# A tunable terahertz photodetector based on electrical confinement

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## ABSTRACT

The terahertz region in the electromagnetic spectrum has attracted much research interest recently, because of its potential applications in many areas, such as biological and medical imaging, free-space communications, and homeland security. Here, a tunable quantum dot photodetector for terahertz detection based on intersublevel transitions is proposed and simulated. The intersublevels are formed by a lateral electric field confinement on quantum wells. The intersublevel spacing can be tuned and in hence different wavelengths in the terahertz region can be detected. Our simulation results show a tunability of peak detection wavelength from ~3.3 to ~12 THz by only changing the electrical confinement voltages and the peak absorption coefficients of the detection are in the range of  $10^3$  cm<sup>-1</sup>. The peak calculated detectivity of the tunable photodetector is as big as  $1.7 \times 10^9$  Jones. Compared with quantum dot terahertz photodetectors produced by self-assembled growth method, the detector presented here is easier to be tuned and the effective sizes have a much higher uniformity, because of the uniform electrical confinement.

Keywords: terahertz, electrical confinement, and photodetector

## 1. Introduction

In the electromagnetic spectrum, there is a gap between the optics and electronic region called terahertz (THz) range. This region has not been fully exploited because of lacking of proper technology in terahertz sources and detection methods. Terahertz waves are non-ionized radiations and able to penetrate a wide variety of non-conducting materials<sup>1</sup>, so it has the potential to be applied into many areas, such as medical and biological imaging, security screening, free-space communication, and chemical molecule sensing<sup>2, 3, 4</sup>. Currently, the terahertz detection methods mostly rely on the methods of frequency conversion or heat production. The THz detectors in the market include Schottky diode mixers<sup>5</sup>, photoconductive antennas<sup>6</sup>, and silicon bolometers<sup>7</sup>. However, these terahertz detectors require sophisticated instrumentation, operate at a very low temperature, or are intrinsically has a very small bandwidth. Quantum dot infrared photodetectors (QDIPs) have also been developed for terahertz detection<sup>8</sup> and promise to have a very fast time response because of the interlevel transition nature. Compared with other photodetectors such as quantum well infrared photodetectors, QDIPs were predicted to have superb properties for photon detection because of the three-dimensional carrier confinement in the quantum dots, such as higher optical gain and lower dark current<sup>9</sup>. However, current QDIPs using the quantum dots grown by self-assembled method cannot achieve the performance as theoretically predicted, mostly because of the non-uniformity of quantum dot sizes<sup>10</sup>.

Here we use an electrical confinement method to form uniform quantum dots<sup>11, 12</sup> and apply them to detecting terahertz radiations, as shown in figure 1(a). We modeled the photodetector device using 3D finite element method (FEM) and simulated the energy state levels and wavefunctions in the quantum dots. We also calculated the performance characteristics of the device, such as absorption spectrum, responsivity, and detectivity. The proposed

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Terahertz Emitters, Receivers, and Applications, edited by Jean-François Lampin, Didier J. Decoster, Manijeh Razeghi, Proc. of SPIE Vol. 7763, 77630G · © 2010 SPIE · CCC code: 0277-786X/10/\$18 · doi: 10.1117/12.861478

photodetector can be tuned electrically to detect the terahertz waves at different wavelengths, and the effective quantum dot sizes are quite uniform because of the well defined electrical confinement.

### 2. Device Structure

A schematic 3D view of the proposed photodetector structure is shown in Fig. 1(b). The diameter of the top contact is designed to be ~200 nm. The circular gate contact surrounding the injector induces the lateral electric field below to form the electrical confinment on the quantum wells. The quantum wells region is designed to be close to the top surface for the maximum electrical confinement by gate contact. Between the gate and top contacts, an electrical insulator is used to electrically isolate them and prevent forming short-circuits in the device. The semiconductor structure used for the models includes 40 nm thickness of  $In_{0.53}Ga_{0.47}As$  (n=5x10<sup>16</sup> cm<sup>-3</sup>), quantum well active layers consisting of doped quantum well  $In_{0.53}Ga_{0.47}As$  layers (n=2x10<sup>17</sup> cm<sup>-3</sup>) and undoped InP barriers, and a bottom layer of doped  $In_{0.53}Ga_{0.47}As$  as a ground contact.

Electrons in the quantum wells are depleted and confined into the central region below the injector, when a negative voltage is applied on the gate contact. With a strong gate confinement on the quantum wells, the in-plane periodic potential of the wells breaks and splits continuous energy bands into discrete energy state levels. Changing the gate voltage it can induce different confinements and change the energy levels in the dots. Therefore, the inter-level separations can be tuned and hence different wavelength detection for the photodetectors can be achieved.



Figure 1- (a) a quantum dot is formed by applying lateral electric field on quantum wells, and (b) a quantum dot photodetector device structure using the electrically tunable quantum dot.

#### 3. Modeling Theory

We used Poisson and continuity equations to model the device and simulate the electrostatic potential and carrier concentrations in the device. Using the result of electrostatic potential distributions, we solved three-dimensional Schrödinger equation to calculate the electron energy levels and states in the QD. All the simulations are performed by our 3D custom numerical finite element method (FEM) method.

The Poisson and continuity equations can be expressed as

$$\nabla \cdot (\varepsilon_0 \varepsilon_i \nabla \phi) = -q(p - n + N^+) \tag{1}$$

$$\nabla \cdot (\mu_n \nabla E_{E_n}) = qR \tag{2}$$

$$\nabla \cdot (\mu_n \nabla E_{E_n}) = -qR \tag{3}$$

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$$R = \frac{n_i^2 \exp(\frac{E_{Fp} - E_{Fn}}{kT})}{\tau_n(p + n_i) + \tau_p(n + n_i)}$$
(4)

where  $\mathcal{E}_i$  is the relative permittivity for different semiconductor layers,  $\phi$  is the electrostatic potential, n and p are concentration distributions for electrons and holes respectively,  $N^+$  is the ionized doping density distribution, q is the electron charge,  $\mu_n$  and  $\mu_p$  are the mobility for electrons and holes,  $E_{Fn}$  and  $E_{Fp}$  are the quasi-Fermi levels for electrons and holes respectively, R is the net recombination-generation rate,  $n_i$  is the neutral electron concentration, T is the temperature, and  $\tau_n$  and  $\tau_p$  are the lifetime of electrons and holes respectively. The quasi-Fermi levels are used in the model to include both electric field drift and carrier diffusion processes. All the variables in the equations are three-dimensional. However, since the device structure has a cylindrical symmetry, we simplified the equations to two-dimensional ones with added components in the equations. To simplify the equations, supposing a variable  $\vec{f} = f_r \vec{r} + f_z \vec{z}$  the divergence of the variable with cylindrical symmetry can be given by

$$\nabla(f) = \left(\frac{\partial}{\partial r} + \frac{1}{r}\right)f_r + \frac{\partial f_z}{\partial z}$$
(5)

$$\nabla \cdot (k\nabla f) = \frac{\partial}{\partial r} \left(k\frac{\partial f}{\partial r}\right) + \frac{k}{r}\frac{\partial f}{\partial r} + \frac{\partial}{\partial z} \left(k\frac{\partial f}{\partial z}\right) = \nabla^* \cdot \left(k\nabla^* f\right) + \begin{cases} \frac{k}{r} \\ 0 \end{cases} \nabla^* f$$
(6)

where k is some constant in the formula,  $\nabla^*$  is the Cartesian Nabla operator in two-dimensional system.

The Schrödinger equation in the cylindrical coordinates can be written as

$$-\frac{\hbar^2}{2m^*}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2} + \frac{\partial^2}{\partial z^2}\right]\psi(r,\theta,z) + V(r,z)\psi(r,\theta,z) = E\psi(r,\theta,z) \tag{7}$$

when  $\hbar$  is the plank's constant,  $m^*$  is the effective mass for electrons at different semiconductor layers,  $\psi$  is the electron state wavefunction, V(r, z) is the potentials obtained from above, and E is the electron energy level. During the simulation we considered the effects of the electron effective mass as a function of the energy levels when solving the Schrödinger equation, so we kept updating the effective mass with the energy level solution until the solution was almost unchanged.

For the absorption spectral calculations for the quantum dots, we used the formula shown in ref. 13, but we also added the in-plane fill factor  $\eta$  of quantum dots since only the area with quantum dots can effectively absorb the light.

$$\alpha(\hbar\omega) = \eta(\frac{\omega}{n_r c\varepsilon_0}) \frac{2}{V} \sum_{i,j} \frac{\left| e \cdot \hat{u}_{i,j} \right|^2 (\Gamma/2)}{(E_j - E_i - \hbar\omega)^2 + (\Gamma/2)^2} (f_j - f_i)$$
(8)

where  $n_r$  is the average refractive index of the active region, V is the QD volume (the factor of 2 is considering the electrons spin degeneracy),  $\hat{u}_{i,j}$  is the transverse optical dipole moment values (which can be calculated by wavefunctions intergral),  $\Gamma$  is the full width at half maximum (FWHM) of the absorption broadening (here is mainly caused by inhomogeneous broadening), and f is the Fermi-Dirac distribution function. Since we are mostly considering the broadening due to inhomogeneous broadening under quasi-parabolic potentials,  $\Gamma$  can be written as<sup>14</sup>

$$\Gamma = 4E_n \xi \tag{9}$$

where  $\xi$  is the size deviation and  $E_n$  is the  $n^{\text{th}}$  eigenstate energy level. Here we used a size deviation of 1% corresponding to a deviation of 2 nm for 200 nm diameter of nanoholes, which is achievable using our developed Super Lens Lithography<sup>15, 16</sup>, which is a fast and economic method to generate highly dense and uniform nanohole arrays.

## 4. Modeling Results & Analysis

Solving Poisson and continuity equations, we have calculated the electrons concentration in the quantum dot device structure and simulated the confinement effects for different gate voltages. Figure 2 shows the electron concentration distribution with an injection voltage  $V_a = 5$  V at different gate voltages  $V_g$ . The color bar shows the relative electron concentration distributions. It clearly shows most electrons are depleted and confined into a nano-channel below the injector under a negative enough gate voltage, such as figure 2(a). With an increased gate voltage, the confinement effect is becoming weaker due to the weaker depletion of the gate voltage such as figure 2 (b) (c) (d). The depletion width is smaller and central confinement region below the injector is wider. Figure 3(a) is the electrostatic potential distribution under  $V_g = -5$  V with potential contour curves in the plot, and Figure 3(b) shows the effective radial potentials in the center of quantum wells region as a function of the radial distance from the injector center. The parabolic potential can effectively trap electrons to the central regions similar as the quantum barriers confine the electrons inside the quantum wells. Using harmonic oscillator approximation, we calculated the full width at half maximum of the ground state wavefunctions at different position along z-direction as shown in figure 3(c). Even at the bottom of the quantum wells active region, the quantum confinement can still form effectively.



Figure 2- (a) Electrons concentration distribution in the device under different gate voltages (a)  $V_g = -5$  V, (b)  $V_g = -3$  V, (c)  $V_g = -2$  V, and (d)  $V_g = -1$  V.



Figure 3- (a) Electrostatic potential distribution in the device, (b) the effective radial potentials in the center of the quantum wells as a function of the radial distance from the injector, and (c) the full width at half maximum of the ground state wavefunction at different z-positions.

Figure 4(a) shows the first four wavefunction states s, p, d, and f, formed by the parabolic wells as a function of the gate voltages. With a more negative voltage, the energy states blue shift. Fig. 4(b) shows the typical energy state wavefunctions. The main effects caused by the electrical confinement in the device are: (1) a pronounced blue-shift of the energy levels in the dot, (2) the tunable energy level separation, and (3) the reduction of homogeneously broadened absorption.



Figure 4- (a) The positions of *s*, *p*, *d*, and *f* electron states as a function of the gate voltages, and (b) typical energy state wavefunctions in the quantum dots.

Figure 5(a) shows the absorption spectral coefficients due to the transverse transitions of electrons at different gate voltages with an injection voltage of  $V_a = 0$  V. The peak absorption wavelength can be tuned from ~50 µm (6 THz) to ~85 µm (3.3 Thz) with the gate voltages from -5 to -2 V. Figure 5(b) shows the absorption spectra under different gate voltages with the injection voltage of  $V_a = 5$  V at 77 K. Because of the applied injection voltage, the parabolic well in the quantum well region becomes steeper, and the peak detection wavelength blue-shifts. We demonstrate that the detection frequency can cover between 3.3 and 14 THz by only changing the voltages of the top and gate contacts. A more negative gate voltage leads to a stronger confinement, which decreases the electrons concentration. So the absorption coefficients decrease.



Figure 5- Normal-incidence absorption spectra coefficient at 77 K for the quantum dots, (a) peak detection cover from ~3.3 to ~6 THz under the injection voltage  $V_a=0V$ , (b) the detection blue shift with  $V_a=5V$ .

Using the Fowler-Nordheim tunneling and thermionic escape model, we calculated the noise current of the photodetector at 77 K at different gate voltages. Figure 6(a) shows the calculation result of the current noise of the photodetector as a function of the bias voltage at different gate voltages. A more negative gate voltage leads to a higher dark current, because the energy levels are closer to barrier and carriers are easier to escape. The peak detectivity of our detector at different gate voltages were also calculated and shown in Figure 6(b). With an increased bias voltage, the detectivity quickly goes up and then drops back to an almost constant. The peak detectivity is almost as large as  $1.7 \times 10^9$  Jones at  $V_g$  of -2 V, which is contributed by the highly uniform effective quantum dot sizes.



Figure 6- (a) The current noise calculated in the QDIP device, and (b) the detectivity at different gate voltages from -2 to -5 V.

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## 5. Conclusions

We have demonstrated and modeled an electrically tunable quantum dot photodetector to detect the THz electromagnetic radiations. Our 3D models showed the electrical confinement and the energy levels in the quantum dots. The normal-incidence absorption spectra under different gate voltages were also shown. The detection frequency of the photodetector can cover the terahertz region from ~3.3 up to ~12.5 THz with a peak absorption in the range of  $10^3$  cm<sup>-1</sup> by changing the voltages on the device. The peak detectivity of the photodetector can be up to  $1.7 \times 10^9$  Jones. With improved processing of forming a denser quantum dot array and a further optimal design of device structure, the photodetector can be further improved in performance for THz detection.

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