Resonant Cavity Enhanced Quantum Ring Terahertz Photodetector

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Abstract— **In this paper, based on effective mass method, we study the absorption characteristics of InAs/GaAs quantum ring photodetector in terahertz range. To enhance the absorption in active region of this photodetector we propose a metallic Fabry-Perot resonant cavity with Au nanoslits as top reflector and Au film as the bottom mirror. It is shown that with this structure at frequency of ~7.1 THz, absorption can be enhanced about 55 times.**

Keywords— quantum ring; absorption; quantum efficiency; Fabry-Perot cavity; nanoslits

I. Introduction

Terahertz (THz) region of electromagnetic spectrum with a range between radio frequency and infrared waves [1] has attained great attention in recent years. Potential applications of this band in various fields such as information and communication technology (ICT) sector, biomedical imaging and security [2] has caused considerable improvement in THz devices.

Currently, several mechanisms exist for absorption of THz waves, which includes Schottky barrier diodes (SBDs) and thermal detectors [3]. The performances of SBDs are based on frequency down-conversion through mixing of received THz signal with coherent signal of a local oscillator (LO). The most significant drawback of the SBD detector is its dependence on relatively high power LO source. Among various types of thermal detectors, bolometers, Golay cells and pyroelectric detectors are the most widely used detectors in THz applications. The main drawback in thermal detectors are low sensivity and slow response speed. Using quantum based photodetector which is based on intersubband transition in active region is another approach for THz absorption. The advantage of having high speed response, integration capability and multiple wavelength detection make them superior over other devices. High performance semiconductor based detectors such as quantum well and quantum dot photodetectors have been designed and fabricated for the detection of infrared radiation [4]. It is difficult for them to extent the absorption spectrum to frequency less than 10 THz. The main complexity in designing photodetector for this range of frequency is due to low energy of incident THz photon. Indeed lack of efficient sources and detectors in THz range have prevented the full realization of THz systems.

Recently quantum ring (QR) nano structure which is derived from quantum dot has been proposed for absorption of THz waves. Huang et al [5] and Lee et al [6] successfully fabricated quantum ring photodetectors to extent the detector response to THz range. Bhowmick et al [7] demonstrated high performance quantum ring photodetector with peak response at 1.82 THz.

Optoelectronic devices are essential part of communication networks, among them photodetector (PD) is one of the main components. To enhance the efficiency of PD, various models such as plasmonic structures and [8] resonant cavity with distributed brag reflector [9] have been reported. In this paper we analyze absorption coefficient with considering broadening effects in QRs and calculate quantum efficiency in quantum ring photodetector. To enhance quantum efficiency at frequency of 7.1 THz we propose a nanoslits cavity. In this structure metallic nanoslits are used as top reflector and Au film as bottom reflector.

The paper is organized as follows. In section 2, the numerical analysis of quantum ring optical characterization is presented. In section 3, resonant cavity enhanced structure is introduced and discussed. Finally in section 4 we conclude the paper.

II. Quantun Ring Structure and Optical Characteristics

We use an effective mass model to calculate the intersubband absorption coefficient in a single layer of uncoupled InAs/GaAs quantum rings of several sizes. Using finite difference method (FDM), we calculate energy levels for various height of QR and compare the results together. In this case only one ground state exists in QR and absorption is due to transition from ground state to continuum states. Due to fluctuation of quantum ring sizes, we consider a Gaussian inhomogeneous broadening (IHB). In addition to IHB, because of various scattering mechanisms and thermal broadening there is a homogenous broadening (HB) in QRs energy states with a Lorentzian shape. Then we calculate the intersubband absorption coefficient of a photon with energy $\hbar\omega$ in quantum ring layers [9].

Fig. 1 shows the calculated absorption coefficient of different height sizes InAs/GaAs quantum ring, with 4.5 meV IHB and 1.5 meV HB. The width of quantum ring is fixed at 15 nm.

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It can be seen that absorption coefficient increases with QRs height. Moreover increasing of QRs height shifts the peak absorption wavelength towards blue rays due to lowering of ground state respect to continuum states. The peak absorption coefficient for wavelength near $\lambda = 42$ μm (ν ~7.1 THz) and height of 1.6 nm, is about 7×10^5 m^{-1}. Also it is noticeable that for a small variation in height, the peak absorption coefficient wavelength shifts very much.

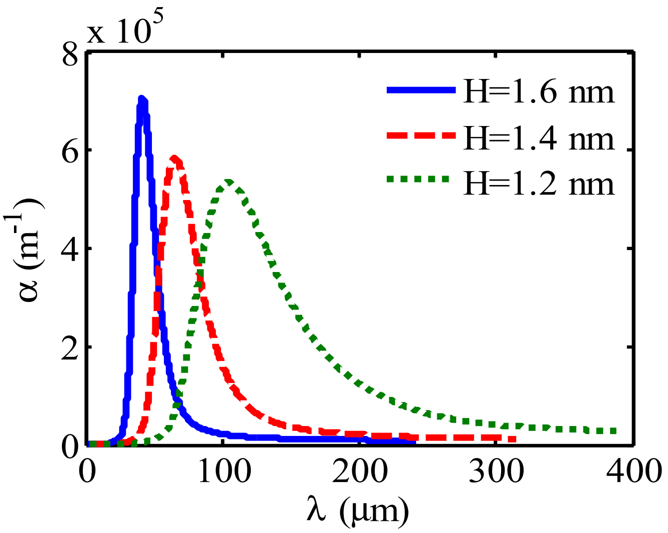

Fig. 1. Intersubband absorption coefficient for different heights of InAs/GaAs QRs with σ = 4.5 meV, γ=1.5 meV.

In Fig. 2 the effect of IHB on absorption spectrum of QRs with 15 nm width and height of 1.6 nm (which have the absorption peak at ν =7.1 THz) is investigated. HB value is 1.5 meV and IHB is considered as a parameter. This figure reveals that large IHB values lead to great degradation of absorption spectra. Large IHB caused by QR size fluctuations. In comparison with quantum dots, IHB values of QRs are less. Because in the range of THz, photon energies are less than infrared region, so if IHB values are greater than photon energies, absorption spectrum becomes much broadened. In other word, for THz detection, size variation is critical and growth process of QRs should be done carefully. Based on the simulation results, the active region of quantum ring photodetector with a multi-layer structure of appropriate QRs is designed. Each layer consists of a group of quantum rings with the average height of 1.6 nm.

One of the important parameters in PDs which should be investigated is quantum efficiency (QE). Quantum efficiency is defined as the ratio of phtoexcited carrier number to the incident photon number and can be calculated from the absorption coefficient and active region thickness. So the QE is given by [9]:

$$\eta(\hbar\omega) = 1 - \exp(-\alpha(\hbar\omega) l_{eff}) \quad (1)$$

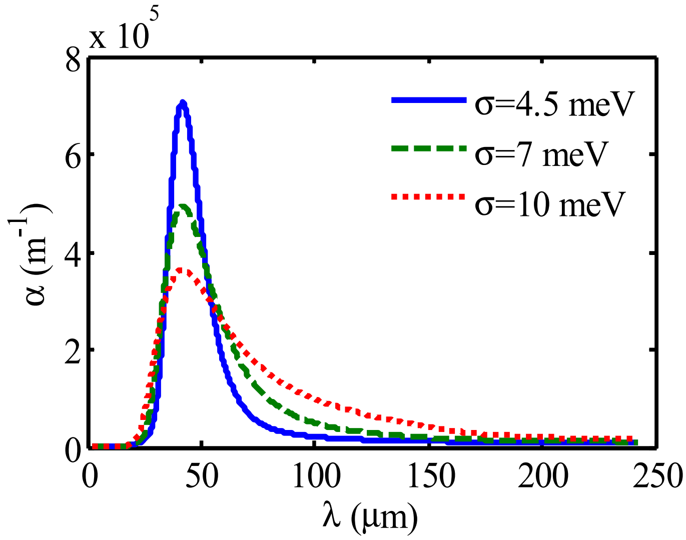

Fig. 2. Intersubband absorption coefficient with 1.6 nm height and γ =1.5 meV for different values of IHB, σ.

where $\alpha(\hbar\omega)$ is absorption coefficient, l_{eff} is the effective absorption region width dependent on the coverage factor of QRs, ξ, Fig. 3 illustrates the QE as a function of incident photon wavelength for different coverage factors of QRs, ξ. We assume 15 layers of QR with H=1.6 nm for active region of photodetector.

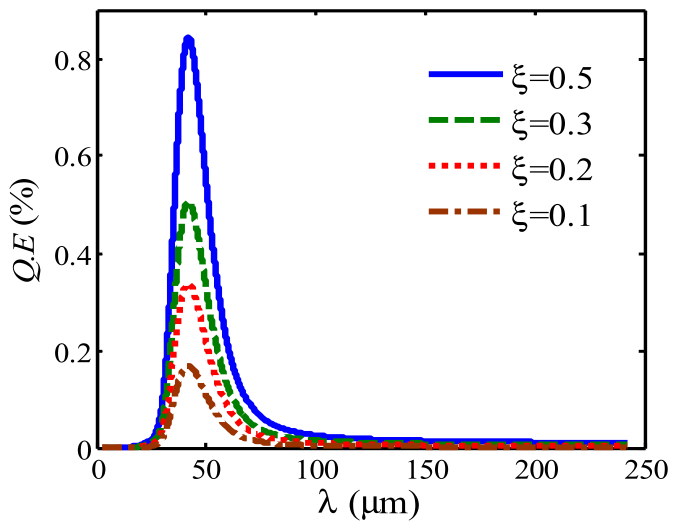

Fig. 3. Quantum efficiency of 15 layers of InAs/GaAs quantum ring photodetector as a function of incident photon wavelength at σ=4.5 meV, γ =1.5 meV and for different values of ξ.

According to results shown in Fig. 5, at λ=42 μm the QE has a maximum value about 0.84 % for ξ=0.5. This value of QE is very low, and must be increased to enhance the quantum ring photodetector performance.

III. ABSORPTION ENHANCEMENT BY RESONANT CAVTIY

As shown in previous section the QE of quantum ring photodetector is very low. This is because of thinness of effective absorption region. Theoretically, the internal QE enhances by increasing the number of QR layers, density of QRs, optimizing the shape, size and uniformity of QRs, and by growing a thicker active region without degrading the quality. All of these ways require further optimization of the growth conditions.

To enhance the absorption in the QR region and thus improve the performance of photodetector one approach is utilizing appropriate resonant cavity (RC). Schematic of the proposed Fabry-Perot (FP) cavity is presented in Fig. 4. Active region which consist of 15 QR layers is sandwiched between two transparent GaAs layers. One dimensional periodic Au nanoslits with a period of T, thickness of H and Au width of P form the top reflector. An Au film with thickness 100 nm serves as a bottom optical mirror. Drude model is used for two Au reflectors [10]. The whole structure is on a GaAs substrate with refractive index constant of 3.5.

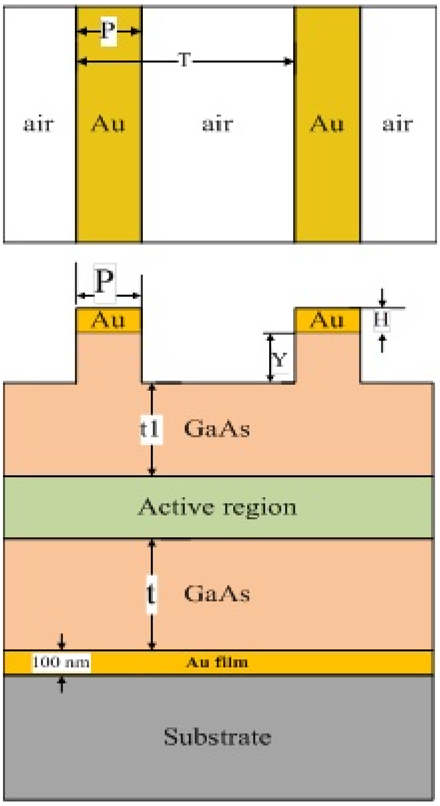

Fig. 4. Schematic of the designed F-P cavity QR-PD.

FP cavity generates multiple resonant frequencies. The fundamental resonant wavelength of the FP cavity can be estimated by [11]:

$$\lambda_{FP} \approx 2L\sqrt{\varepsilon_{cavity}} \tag{2}$$

where L is the cavity length and ε_{cavity} is the dielectric constant of different layers in cavity. The thickness of two transparent layers is tuned to keep the fundamental resonant frequency at 7.1 THz.

At the fundamental mode, the field will be maximal in the middle of the cavity, so if the active region of photodetector is located here, the absorption can be enhanced. The top Au slits should have a period smaller than the incident wavelength, so we consider T =3 μm in this simulation and the effects of filling factor (P/T) on absorption spectrum and absorption enhancement is investigated.

Imaginary part of refractive index in the active region is justified as it reproduces the peak QE value of 0.84% that agrees with a QE calculated without resonant cavity enhanced [12].

The one dimensional Au slits can only reflect light for TE polarized waves, in other word, the electric field (E) is parallel to the Au slits. Fig. 5 shows the absorption of normal incidence for different values of Au width. The period of structure is considered constant at 3 μm. The absorption peaks are found very close to the target frequency. Nearly 90% light is absorbed by the cavities at the resonant wavelength for P =100 nm. As shown in Fig. 5 the absorption spectrum decreases for larger fill factor (P).

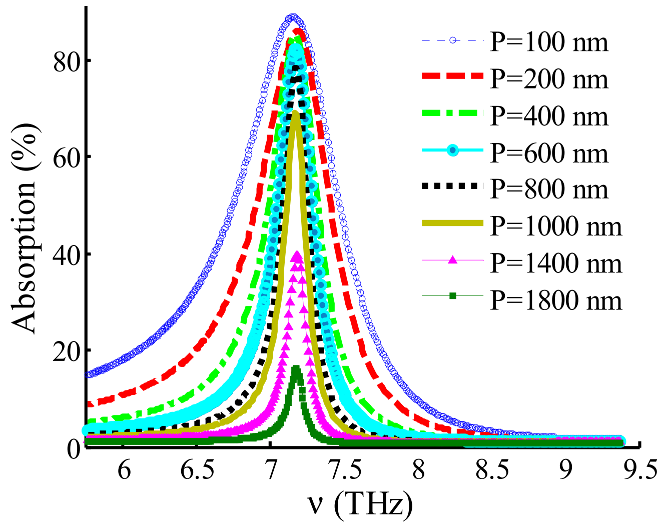

Fig. 5. Absorption spectra under normal incidence, at Y=0, T=3 μm, H=100 nm for different values of P.

To make the comparison straightforward, we use an absorption enhancement function, defined as the ratio of absorbed energy by the same active region with and without adding the resonant cavity structure throughout our simulation. Equations for the steady state distribution are solved using 2D finite element software (COMSOL 3.5). The computational domain is a single unit cell surrounded by periodic boundary conditions. Plane wave is incident normally from the air layer above the Au slits and for boundary condition in top and bottom of structure, perfectly matching layers are used.

The absorption enhancement with different structural parameters is calculated. Fig. 6 illustrates the simulation results of absorption enhancement for three values of Y as a function of Au width (P). This absorption enhancement is attained at the peak of input absorption spectrum (7.1 THz).

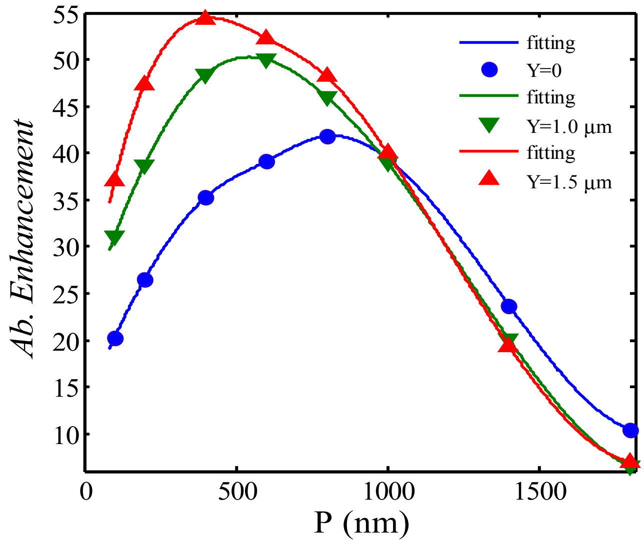

Fig. 6. Absorption enhancement as a function of Au width (P) for different values of Y, with σ =4.5 meV, γ =1.5 meV and ξ =0.5.

It can be seen that TE_0 absorption enhancement has an inversed bell-shape as a function of P. For three values of Y the trend of the FP resonance-related enhancement is similar. By increasing the Y values, larger enhancement are observed, and the peak enhancement is occurred at smaller values of P. Compared to a structure without the Au slits and Au film the absorption is enhanced by a factor of 55 in the case of Y=1.5 µm. This enhancement occurs nearly at P = 400 nm. This large value of Absorption enhancement dramatically improves the performance of quantum ring photodetector and leads to higher detectivity and responsivity of THz photodetector.

IV. CONCLUSION

Based on effective mass method, we studied the characteristics of the self-assembled InAs/GaAs QRs using FDM. We calculated the absorption coefficient of the QRs with considering homogenous and inhomogeneous broadenings. QE for 15 layers of QRs in active region of photodetector with various coverage factors was studied. Finally for increasing the absorption in QR region, we designed a FP cavity with two reflectors of Au slits and Au film. With optimizing slits parameters, the absorption could be enhanced by about 55 times in the QR region.

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