

Gaussian beam response of infrared photodetector with quantum dot nanostructure

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The photo-response of the quantum dot infrared photodetector attracts more and more attentions. In this paper, the photo-response of the quantum dot infrared photodetector is studied by considering the influence of the photoconductive gain, the quantum efficiency and incidence light distribution. The corresponding calculated results show the dependence of the photocurrent of the QDIP on the related parameters of the incident light, and but also give the contributions of the electric field to the photocurrent.

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1. Introduction

With the wide application of the infrared device in the medical field, the needs of the high performance infrared photodetector also become more and more urgent to meet the practical application. Quantum dot infrared photodetector is a novel infrared photodetector adopting the quantum dot nano-structure, and attracts a wide attentions due to its superior photo-electrical properties [1-3]. Now, the majority of the researches on the QDIP focus on the photo-performance estimation of the QDIP. To be specific, In 2001, V. Ryzhii proposed a device model of the QDIP by considering the continuous potential distribution and the thermal emission of the electrons [4,5] to estimate the photocurrent and responsivity of the QDIP. In 2010, I. Mahmoud Imbaby calculated the photo-performance of the QDIP with the consideration of the field-assisted tunneling emission of the electrons [6]. And H. Liu rebuilt the device model of the QDIP used to calculate the photocurrent, the responsivity and so on in 2012 [7,8], which includes the microscale electron transport and the nanoscale electron transport. In conclusion, these models can well calculate and simulate the performances of the QDIP, but, in these models, the consideration of the incident infrared light is too simply, and the characteristics of the incident light aren't fully considered, which has a big effect on the performance of the photodetector. Therefore, in our paper, it is assumed that the incident infrared light satisfies the distribution characteristics of Gaussian beam to increase the calculation accuracy of the photo-detection performance of

the QDIP such as the photocurrent, furthermore, the corresponding calculated results are also given to show the correctness and the validity of this model.

2. Theory

In this section, a photocurrent model of the QDIP is built, which includes the contribution of the quantum efficiency, the photoconductive gain and the distribution characteristics of the incident infrared light.

Quantum dot infrared photodetector is made up of many quantum-dot composite layers, if the infrared light is incident on the active regions of this photodetector, the photocurrent will be obtained under the applied bias voltage. According to the photoelectric detection mechanism of the QDIP, and this photocurrent can be written as:

$$I_{ph} = e \bar{v} g \eta P \quad (1)$$

Where e is the electron charge, η is the quantum efficiency, and g_p is the photoconductivity gain, h is Planck constant, ν is the frequency of the incident light, P is the optical-power of the incident infrared light on the photodetector. In our model, it is supposed that the incident infrared light meets Gaussian beam distribution, that is to say, the wave function of the incident light meets the following distribution [9]:

$$E(\rho, z) = A_0 \frac{\omega_0}{\omega(z)} \exp\left[-\frac{\rho^2}{\omega^2(z)}\right] \exp\left[-jkz - jk\frac{\rho^2}{2R(z)} + j\zeta(z)\right] \quad (2)$$

Furthermore, and its light intensity can be written as:

$$I(\rho, z) = A_0^2 \left[\frac{\omega_0}{\omega(z)}\right]^2 \exp\left[-\frac{2\rho^2}{\omega^2(z)}\right] \quad (3)$$

where $\rho^2 = x^2 + y^2$, ω_0 is the waist radius of the incident Gauss light, and it can be calculated by $\omega_0 = [\lambda z_0 / \pi]^{1/2}$ (where, z_0 is Rayleigh distance, λ is the wave length of the incident light), $\omega(z)$ is the beam radius of the Gauss light, which can be obtained by $\omega(z) = \omega_0 [1 + (z/z_0)^2]^{1/2}$.

As we all known, the quantum dots infrared photodetector is made up of many quantum dots composite-layers which constitute the active region of the photodetector, the cross section of the composite-layers is assumed as the circle shape with the radius a , and thus, when the gaussian light irradiates on the active region of the photodetector, the power of the incident light can be obtained by the Eq.(4).

$$\begin{aligned} P &= \int_0^{a/2} I(\rho, z) 2\pi\rho d\rho \\ &= \int_0^{a/2} A_0^2 \left(\frac{\omega_0}{\omega(z)}\right)^2 \exp\left(-\frac{2\rho^2}{\omega^2(z)}\right) 2\pi\rho d\rho \\ &= \frac{A_0^2 \lambda z_0}{2} \left[1 - \exp\left(-\frac{a^2 \pi z_0}{2\lambda z_0^2 + 2\lambda z^2}\right)\right] \end{aligned} \quad (4)$$

In the QDIP, the photoconductive gain g_p can be obtained by calculating the ratio of the capture time of the electrons (the lifetime of the electrons) to the transition time of the electrons across the whole detector, and according to Ref.[10] & [11], it can be determined as:

$$g_p = \frac{(K+1)L\mu E \left[1 + (\mu E / v_s)^2\right]^{-1/2}}{K\pi a_{QD}^2 h_{QD}^2 \Sigma_{QD} V_t} \quad (5)$$

where L is the distance between quantum dot layers, K the total number of the quantum dot composites layers in the QDIP, Σ_{QD} the quantum dot density in each quantum dot layer, a_{QD} the lateral size of the quantum dots, h_{QD} the height of the quantum dot, V_t the capture rate of electrons, μ the mobility of the electrons, v_s is the saturation velocity of the electrons.

In the QDIP, the quantum efficiency η is related to the average number in a quantum dot [7,8], which can be shown as:

$$\eta = \delta \langle N \rangle K \Sigma_{QD} \quad (6)$$

where δ is the electron capture cross section coefficient and it is adjusted to meet experimental comparison, $\langle N \rangle$ is the average electron number in a quantum dot, and it can be calculated from the dark current balance relationship [7], which can be shown as:

$$2ev \left(\frac{m_b kT}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\frac{E_{a,micro} + E_{a,nano}}{kT}\right) = A^* T \frac{\Theta}{\langle N \rangle} \exp\left[e \frac{V + V_D - ((N)/N_{QD})V_{QD}}{(K+1)kT}\right] \quad (7)$$

Where v is the drift velocity of electrons, m_b is the effective mass of electron, k is the Boltzmann constant, T is the temperature, \hbar is the reduced Planck constant, $E_{a,micro}$ and $E_{a,nano}$ respectively represent the activation energies under the microscale and the nanoscale transport, A^* is the Richardson constant, N_{QD} is the maximum in the number of electrons which can occupy each quantum dot, Θ , V_D , V_{QD} , and \mathcal{G} are the characteristic parameters related to the structure and material of the photodetector.

Substituting Eq.(4), Eq.(5), Eq.(6) into Eq.(1), then we can get the expression of the photocurrent which can be shown as:

$$J_{photo} = \frac{e\delta \langle N \rangle K \Sigma_{QD} A_0^2 \lambda z_0 (K+1) L \mu E A \left[1 + (\mu E / v_s)^2\right]^{-1/2} \left[1 - \exp\left(-\frac{a^2 \pi z_0}{2\lambda z_0^2 + 2\lambda z^2}\right)\right]}{2\hbar v K \pi a_{QD}^2 h_{QD}^2 \Sigma_{QD} V_t} \quad (8)$$

3. Results

In this section, the photodetection performance of the quantum dot infrared photodetector is simulated and calculated; the corresponding results are shown in Fig. 1-3. In addition, Table 1 shows the values of some parameters in our simulation, which are the same as those parameters from the literature [7,8,10].

Table 1. Values of related parameters

$\mu = 2000 \text{cm}^2 \text{v}^{-1} \text{s}^{-1}$	$a = 100 \mu\text{m}$	$K = 10$
$\Sigma_{\omega} = 4 \times 10^{10} \text{cm}^{-2}$	$A_0 = 1$	$a_{\omega} = 22 \text{nm}$
$v_s = 1.6 \times 10^8 \text{cm/s}$	$z_0 = 5 \text{m}$	$L = 31.5 \text{nm}$
$\delta = 1.6 \times 10^8 \text{cm}^2$	$V_t = 2.5 \times 10^3 \text{Hz}$	$h_{QD} = 6 \text{nm}$

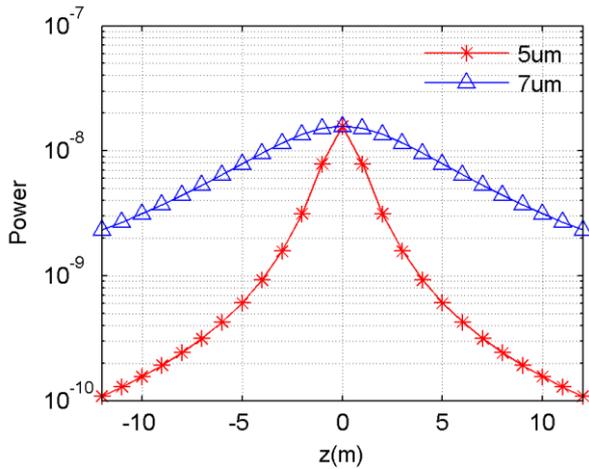


Fig. 1. Optical power of gaussian beam

Fig. 1 shows the optical power of the incident infrared light. In this figure, the curve with “*” describes the values of the power of the gaussian beam at the wavelength $5\mu m$, the other curve including “ Δ ” represents the data of the power of the gaussian beam at the wavelength of $7\mu m$. The two curves have the clear characteristics, which are as follows. Optical power meets Gaussian distribution with the increase of the distance z . And the values of the optical power at $z=0$ is the biggest in all values in the two curves. If let these gaussian beams irradiate the active regions of the quantum dot infrared photodetector, the photocurrent will be obtained under the condition of the applied bias across the photodetector. And furthermore, the photocurrent of the QDIP can be shown in Fig. 2. The curve with “*” stands for the photocurrent values under the wavelength $5\mu m$, the other curve including “ Δ ” presents the photocurrent values of the QDIP at the wavelength of $7\mu m$. It is very clear that the two curves have the same properties which are that the photocurrent meets the gaussian distribution with the increase of the distance z . To be concrete, the photocurrent shows a decreased trend with the increase of the distance z when $z>0$, and it increases with increase of the distance at $z<0$. In nature, this change trend of the photocurrent is from the gaussian distribution of the infrared light. Of course, it can be found that the influence of the wavelength of the incident light on the photocurrent. At constant the distance $5m$, the photocurrent at wavelength $5\mu m$ is $1.017 \times 10^7 A$, and it sharp increases to $1.425 \times 10^7 A$ when the wavelength is changed to $7\mu m$, which is $0.408A$ bigger than that at $5\mu m$. The similar increase change trend of the photocurrent with the increase of the wavelength can be also seen in the other values in the two curves.

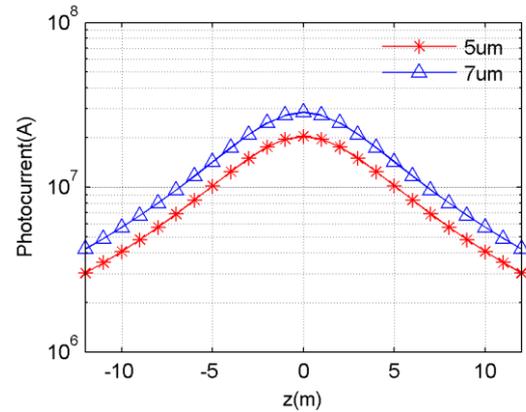


Fig. 2. Photocurrent as function of distance

Fig. 3 shows the dependence of the photocurrent of the QDIP on the electric field density. Here, our calculated photocurrent values are plotted as the curve with “*”, the experimental data is collected to form the curve including “ \blacklozenge ”, which is from the QDIP device made up of 10-periods 30nm GaAs / 3ML InAs QD / 30nm GaAs layers [12]. Compared with the two curves, it can be noted that they have a good consistency with each other, which verifies the validity and the rightness of our method. Furthermore, as what the Fig. 3 shown, the photocurrent increases with the increase of the electric field density. Our calculated results (corresponding to the curve marked as “calculated”) are taken as an example, at the constant wavelength $6.36\mu m$, when the electric field density is changed from $4kV/cm$ to $10kV/cm$, the photocurrent values correspondingly show the similar increase trend, which have the increase from $0.428A$ to $1.30A$. The similar increase trend can be seen in the experiment values of the photocurrent (corresponding to the curve “experimental”). In nature, this increase trend of the photocurrent with the increase of the electric field can be explained as follows. When the electric field density is increased, the electrons speeds up, and the electrons used to form the photocurrent of the QDIP have a smaller values in the capture probability. As a result, the large photocurrent can be obtained.

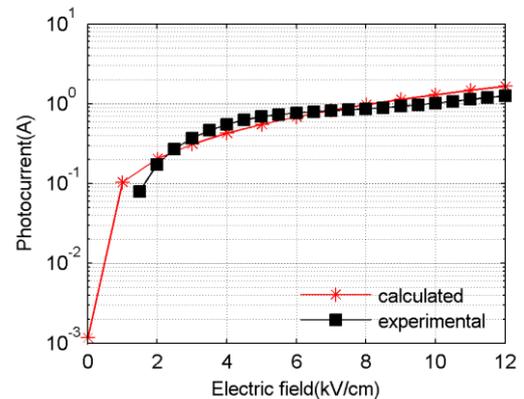


Fig. 3. Photocurrent of the QDIP as function of electric field

4. Conclusions

In this paper, the photocurrent of quantum dot infrared photodetector is simulated and calculated by considering the influence of the distribution of the incident infrared light beam. The influences of the wavelength and the electric field density on the photocurrent of the QDIP are also further discussed in our paper.

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References

- [1] M. A. Naser, M. J. Deen, D. A. Thompson, *Journal of Applied Physics* **104**, 014511-1-11 (2008).
- [2] H. Liu, Q. Tong, G. Liu, C. Yang, Y. Shi, *Optical and Quantum Electronics* **47**, 721 (2015).
- [3] P. Martyniuk, A. Rogalski, *Progress in Quantum Electronics* **32**, 89 (2008).
- [4] V. Ryzhii, *Journal of Applied Physics* **89**, 5117 (2001).
- [5] V. Ryzhii, I. Khmyrova, V. Pipa, et al. *Semiconductor Science and Technology* **16**, 331 (2001).
- [6] I. Mahmoud Imbaby, A. Konber Hussien, S. El-Tokhy Mohamed, *Optics and Laser Technology* **42**, 1240 (2010).
- [7] H. Liu, J. Zhang, *Infrared Physics & Technology* **55**(4), 320 (2012).
- [8] H. Liu, J. Zhang, *Optics and Laser Technology* **44**, 1536 (2012).
- [9] Herwig Kogelnik, *Applied Optics* **4**(12), 1562 (1965).
- [10] P. Martyniuk, A. Rogalski, *Bulletin the Polish Academy of Sciences Technical Sciences* **57**, 103 (2009).
- [11] Hongmei Liu, Jianqi Zhang, *Applied Optics* **51**(14), 2767 (2012).
- [12] S. Lin, Y. Tsai, S. Lee, *Jpnese Journal of Applied Physics* **40**, L1290 (2001).

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