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Resonant tunneling diode photodetector with nonconstant responsivity

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ABSTRACT

Resonant tunneling diode with an $In_{0.53}Ga_{0.47}As$ absorption layer is designed for light detection at 1550 nm. The responsivity of the detector is simulated by solving the Tsu–Esaki equation. The simulation results show that the responsivity of the detector is nonconstant. It decreases with the increment of the power density of the incident light. Samples of the detector are fabricated by molecular beam epitaxy. The experimental results show that the responsivity increases while the power density of the incident light decreases which agree with the simulation results. The responsivity reaches 4.8×10^8 A/(W/μm^2) at room temperature and 5.0×10^9 A/(W/μm^2) at 77 K when the power density of the incident light is 1×10^{-13} W/μm^2.

1. Introduction

Light detection at wavelength of 1550 nm with high sensitivity is of great importance for quantum communication [1–3]. At present, many types of detectors have been investigated such as avalanche photodiode (APD) and superconducting single-photon detector (SSPD) [4–7]. As APD rely on the avalanche multiplication effect, it has disadvantages of high dark count rate and afterpulse noise [8]. The SSPD is based on superconducting materials' sensitivity to the change in temperature. The SSPD is suitable for operation at 1550 nm with low dark count rate, high detection efficiency and speed. However, SSPD has to be operated at extremely low temperature which is a serious constraint for its applications[9,10].

In 2005, Blakesley [11] showed that resonant tunneling diode (RTD) which contains a quantum dot layer and absorption layer is capable of single photon detection around 850 nm. When the incident photons are absorbed by the absorption region, the photo-excited holes will move to the emitter side and be captured by the quantum dots layer, which causes holes accumulation and potential modulation near the double barrier structure (DBS). In 2007, the detection wavelength of this type of detector was extended to 1310 nm by utilizing $In_{0.53}Ga_{0.47}As$ absorption layer [12]. This type of detector works at temperature lower than 77 K to achieve single photon sensitivity. In 2012, Hartmann [13] implemented light detection at 1.3 μm by adding a GaInNAs absorption layer into GaAs/AlGaAs RTD. Without a quantum dot layer, this type of detector is still capable of light detection with responsitivity of 1000 A/W at room temperature. The resonant tunneling diode photodetector (RTD-PD) has advantages of low working voltage, high quantum efficiency and low dark count rate, which is promising for light detection with high sensitivity at room temperature.

In this paper, we add $In_{0.53}Ga_{0.47}As$ absorption layer into InGaAs/AlAs RTD to implement light detection at 1550 nm with high sensitivity. We find out the responsivity of the RTD-PD is nonconstant, which has not been reported.

2. Structure of the RTD-PD

The structure of the RTD-PD is shown in Fig. 1. The n-type $In_{0.53}Ga_{0.47}As$ layers on the top and bottom act as collector and emitter. The DBS consists of 1.4 nm AlAs, 6 nm $In_{0.53}Ga_{0.47}As$ and 1.4 nm AlAs. 500 nm intrinsic $In_{0.53}Ga_{0.47}As$ absorption layer is placed between collector and the DBS for light absorption. 15 nm $In_{0.53}Ga_{0.47}As$ spacer is placed between the DBS and emitter to prevent impurity scattering from emitter to the DBS. A ring contact is deposited on the top to form electrical contact and clear aperture. The diameter of the clear aperture and the ring contact is 25 μm and 29 μm respectively.

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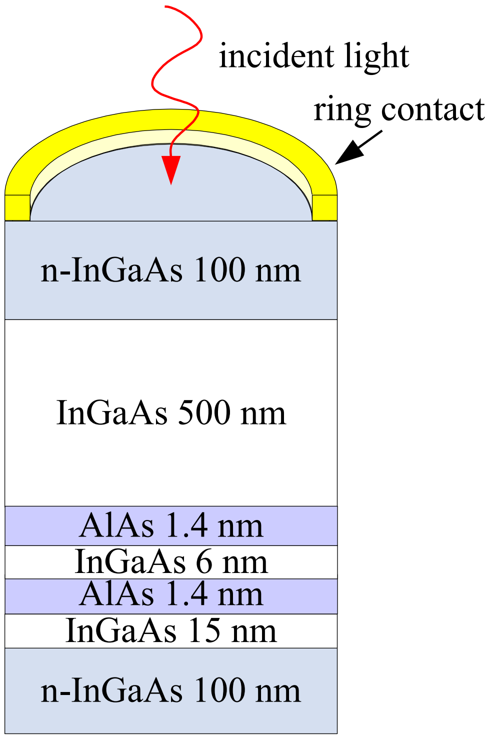

Fig. 1. Structure of the RTD-PD. The DBS is consisted of 1.4 nm AlAs, 6 nm $In_{0.53}Ga_{0.47}As$ and 1.4 nm AlAs. A ring contact is deposited on the top to form electrical contact and clear aperture.

Incident light at wavelength of 1550 nm is absorbed by the $In_{0.53}Ga_{0.47}As$ absorption layer, producing photogenerated electron–hole pairs. When the detector is under positive bias, the photogenerated holes will drift to the emitter side and accumulate at the interface between the DBS and the absorption layer. This causes band bending through the DBS, resulting to the variation of the tunneling current density of the RTD-PD. Meanwhile, if the incident light is not fully absorbed by the absorption layer, the light will be further absorbed by the spacer layer generating electron–hole pairs. The photogenerated electrons will accumulate near the interface between the DBS and the spacer layer, inducing holes on the other side of the DBS. This effect can promote the photo-response of the RTD-PD, but considering the thickness of the spacer layer is only 15 nm, this effect is negligible.

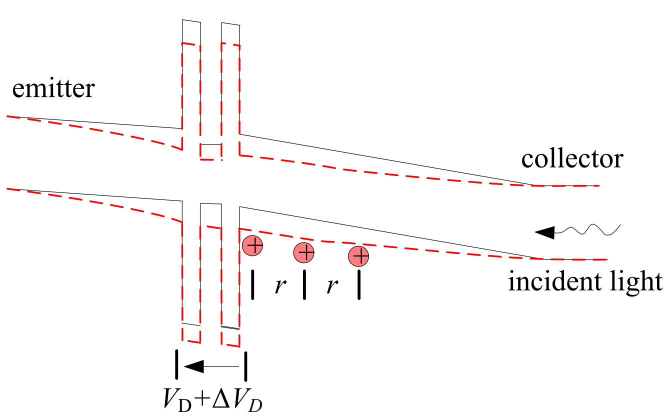

Fig. 2. Schematic band diagram of the RTD-PD under light. Due to the lowering of the energy level of the double barrier structure and the repulsive force of the accumulated holes, each photogenerated hole keeps a spacing of r. The potential drop along the DBS (V_D) will increase by ΔV_D due to the holes accumulation.

3. Simulation of the responsivity of the detector

The responsivity of the detector comes from the variation of the tunneling current density (ΔJ). To quantify ΔJ, both the dark current density and the photocurrent density should be quantified. The tunneling current density of DBS can be calculated by the Tsu–Esaki equation [14]

$$J_{RT} = \frac{em^* k_B T}{2\pi^2 \hbar^3} \int_0^\infty D(E) \ln\left(\frac{1+\exp\left[(E_f - E)/k_B T\right]}{1+\exp\left[(E_f - E - eV_D)/k_B T\right]} \right) dE \quad (1)$$

where e is the electron charge, m^* is the effective mass in emitter, k_B is the Boltzmann constant, $\hbar$ is the reduced Planck constant, T is the absolute temperature, E_f is the Fermi energy in emitter, E is the electron energy along the longitudinal growth direction of the detector, V_D is the potential drop along the DBS, and $D(E)$ is the transmission coefficient of the DBS which can be calculated by transfer matrix method [15], given by

$$D(E) = \left(M_{11}^* M_{11} \right)^{-1} \quad (2)$$

where M_{11} is the element in the first row and first column of the transfer matrix.

When the detector is under light, there will be photogenerated holes accumulating near the interface between the DBS and the absorption layer, which results to an increment of V_D, as shown in Fig. 2. At first, the photogenerated holes will accumulate at the interface of the DBS and the absorption layer. However, due to the lowering of the energy level of the DBS and the repulsive force of the accumulated holes, subsequent photogenerated holes will not accumulate at the interface, but keep a distance away from it. Assuming that each photogenerated hole has a spacing of r, the increment of V_D can be calculated by

$$\Delta V_D = \frac{e}{4\pi\varepsilon} \sum_{n=1}^{p} \left[l + (n-1) * r \right]^{-1} \quad (3)$$

where ε is the relative permittivity, p is the number of the accumulated holes, l is the thickness of the DBS.

To calculate the total current density of the RTD-PD, the excess current component should be considered. The excess current is mainly composed of thermionic current, which can be calculated by

$$J_{TH} = \left(\frac{4k_B T B J_{RT}}{A \cdot V_D} \right)^{1/2} \quad (4)$$

where B and A are the bandwidth and area of the RTD-PD respectively.

According to equation (1)–(4), the current density of the RTD-PD with varying numbers of accumulated holes is simulated as shown in Fig. 3. During the simulation, the temperature is set at 300 K, r is set as 5 nm, B is set as 100 kHz and A is set as 500 μm^2. As there is a positive correlation between the power of the incident light and the numbers of the accumulated holes, the simulation results can represent the photo-response of the RTD-PD.

Negative differential resistance (NDR) is obtained in each curve in Fig. 3, resulting from the off-resonance between the electron energy and the resonance level of the DBS. When there are photogenerated holes accumulating near the interface of the DBS and the absorption layer, the peak voltages of the detector become lower. When p varies from 0 to 1, the peak voltage decreases by 0.03 V. However, when p varies from 200 to 300, the peak voltage only decreases by 0.01 V. Meanwhile, as RTD-PD possesses lower excess current density at lower bias voltage, the peak current density also decreases with the increment of p.

Fig. 4 shows the calculated ΔJ with varying numbers of accumulated holes. When V_D is lower than the peak voltage, ΔJ