennerly, D. W., Beekman, and M., Dutta,"**Self-assembled InAs-GaAs quantum-dot intersubband detectors**," *IEEE J. Quantum Electron.*, Vol. 35, pp. 936-943, June 1999

2) A., Rogalski. " **Infrared detectors: status and trends**" *prog. Quant.Elect.*, Vol. 27, pp. 59-210, 2003

3) A. M. Barnett, J. E. Lees, D. J. Bassford, J. S. Ng, C. H. Tan, R. B Gomez. " **Modeling results of avalanche multiplication in AlGaAs soft X-rat APDs**", *Nucl.Instr. and meth. A 626-627(2011) 25-30.*

4) T., Nakata, I., Watanabe, K., Makita, and T., Torikai, "**InAlAs avalanche photodiodes with very thin multiplicationlayer of 0.1 _m for high-speed and low-voltage- operation optical receiver**," *Electron.Lett.36(21),* pp. 1807–1808 2000.

5) M., Zavvari, V., Ahmadi, A., Mir and E., Darabi," **Quantum dot infrared photodetector enhanced by avalanche multiplication**" *electronics letters,* Vol. 48, NO. 10 2012.

6) J. C., Campbell, A. Madhuka, " **Quantum – dot infrared photodetectors**" *J. IEEE.*, Vol. 95, No. 9, September 2007.

7) B., Kochman, A. D., Stiff-Roberts, S., Chakrabarti, J. D., Philiphs, S., Krishna, J., Singh and P. Battacharya, " **Absorption, Carrier Lifetime, and Gain in InAs/GaAs Quantum Dot Infrared Photodetectors**", *J. IEEE,* Vol. 39, No. 3, March 2003.

8) B.K., Ridley, " **Quantum Process in Semiconductors** ". *Oxford, U. K: Clarendon, Third Edition,*15 July 1993.

9) L. D., Landau , E. M., Lifshitz," **Quantum Mechanics-Non-Relativistic** ", *Theory, 3rd ed.Pergamon, Elmsford, New York,* 1997.

10) X., Su, S., Chakrabarti, P., Bhattacharya, G., Ariyawansa, and. G. U., Perera, " **A Resonant Tunneling Quantum Dot Infrared Photodetector**" *IEEE. J. Quant. Elect,* Vol. 41, NO. 7, pp. 974-979, 2005.

11) K., Sugihara, E., Yagyu, and Y., Tokuda, " **Numerical Analysis of Single photon Detection Avalanche Operated in the Geiger mode**" *J. Appl. Phys,* Vol. 99, 124502 (2006).