Spectral tuning in quantum rings by magnetic field: detection from NIR to FIR regime

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Abstract
In this work, we have proposed a new method for absorption spectrum tuning of the quantum ring (QR) in a wide interested range of IR (1.24–103 µm) using an external vertically magnetic field. We have used a tight binding method (TBM) to investigate the optical properties of the structure. The effect of the external magnetic field on the absorption spectrum has been investigated as the post-processing method. Also, the effect of different geometrical parameters like the number of QWs, QR radius, and constructed material considered as processing methods for tuning absorption. The results show for GaAs based QR with the radius of 100/π nm consist of 4 QWs, absorption peak linearly increase from 100 meV (12.4 um) in long wavelength infrared (LWIR) regime and shifts to 200 meV (6.2 um) in mid-infrared (MIR) regime with increasing external magnetic field. Also for a QR with a radius of 200/π nm, by changing the magnetic field different absorption peaks appear and disappear in an absorption spectrum and a multi-color detector converts to single-detector in the near-infrared (NIR) regime. This results help experimentalist to select proper materials with optimized geometrical parameters to achieve desired wavelength for various detection applications.

Keywords IR detector · Spectral tuning · Quantum ring · Magnetic field · NIR · MIR · FIR

1 Introduction

Infrared detectors used in the range of 0.7 um up to hundreds of micrometers have different industrial and technological applications (Menzs et al. 2019; Du et al. 2018; Fernandes et al. 2015; Negi et al. 2013; Gunapala et al. 2014; Rogalski 2003; Chen et al. 2018). In this field, movement in this wide range via processing or post-processing method to locate in the desired wavelength is an important issue and attracts much attention (Talghader et al. 2012; Zhu et al. 2017). A review on spectral selectivity in infrared thermal detection especially those operating at non-cryogenic was made in Talghader
et al. (2012). In (Zhu et al. 2017) a graphene-based structure used as a tunable mid-infrared biosensor. It showed optical conductivity of graphene affect the resonance frequency that important in detection wavelength. For lower wavelength, Schottky-like contact at the InP nanowire–ITO interface investigated for bias-dependent tuning of the spectral shape of the responsivity of photodetector (Jain et al. 2017). In this filed QWs and QDs based detectors play an important role in the progress of tunable IR detectors (Jain et al. 2017; Jang et al. 2012; Diedenhofen et al. 2015) Quantum dot infrared photodetectors (QDIPs) have been used as their bias-voltage-dependent spectral response via the post-processing method (Sakoglu et al. 2004; Bhattacharya et al. 2001; Krishna et al. 2002). In Sakoglu et al. (2004), bias-dependent spectral in QDIP was used for spectral tunability in the range of 2–12 μm limited in mid-infrared (MIR) range. Also plasmonic nanofocusing lenses are used for tuning response of integrated colloidal quantum dot photodetectors in near-infrared (NIR) range.

In this paper, we have studied the effect of the vertically magnetic field on the absorption spectrum of a quantum ring (QR) through numerical diagonalization of a one-dimensional tight-binding Hamiltonian. QRs are certain types of zero-dimensional structures. Similar to quantum dots, the number of electrons confined inside such structures can be tuned (Bagraev et al. 2008). Their electronic and optical properties can greatly be regulated, which makes them appropriate candidates for designing nanoelectronic devices. However, the physical properties of QRs is considerably different from quantum dots. These structures have been studied both experimentally (Bagraev et al. 2008; Garcia et al. 2004) and theoretically. These nano-rings can be fabricated by various techniques (Lorke et al. 2000; Warburton et al. 2000; Kong et al. 2004; He et al. 2010; Strom et al. 2007; Wang and Vasilopoulos 2007; Emperador et al. 1999). Physical properties of the QRs can be obtained using well known methods like transfer matrix method, K.P method, Hartree–Fock method, Density-functional method, Monte Carlo method, tight binging method and etc. (Emperador et al. 1999; Vagner et al. 2006; Jia et al. 2010). Some studied have been done to investigate on properties of QRs. Among them, transport properties in QR under the effect of spin orbit interaction (Jana et al. 2011; Wang and Chang 2008), Fano effect, Aharonov-Bohm effects and persistent currents (Schelter et al. 2012; Zhou et al. 1994; Kobayashi et al. 2003) are some of interesting studies. So far the effects of hydrostatic pressure and spin–orbit coupling (Mughnestsyan et al. 2013), cconfinement potential (Liang et al. 2011), applied electric field (Barseghyan et al. 2012), intense laser field radiation (Radu et al. 2014), etc. on the optical properties quantum rings are considered.

In our earlier works, we have studied the optical properties of clean (Solaimani 2014), two-electron (Solaimani et al. 2015), three electrons (Solaimani 2018a) and impurity included (Mahboubeh and Solaimani 2016) quantum rings and dots through compact density matrix formalism with the effective mass envelop function approach. Then, by using a one-dimensional tight-binding (1D-TB) model we studied the optical properties of QRs, as a proposal, to be used in THz detection quantum devices (Mobini and Solaimani 2018). By using a 1D-TB model we have also studied the electronic properties of a QR in the presence of magnetic flux (Solaimani 2018b). In the present work, we have studied the effect of vertically applied magnetic field on absorption spectrum as a post-processing method. We achieved that this post-processing method that can tune spectrum response in wide interested IR range (1.24–103 μm) comparing other existing methods. Also geometrical parameters like the number of QWs, QR radius, and constructive material studied for tuning absorption response as processing method.
2 Structure and simulation method

The Schematic of atomic view of a quantum ring with the effective site (quantum well) in the presence of the external applied magnetic field B, depicted in Fig. 1.

A QR with N numbers of sites of atoms can be modeled by tight-binding Hamiltonian as (Lisowski and Zipper 1998):

$$\hat{H} = \sum_{n=1}^{N} \left[ (2t + V_n) c_n^\dagger c_n - t e^{i \theta_{n,n+1}} c_{n+1}^\dagger c_n - t e^{-i \theta_{n,n+1}} c_{n+1}^\dagger c_n \right]$$  \hspace{1cm} (1)

where $t$, $N$, $c_n^\dagger$ and $c_n$ are the hopping matrix element, the number of sites, and creation and annihilation operators, respectively. Also, the additional on-site potentials $V_n$ forms a rectangular potential well of depth $V_{\text{Conf}}$ within the circumstance of the quantum ring. $\theta_{n,n+1}$ comes from the magnetic flux $\phi$,

$$\theta_{n,n+1} = \frac{e}{\hbar} \int_{r_n}^{r_{n+1}} A \, dl = \frac{2\pi}{N} \frac{\phi}{\phi_0} = \theta$$  \hspace{1cm} (2)

where $A$ is the vector potential, and $\phi_0 = \hbar/e$ is the flux quantum. By diagonalizing the Hamiltonian from Eq. (1) the eigen energies of the system can be obtained. Now, we study the absorption spectrum which can be calculated from Wang and Chang (2008):

$$A(E) = \frac{1}{N} \sum_{\beta} \delta(E - E_\beta) F_\beta$$  \hspace{1cm} (3)

where $E_\beta$ is the $\beta$ energy eigen value, $\delta(E - E_\beta)$ is the Dirac delta function and $F_\beta$ is the oscillator strength associated with the eigenvalue $\beta$, i.e. (Wang and Chang 2008).

$$F_\beta = \left[ \sum_{n=1}^{N} \psi_n(E_\beta) \right]^2$$  \hspace{1cm} (4)

Here, $\psi(E_\beta)$ is the eigenfunction corresponds to energy eigen value $E_\beta$.

Fig. 1 Schematic of atomic view of a quantum ring with the number of effective site (quantum well) in the presence of the external applied magnetic field B
3 Simulation and results

We consider a QR made of four GaAs/Al$_{0.3}$Ga$_{0.7}$As QWs. The barrier has 228 meV height (Vagner et al. 2006). We assumed the equal widths of the wells and barriers. The ring has a circumstance of 100 nm and $m^*$ is considered as 0.067$m_0$. The numerical values of the effective masses are taken from ref. (Mobini and Solaimani 2018). Using the tight-binding method eigenvalues of the Hamiltonian matrix and corresponding eigen functions for this structure are calculated. Considering Eq. (3), absorption spectrum as a function of the photon energy and magnetic flux for GaAs QR consists of 4 QWs, and for different values of QR radius: 100/$\pi$, 150/$\pi$, 200/$\pi$, and 250/$\pi$ nm has calculated and depicted in Fig. 2a, b, c and d, respectively. As seen in Fig. 2a, without a magnetic field, absorption occurs in 100 meV (10.24 um) in the short wavelength infrared (SWIR) regime and with applying magnetic field single absorption peak linearly increase and shift to 200 meV (5.1 um) in long wavelength infrared (LWIR) regime for $\Phi = 2\Phi_0$. For greater radius, the single peak converts to double and triple peaks in different wavelengths. For $R = 150/\pi$ and $200/\pi$ nanometer, double peaks occur in 100 and 150 meV and 75 and 100 meV, respectively. For $R = 250/\pi$ nm, triple peaks occur almost in 50, 75 and 200 meV. These double and triple peaks are fix vs magnetic field.

In the following, we investigated the effect of the radius in the structure with the lower number of QW. The absorption spectrum as a function of the photon energy and magnetic flux for GaAs based QR consists of 1 QWs and for different values of QR radius i.e. 100/$\pi$, 150/$\pi$, 200/$\pi$, and 250/$\pi$ nanometer has calculated and depicted in Fig. 3. For this structure, there is multicolor absorption with definite peaks. For the radius of 100/$\pi$ nm, there are two peaks in 31 and 120 meV in LWIR and MIR regimes, respectively. When the radius increases to 150/$\pi$ nm, three peaks can be seen in absorption spectrum in 18, 70 and 145 meV for a low magnetic field. With increasing magnetic field to $\Phi > 2.2\Phi_0$, the first peak in 18 meV disappeared. This occurs for the second peak for $\Phi > 3\Phi_0$ and only single–color remains in 145 meV. Also, for the radius of 200/$\pi$ nm, the peaks are in 12,
42, 92 and 160 meV, that covers MIR to the far-infrared (FIR) regime. In this condition, for \( \Phi > 2.2 \Phi_0 \) the first peak vanished. This occurred for the second peak when \( \Phi > 3.2 \Phi_0 \), and only two peaks remain in 92 and 160 meV. By increasing \( \Phi \) to value of \( \Phi = 4.1 \Phi_0 \), only one peak remains in 160 meV, that makes possible single-color detection. For the greater radius of 250/π nm, we have a detector with a multi-color absorption spectrum with different peaks from MIR to the FIR regime depicted in Fig. 3d. A similar trend like the previous (\( R = 250/\pi \) nm) occurred for this detector of greater radius and absorption peaks in lower energies vanish with increasing magnetic field and finally for \( \Phi > 5.2 \Phi_0 \) the single peak in 174 meV remains.

In the following, we investigate the effect of the number of QWs on the absorption spectrum. Absorption spectrum versus photon energy and magnetic flux for GaAs based QR with \( V_{\text{Conf}} = 228 \) meV, radius = (200/π nm) and different numbers of QW = 1, 2, 3 and 4, calculated and depicted in Fig. 4. For the structure based on the one QW, the absorption peak occurs in 12, 42, 92 and 160 meV as discussed before. For a structure based on 2 QWs, four peak integrated to two peaks in 34 and 125 meV with larger FHWM of 13 meV. In this manner the first peak vanished when \( \Phi > 4.12 \Phi_0 \). Also for 3 number of QWs, double convert to triple peaks in to 54 and 77 and 190 meV and finally for 4 number of QWs, we have double color photodetection in 77 and 103 meV.

Now we decrease the radius to 100/π nm and repeat the calculation. The absorption spectrum versus photon energy and magnetic flux for GaAs based QR with \( V_{\text{Conf}} = 228 \) meV, radius = 100/π nm and different numbers of QW = 1, 2, 3 and 4 has shown in Fig. 5. As seen in Fig. 5a, for 1 QW based structure, the absorption peaks occur in 31 and 125 meV, that the first one’s disappears for \( \Phi > 2.2 \Phi_0 \) and only one peak remains. For 2 QWs based structure, double peaks integrated to one peak in 80 meV with large FHWM of 14 meV for lower value of \( \Phi \), but when \( \Phi \) increased to 2.8\( \Phi_0 \) the FHWM parameter decreased to 7 meV that leads the sharp absorption. For the structure with 3 number of QWs, there are
two wide absorption peaks in 115 and 167 meV that are fixed vs $\Phi$. But for structure with 4 QW and R of 100/π nm there is a single color photo response that has blueshift with increasing $\Phi$.

Now it’s time to investigate the effect of different materials on the absorption spectrum of QRs. We have done this for 4 numbers of QW and both radius of 200/π and 100/π nanometer with different materials of Al$_{0.3}$Ga$_{0.7}$As/GaAs, GaN/AlN, InSb/GaSb and ZnSe/
CdSe. The confining potential depth and electron effective mass for these materials have been used in this study are shown in Table 1.

The results are shown in Figs. 6 and 7. As seen in Fig. 6a, b and c, there are wide double peaks in the absorption spectrum that start from 60 meV for GaAs in FIR up to 370 meV for InSb in the MIR regime. But for a ZnSe, there is absorption response with different distinct peaks started from 100 meV up to 1000 meV covering SWIR, MIR, LWIR and NIR regime.

Now we decrease the radius to 100/π nm and repeat the calculation. In this manner, because the size of the structure decreased we expect that the number of bands and transitions would decrease. The calculated results shown in Fig. 7. As seen in this figure, there is single-color absorption for GaAs and InSb based structure that linearly increased vs magnetic field. For GaAs based structure, absorption starts from 100 meV from LWIR regime for B = 0 and increased up 200 meV in MIR regime and the remaining band covered with InSb based structure as started form 250 meV for B = 0 and increases up to 500 meV in the SWIR regime. For GaN and ZnSe there are fixed absorption peaks in 140, 190 and 460 and 210, 280, 774 and 1000 meV vs magnetic field, respectively. But FWHM of absorption spectrum decreases with an increasing magnetic field.

### Table 1

| Material                  | $m^*$                      | $V_{\text{conf}}$(eV) |
|---------------------------|----------------------------|-----------------------|
| GaAs/Al$_{0.3}$Ga$_{0.7}$As | $0.067/(0.067 + 0.083x)m_0$ (Adachi 1985) | 0.228 (Solaimani et al. 2013a) |
| GaN/AlN                   | $0.15/0.25m_0$ (Vurgaftman and Meyer 2003) | 1.28 (Solaimani et al. 2013b) |
| InSb/GaSb                 | $0.014/0.045 m_0$ (Lundstrom 2000), | 0.542 (Magri et al. 2005) |
| ZnSe/CdSe                 | $0.16/0.11$ (Piprek 2003) | 0.47 (Li et al. 2009) |

Fig. 6 Absorption spectrum as a function of the magnetic flux and photon energy for QW = 4, radius = 200/π nm and different materials Al$_{0.3}$Ga$_{0.7}$As/GaAs, GaN/AlN, InSb/GaSb and ZnSe/CdSe
4 Conclusions

In this paper, we have proposed a new post-processing method for tuning absorption spectrum of a quantum ring in a wide IR range utilizing vertically magnetic field. The wide range of absorption has achieved for a ZnSe based structure from 100 meV up to 1000 meV covering SWIR, NIR, MIR, LWIR regime. Using the tight-binding method, the effect of other geometrical parameters like QR radius and number of QW investigated on the absorption spectrum and optimized parameters proposed to cover the desired wavelength in the IR range. These comparisons help experimentalist to select proper materials with optimized geometrical parameters to achieve desired optical properties in various optical applications. The results show there are wide double peaks in the absorption spectrum that start from 60 meV for GaAs based structure in FIR up to 370 meV for InSb based structure in MIR regime. This work is performed using the same lengths for well and barrier widths. This work can be developed to different arrangements of the quantum wells and also non uniform lengths for well and barrier widths.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.
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