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Resonant tunneling diode with a multiplication region for light detection

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ABSTRACT

A resonant tunneling diode (RTD) with a multiplication region is designed for light detection in this paper. Via adding a n^+–i–p^+ multiplication region, we focus on promoting the photocurrent and light sensitivity of the detector. Through the calculation of the multiplication factor, the thickness of the multiplication region is determined. The influence factors of the electric field and potential distribution of the detector are investigated, thereby the thickness and doping concentration of the doped layers besides the double-barrier structure (DBS) are decided. Detectors with and without a multiplication region are fabricated from semiconductor heterostructures grown by molecular beam epitaxy. The current–voltage (*I*–*V*) and light sensitivity tests show that the detector with a multiplication region has better performance in peak photocurrent and light sensitivity.

1. Introduction

Over the last years, light detection at telecommunication wavelength are attracting more and more interest [1,2]. At present, avalanche photodiodes are widely used as photodetectors at telecommunication wavelength [3–6]. However, it suffers from high dark count rate and afterpulse noise. To overcome these problems, detectors based on other mechanisms have been researched. RTD with an absorption region belongs to one of these emerging detectors [7–10], the photon detection mechanism of which is that the photo-excited electron–hole pairs in the absorption region are locally separated under electric field and cause modulations of the internal potential.

In 2005, Blakesley [11] showed RTD containing a layer of quantum dots and GaAs absorption layer were capable of light detection up to ~850 nm. Afterwards, Li [12] extended the detection wavelength to 1.3 μm by utilizing $In_{0.53}Ga_{0.47}As$ as the material of absorption layer. These detectors rely on the capture of photoexcited holes by a layer of quantum dots adjacent to the DBS. In this paper, we replace the layer of quantom dots by a thin layer of $In_{0.53}Ga_{0.47}As$, and show RTD without a layer of quantum dots also has light sensitivity. By adding a multiplication region, the photocurrent and light sensitivity of our detector are further improved.

2. Structure of the detector

The structure of our detector is shown in Fig. 1. The basic structure of the detector is a RTD with $In_{0.53}Ga_{0.47}As$ absorption layer. The DBS contains 5ML AlAs as the top and bottom barrier respectively and 6 nm $In_{0.53}Ga_{0.47}As$ as the quantum well. $In_{0.52}Al_{0.48}As$ is applied as the material of the multiplicaiton region which ultilizes n^+–i–p^+ structure for more potential drop. A thin $In_{0.53}Ga_{0.47}As$ spacer is placed between the DBS and the multiplication region for charge accumulation.

As shown in Fig. 1, when the detector is under forward bias, photo-excited electrons in the absorption region move toward the collector while photo-excited holes access the multiplication region under electric field. Then the photo-excited holes are multiplied generating more electron–hole pairs. New generated holes will accumulate and furthermore modulate the electric field near the DBS which will finally change the current–voltage characteristics of the detector.

3. Design of the multiplication region

For better performance of the detector, the multiplication factor of the multiplication region should be properly controlled. A high multiplication factor will result in significant noise while a low one will have no effect on improving the detector's performance. In practice, an applicable multiplication factor should be in

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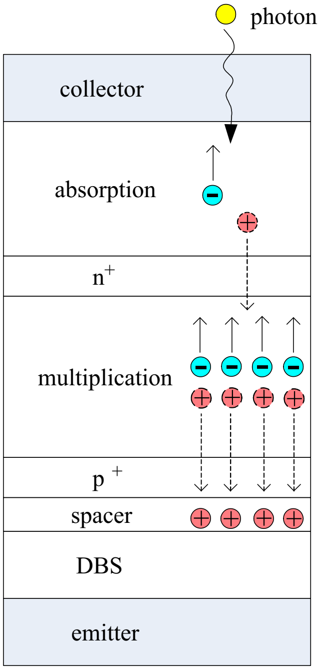

Fig. 1. Structure of the detector.

the range from 2.5 to 3.5. The multiplication factor of $In_{0.52}Al_{0.48}As$ is calculated by

$$M = \frac{1 - \alpha_h/\alpha_e}{\exp[-(\alpha_e - \alpha_h)d] - \alpha_h/\alpha_e} \tag{1}$$

where α_h and α_e are the impact ionization coefficient of the hole and electron respectively, d is the thickness of the multiplication region. α_h and α_e can be calculated by [13]

$$\alpha_h = 2.3 \times 10^7 \exp(-4.5 \times 10^6/E)$$

$$\alpha_e = 8.6 \times 10^6 \exp(-3.5 \times 10^6/E)$$

where E denotes the electric field within the multiplication region. According to Eq. (1), the multiplication factor of the multiplication region is simulated which is shown in Fig. 2.

When d and E are less than 300 nm and 5×10^5 V/cm, there is basically no multiplication in this region. However, the multiplication factor is more than 10 and increases sharply when d and E are larger than 300 nm and 6×10^5 V/cm which is not appropriate for the detector. The applicable range $2.5 < M < 3.5$, corresponding $0.4 < \log M < 0.55$, mainly locates at $300 < d < 400$ and $5 \times 10^5 < E < 6 \times 10^5$. Therefore, we further simulate the multiplication factor for $5 \times 10^5 < E < 6 \times 10^5$ while d increases from 300 to 400 by a step of 20. The result is illustrated in Fig. 3.

It can be seen that the multiplication factor is less than 3.5 when $d < 340$ while a relatively large part of it lies in 2.5–3.5 when d equals 360 nm. When d equals 380 and 400 nm, the multiplication factor has already reached more than 4. As a result, d is set to be 360 nm.

4. Electric field and potential distribution of the detector

One of the keys for the good performance of the detector is the electric field control in the multiplication region. As discussed in Section 3, the electric field within the multiplication region should be in the range of $5 \times 10^5 < E < 6 \times 10^5$. Moreover, the potential drop across the DBS should be low enough for resonant tunneling. A n^+–i–p^+ structure is used in the multiplication region so that a depletion region will be formed. According to the Poisson equation [14], the electric field $E(z)$ along the growth orientation of the detector satisfies

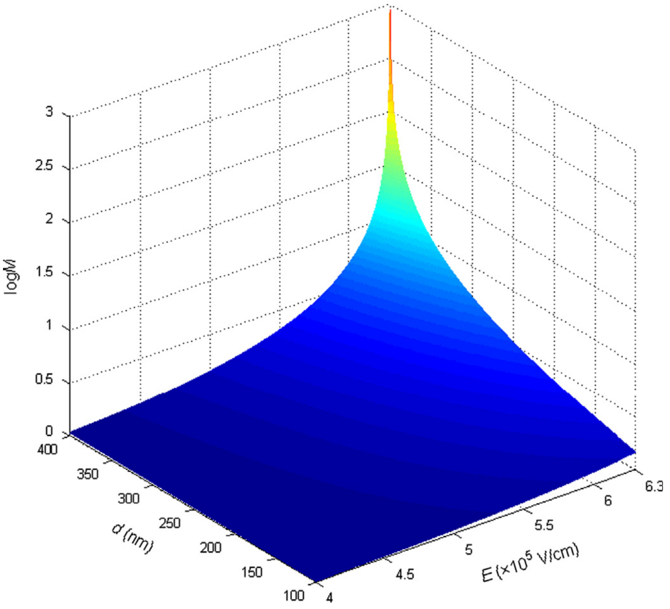

Fig. 2. The multiplication factor of the multiplication region.

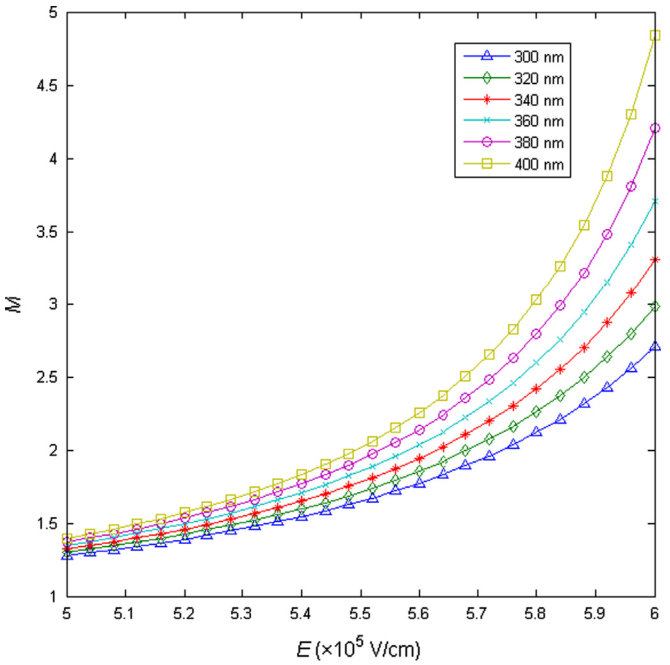

Fig. 3. The multiplication factor when $300 < d < 400$ and $5 \times 10^5 < E < 6 \times 10^5$.

$$\frac{dE(z)}{dz}\varepsilon = e[N_d(z) - n(z)] \tag{2}$$

where ε is the dielectric constant, e denotes the charge of carrier, and N_d is the ionized donor concentration and

$$n(z) = \int_{E_c}^{\infty} 4\pi \frac{(2m^*)^{3/2}}{\hbar^3} \frac{(E_e - E_c)^{1/2}}{1 + \exp[(E_e - E_F)/(k_B T)]} dE_e \tag{3}$$

where E_c is the conduction band profile, m^* is the effective mass, $\hbar$ denotes the reduced Planck constant, k_B denotes the Boltzmann constant, T represents the temperature, E_e denotes the electron energy level, and E_F denotes the Fermi level. Meanwhile, the