A new approach for modeling of dark current characteristics of quantum wire infrared photodetectors

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In order to study the dark current characteristics in a quantum wire infrared photodetector (QRIP), the average number of electrons in quantum wires (QRs) must be got, which is mostly too complicated. In this paper we give a simple formula to calculate the average number of carriers in a quantum wire (QR) that can be easily evaluated by mathematical softwares, and then we use this formula to study dark current characteristics of a quantum wire infrared photodetector (QRIP).

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Quantum wire infrared photodetectors (QRIPs) have been under focused consideration among the new nano-sized intersubband photodetectors, mostly because of their low dark current[1], wide spectral range, ability of absorbing the normal incident light[2], and high bit rate of data transfer[3]. Confinement of electrons in one dimensional quantum wires will lead to discrete bound energy levels so that the capture probability and relaxation time of electrons will increase[2]. These phenomena eventually give lower dark current, more enhanced responsivity, and better signal-to-noise ratio. The materials of their vertical-based nano-heterostructure have been under different examinations[2,3]. Among some qualifying materials, for example, GaAs, AlGaAs, and InGaAs, have been chosen[1,3]. One of the most important parameters of QRIPs is the dark current, which flows even without the presence of the incident light, so it is taken as a major part in noise of QRIPs. The major contribution to dark current formula in QRIP was carried out by V. Ryzhii[4,5].

Different treatments have been applied to model the characteristics of QRIPs[6-15]. In this paper, we utilize a new simple mathematical formulation to consider the characteristics of a QRIP under dark current condition.

Under dark current condition, the space charge in the active region of a QRIP changes due to two counteracting processes: electron capture into quantum wires, and thermo emission of electrons from them. Then the dominant source of dark current in QRIPs is the thermionic origin. Let's consider the simplified structure of a QRIP shown in Fig.1.

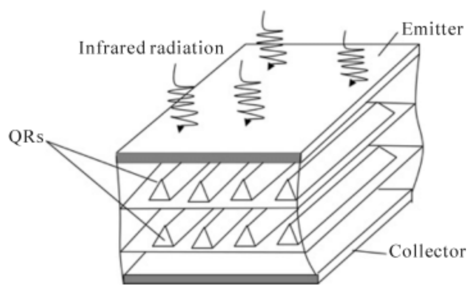

Fig.1 Simplified structure of a QRIP

Under no light exposure, we assume that there are $\{k=1, 2, \ldots, M\}$ layers of QR arrays, each layer containing electrons with average number of $<Nk>$. In the active region of a QRIP, the drift current due to electrons captured and excited from QRs is governed by[1]:

$$\langle j_{\rm d}\rangle = q\sum_{\rm QR} G_k/P_k \ , \tag{1}$$

in which $j_{\rm d}$ is the dark current, density q is the electron charge, G_k is the electron thermo – excitation from QRs, and P_k is the probability of electron capture. For voltages satisfying $qV> qV_0 >>KT$, the mobile carriers injected from the emitter contact reach the first QR layer plane and then overcome the barrier height ($qV_{\rm o}= E_{\rm QR}$). Now the dark current formula takes this form[1]:

$$j_{\rm d} = j_{\rm m} \ \exp(\frac{q(\langle\varphi\rangle+\varphi)}{KT}) \ , \tag{2}$$

where $j_{\rm m}$, φ, K and T represent maximum current density

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injected from emitter, potential in the QR base plane, where symbol <…> means averaging over the base plane, Boltzman constant and temperature, respectively.

To calculate the average potential, we begin with the Poisson's equation[2]:

$$\frac{d^2 <\varphi>}{dz^2} = \frac{4\pi q}{\varepsilon}\sum_{k=1}^{M}(\langle N\rangle \Sigma_{QR} - \Sigma_D) . \tag{3}$$

And the potential in the QR base plane is given by[1]:

$$\varphi = \frac{2\sqrt{2}}{\varepsilon} < N > q(0.36 - \frac{1}{2}\sum{}_{QR}(x^2+y^2)) . \tag{4}$$

By numerical solution of Eq.(3) and two boundary conditions: $\varphi|_{z=0}=0$ (at the emitter) and $\varphi|_{z=(M+1)L}=V$ (at the collector), we get[1]:

$$<\varphi> = \frac{V}{M+1} - \frac{2\pi qML}{\varepsilon}(< N > \sum{}_{QR} - \sum{}_{D}) . \tag{5}$$

The capture probability in a QR has this form[1]:

$$C = P_k(\frac{N_{QR} - < Nk >}{N_{QR}})\exp(\frac{-q^2 < Nk >}{CKT}) , \tag{6}$$

in which $C = 0.36\sqrt{a_{QR}}$ is the capacitance of a QR and ε is the matter permittivity.

Now we solve Eq.(6) to find <*Nk*>. As <*Nk*> is the same for all indices (i.e., <*Nk*> = <*N*>), we can use <*N*>. Assuming: $A_1 = \frac{q^2}{CKT}, A_2 = N_{QR}\frac{P_C}{P_0}$, $A_1 < N >= x, A_1A_2 = A_3$, we have:

$$A_3 = A_1(N_{QR} - < N >)e^{-x}, \tag{7}$$

$$A_3 e^x = A_1 N_{QR} - x . \tag{8}$$

Then using the Maclaurin series of e^x up to third harmonics, we get:

$$A_3(1 + x + \frac{x^2}{2!} + \frac{x^3}{3!}) = A_1 N_{QR} - x . \tag{9}$$

Now we can easily solve the cubic equation using following formula:

$$x = u - \frac{q}{3u} - \frac{q}{3}, \quad < N >= \frac{x}{A_1}, \tag{10}$$

where

$$p = 6(1 + \frac{1}{A_3}) - 3,$$

$$q = 6(1 - \frac{A_1}{A_3}N_{QR}) - 6(1 + \frac{1}{A_3}) + 2,$$

$$u = [-\frac{q}{2} + \sqrt{\frac{q^2}{4} + \frac{p^3}{27}}]^{1/3}. \tag{11}$$

Integrating $\langle j_d\rangle$ over the in-plane coordinates, we get the average current density as[1]:

$$< j_d >= \sum{}_{QR}\int_{-\frac{L_{QR}}{2}}^{\frac{L_{QR}}{2}}\int_{-\frac{L_{QR}}{2}}^{\frac{L_{QR}}{2}} j_d \, dx\, dy , \tag{12}$$

in which L_{QR} is the longitudinal length size of QRs. Solving Eq.(12) by numerical methods, we have:

$$\langle j_d\rangle = j_m \frac{\theta}{\langle N\rangle}\left(\frac{0.1q(V + C_1 - \langle N\rangle C_2)}{(M+1)KT}\right) , \tag{13}$$

where θ is the non-uniformity parameter denoted as:

$$\theta = 21.45 erf(0.48qL_{QR}\sqrt{\frac{< N > \sqrt[3]{\Sigma_{QR}}}{\varepsilon KT}})\frac{\varepsilon KT}{q^2\sqrt{\Sigma_{QR}}} ,$$

$$C_1 = \frac{2\pi q}{\varepsilon}M(M+1)L\Sigma_D ,$$

$$C_2 = \frac{2\pi q}{\varepsilon}M(M+1)\sum{}_{QR}L(1 - 0.32/ML\sqrt{\Sigma_{QR}}) , \tag{14}$$

in which Σ_{QR}, Σ_D and L stand for the density of QR arrays, the donor density of QR arrays and the transverse spacing between QRs, respectively. Now substituting the value of <*N*> from Eq.(10) and θ in Eq.(14), the final equation for dark current will be

$$\langle j_d\rangle = \frac{21.45}{x} erf(0.48qL_{QR}\sqrt{\frac{x\sqrt[3]{\Sigma_{QR}}}{\varepsilon KT}})\frac{\varepsilon KT}{q^2\sqrt{\Sigma_{QR}}}\times (q(V + C_1 - xC_2)/(M+1)KT) . \tag{15}$$

The behaviors of dark current in QRIPs versus bias voltage for different parameters are shown in Figs.2-4. These curves prove the semi exponential equation of dark current that we come to in this paper. In conclusion, we show that using a simple formula, an easier way is got in order to avoid dealing with complicated calculations for studying dark cur-

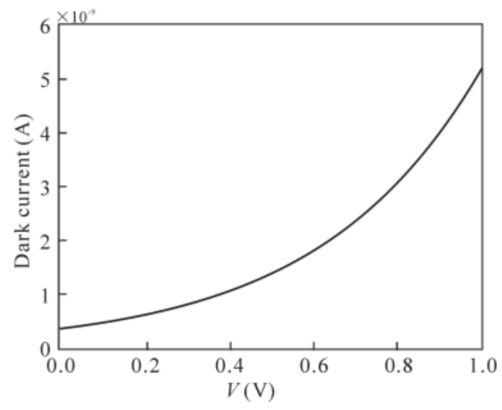

Fig.2 Dark current versus bias voltage for Σ_{QR} = 1.5 × 10[10] cm[-2], T = 40 K, a_{QR}= 10 nm

rent characteristics of QRIPs. As we expect, the operating temperature should be low (<50 K) to get low dark current and hence lower noise. By increasing the density of quantum wires Σ_{QR}, the dark current will increase.

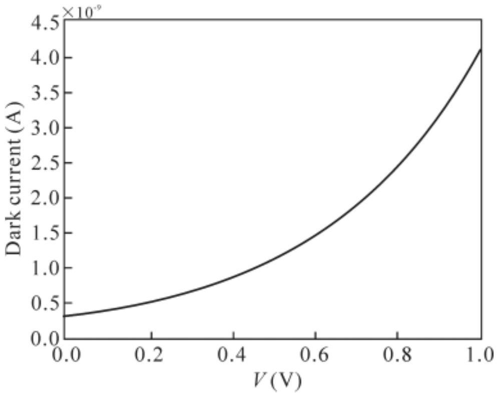

Fig.3 Dark current versus bias voltage for Σ_{QR}=10^{10} cm^{-2}, T = 50 K, a_{QR}= 15 nm

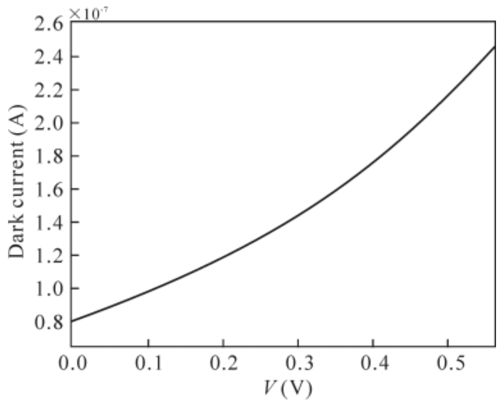

Fig.4 Dark current versus bias voltage for Σ_{QR}= 10^9 cm^{-2}, T=50 K, a_{QR}= 10 nm

In this article we have considered quantum wire infrared photodetector under dark current condition and also its model. A new simple mathematical procedure is given to find the dark current formula in QRIP. The analysis is carried out by considering important parameters of QRIP, including the maximum number of electrons in quantum wires <N>, the lateral characteristic size, and the nonuniformity factor. The results are in good agreement with those of Refs.[1, 2].

References

[1] V. Ryzhii, I. Khmyrova, M. Ryzhii and V. Mitin, Semicond. Sci. Technol. **19**, 8 (2004).

[2] A. Nasr, A. Aboshosha and S. M. Al-Adl., IET Optoelectron. **1**, 140 (2007).

[3] S. M El-Tokhy, I. Mahmoud and H. Konber, Infrared Physics and Technology **53**, 320 (2010).

[4] V. Ryzhii, I. Khmyrova, M. Ryzhii and M. Ershov, Journal de Physique IV **6**, 1996.

[5] V. Ryzhii, J. Appl. Phys. **81**, 6442 (1997).

[6] A. Nasr, J. Opt. Communication **30**, 126 (2009).

[7] A. Nasr, Optics and Laser Technology **41**, 345 (2009).

[8] P. Harrison, Quantum Wells, Wires and Dots: Theoretical and Computational Physics of Semiconductor Nanostructures, John Wiley and Sons, 2005.

[9] J. L. Pan and C. G. Fonstad, IEEE Journal of Quantum Electronics **35**, 1673 (1999).

[10] Y. H. Chee and G. Karunasiri, Physica E **7**, 135 (2000).

[11] Y. P. Chen, Y. E. Xie and X. H. Yan, Physica B **373**, 253 (2006).

[12] L. Wang, D. Wang and P. M. Asbeck, Solid-State Electronics **50**, 1732 (2006).

[13] T. Vazifeshenas, Phys. Stat. Sol. **6**, 1302 (2008).

[14] E. Lhuillier, I. Ribet-Mohamed, A. Nedelcu, V. Berger and E. Rosencher, Infrared Physics and Technology **52**, 247 (2009).

[15] A. Nasr, Optics and Laser Technology **41**, 871 (2009).