# High Detectivity in GaN Self –Assembled QDIP at Room Temperature

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## Abstract

*In this paper, we present a self-assembled (pyramidal shaped) QDIPs, which operates in the long wavelength IR. A pyramidal shaped 6×6×3 $nm$ GaN quantum dot (QD) in a large rectangular cube box of 18×18×9 $nm$ dimensions. Solves single-band effective mass Schrödinger equation for the gamma conduction band in order to calculate the QD electronic structure. The temperature dependence of the dark current was shown and the amount of dark current at room temperature was equal to* $1 \times 10^{-2}\ A$*, which is an acceptable value. The pyramidal GaN QDs has demonstrated exceptionally low dark current, and high detectivity. Detectivity up to* $4 \times 10^{9}\ cm\sqrt{Hz}/W$*, at room temperature will be the strength of this research.*

**Keywords:** Photodetector, self-assembled (pyramidal shaped) QDIPs, detectivity, room temperature.

## 1-Introduction

Research efforts at the nitride quantum dot are now largely focused on understanding and controlling their optical properties. These properties are strongly affected by the existence of internal electric fields in the range of MV / Cm. The use of nitrite materials results in a sharp reduction in gap energy of 100 meV per 1% nitrogen used in this material [1].

The use of nitride quantum dots in the active area of optical components leads to higher temperatures. The use of these materials of quantum dots makes the optical response almost insensitive to the displacement density. As an example of these nanostructures, the single-photon emission in a GaN-based quantum dot structure at a temperature of 200 K can be controlled by a cooling system, while it is possible in a material such as InAs at a much lower temperature [2].

Nitride-based quantum dots can be generated by a variety of growth techniques such as MBE and MOCVD and other less developed methods, such as the solid-liquid-gas mechanism, and the likes. Nitride based semiconductors are commonly thought of in optical sources and detectors in the near-infrared region and the visible area and the ultraviolet region. Nitride compounds are commonly used as AlN, GaN, and InN, and triple and quaternary compounds [3].

The development of optoelectronic devices requires a better understanding of the optical, electrical, thermal, and mechanical properties of nitride semiconductors. Information in the articles about the physical properties of nitrides, in particular AlN and InN, still faces challenges in the evolution process [4].

III-nitride materials are made in two

1- wurtzite (WZ), 2- zinc-blend (ZB). In wurtzite structures, electronic states and optical properties are influenced by the electric field produced by spontaneous (Ps) and piezoelectric (Pz) polarizations. The built-in electric field amplitude is estimated in the order of MV / cm. These attributes do not exist in the ZB structure because they have high crystalline symmetry [5].

The semiconductors with wurtzite crystal structure is a direct energy bandgap semiconductor and it has many unparalleled features including wide bandgaps, high absorption, high-saturation velocity and radiation coefficients and stronger excitonic effects [6-10]. The quantum dot (QDs) based on these materials, can be used to produce from infrared to ultraviolet frequency, by varying the dot size and composition [11].

Recently, optical detectors based on quantum dots (QDs) have been studied. The significant characteristics of these structures are 3D quantum wells, reduced electron-phonon scattering, their ability to operate at high temperatures and high current gain [12-14].

In order to improve the performance of these photodetectors, Various structures with different materials have been investigated until now [15, 16].

Recently, many studies have been done on Wurtzite III-nitride quantum dots (QDs) for their potential use, in other optical devices. GaN-based quantum dot structure, possess more valuable properties such as, higher thermal stability, large band gap and larger saturation velocity, compared to other III-V materials [17]. But the execution of this kind of detectors is in the preliminary stages and supports from the restriction of the parameters. A model of nitride-based detector is proposed for high temperature performance [18].

Recently AlGaN/GaN quantum structure has been proposed with detectable photocurrent at mid-infrared (3–5 μm) [19].

Here we tried to a pyramidal shape (self-assembled) GaN dots and first we calculate the Eigen functions, Eigen values and other physical parameters. Then, the photodetector parameters such as absorption coefficient, dark current as a function of electric field, noise current and detectivity as a function of applied electric field with different temperature were evaluated precisely.

## 2-Models

In this paper, a pyramidal shape (self-assembled) GaN dots, which has been surrounded by $Al_{0.2}Ga_{0.8}N$ capping layers, has been considered as a unit cell. The schematic representation of the theoretical configuration used in the calculations shown in Figure 1.

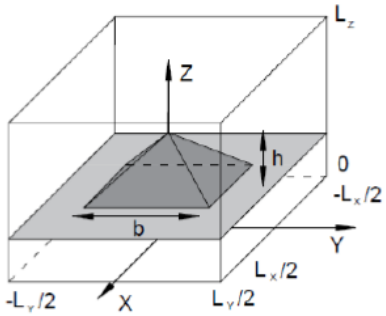


**Fig. 1.** Schematic diagram of pyramidal QD

The total number of the quantum dot layers are 10, the lateral size of quantum dots is 18nm, the height of the quantum dots is 7nm and QD density of $Nd=10^{24}m^{-3}$ is used as active region of the device.

To express the electronic structure of quantum dots, the easiest method is an effective mass theory. This method, which has a high degree of accuracy, has also been studied by many authors.

In this method, it is assumed that the QD is placed inside a larger box. The product on the box and the QD is different. Alternatively, by placing boxes next to each other, a set of QDs is formed. Waveforms obtained throughout the entire subsystem, The QD and the box or the level between the cells must be continuous. Thus, by passing from one cell to another, the shape of the wave function will be repeated in the same way. Cells must be selected in such a way that the energy states inside the QD do not change with a small change in cell dimensions. The parameter that changes through the QD to the box is an effective mass and a semiconductor band gap. It is assumed that the change in the effective mass, in the interface between the two substances, is sudden.

The shape of a box or cell is chosen proportional to the symmetry in the form of QD. Then, eigenfunctions of the energy states of the QD, depending on the eigenstate of the large box that is known to be explicit, for example, if a QD is in the form of a cube, the cell is also considered as a cube, and we extend the wave functions in terms of plane wave functions.

Due to the fact that in the detector to collect the stimulated and excited carriers from the quantum dots, the device is always biased and considering the properties of nitride materials that have a significant internal field, hence the Hamiltonian can be written as:

$$H = \frac{-\hbar^2}{2}\nabla\frac{1}{m^*(x.y.z)}\nabla + V(x.y.z) + e\vec{F}\cdot\vec{r} \qquad (1)$$

In which $m^*$ is the electron effective mass, and $(x, y, z)$ is given by:

$$V(x.y.z) = \begin{cases} 0 & inside\ QD \\ \Delta E_c & else \end{cases} \qquad (2)$$

Where $\Delta Ec$ is the conduction and valence band discontinuity [20]:

$$\Delta E_C = 0.7 \times \left(E_{g(Al_xGa_{1-x}N)} - E_{g(GaN)}\right) \quad (3)$$

Where x is mole fraction of Al, and $\vec{F}$ refers to both the external and built in electric fields. Therefore, in nitride based quantum dots, the carriers, in addition to the three-dimensional confinements, also have a strong built in electric field, which makes modeling and simulation of these structures is challenged.

The built in electric field which applied in the equation is [21]:

$$F_d = \frac{L_{br}\left(P_{tot}^{br} - P_{tot}^{d}\right)}{\varepsilon_0(L_d\varepsilon_{br} + L_{br}\varepsilon_d)} \qquad (4)$$

Where $L_{br}$ , $L_d$ are the width of the barrier and height of the dot, $P_{tot}^{br}$ , $P_{tot}^{d}$ are total polarization and $\varepsilon_{br}$ , $\varepsilon_d$ are the relative dielectric constant of the barrier and dot respectively.

The total polarization includes piezoelectric polarization and spontaneous polarization. The piezoelectric polarization itself consists of two components, one relating to the lattice mismatch (ms), and the other to the polarization created by the thermal strain (ts): $\mathrm{P_{piezo}^{br/d}} = \mathrm{P_{ms}^{br/d}} + \mathrm{P_{ts}^{br/d}}$ , where $P_{ms}^{br/d} = 2\left(e_{31} - \frac{C_{13}}{C_{33}}e_{33}\right)\left(\frac{a-a_0}{a}\right)$, and $P_{ts}^{d} = -3.2 \times 10^{-4}\ {}^{C}/_{m^2}$ [21]. $e_{31}$, $e_{33}$ are the piezoelectric coefficient, $C_{13}$, $C_{33}$ are elastic constants, and $'a'$ is the lattice constant of $Al_xGa_{1-x}N$ which is dependent on the aluminum molarity and is: $a = (0.077x + 3.189)$ Å [22].

The spontaneous polarization of $Al_xGa_{1-x}N$ is dependent on the molarity of

Al and is given by : $P_{sp} = (-0.052x - 0.029)$.

In the pyramid QD, one can use a large rectangular cube box to capture the pyramidal dot, and then develops QD wave functions based on sinusoidal and cosine wave functions of the unit cell. If the dimension of the unit cell is considered to be $\left[\frac{-L_x}{2}.\frac{L_x}{2}\right].\left[\frac{-L_z}{2}.\frac{L_z}{2}\right].\left[0.L_y\right]$ can be written [23]:

$$\Psi(x.y.z) = \sum_{lmn} a_{lmn}\varphi_{lmn}(x.y.z) \qquad (5)$$

Where

$$\varphi_{lmn} = \sqrt{\frac{2}{L_x}} sin\left[l\pi\left(\frac{1}{2}-\frac{x}{L_x}\right)\right] \sqrt{\frac{2}{L_y}} sin\left[m\pi\left(\frac{y}{L_y}\right)\right] \sqrt{\frac{2}{L_z}} sin\left[n\pi\left(\frac{1}{2}-\frac{z}{L_z}\right)\right] \qquad (6)$$

$L_x . L_y$ *and* $L_z$ are lengths of the unit cell along the x, y and z directions respectively. The advantage of the normalized plane wave approach is the fact that there is no need to explicitly match the wave function, across the boundary of the barrier and quantum dot [23]. Therefore, this method is easy to apply to an arbitrary confining potential. We used 17 normalized plane waves in each direction to achieve the convergence of the electron energy eigenvalues to less than 1 mev, thus forming a 4913×4913 matrix. By considering the built in electric fields and the bias, in Schrödinger equation, eigenfunctions and eigenvalues are calculated.

## 3-Results and Discussion

Based on the discussion of the previous section and the equations referred to in article [20], in this section simulation results are presented for self-assembled quantum dot, which shows very low dark current and high detectivity at room temperature. We first obtained the intraband absorption characteristic in the conduction band, which shows that the detector absorbed more than $3.2\times10^{6}\ {}^{1}/_{m}$ at wavelength of λ= 10 $\mu m$, which is related to the wavelength of the infrared region.

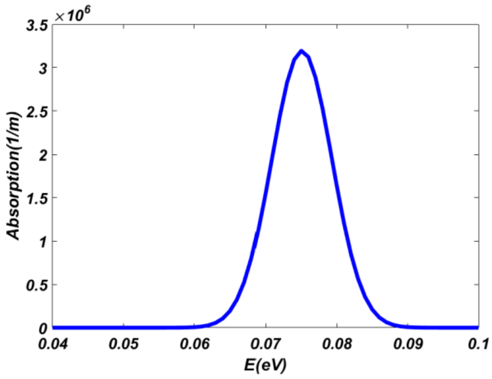


**Fig. 2.** Absorption coefficient (ground to first excited state) for $Al_{0.2}Ga_{0.8}N/GaN$ and Γ=3 $meV$ (the QD sizes are 6×6×3 $nm$)

### 3-1- Dark current

In quantum dot detectors, in the absence of light, there is a current in the device, which is a dark current. In quantum dots, this unwanted current is due to factors such as thermionic emission, field induced emission and ground state sequential tunneling.

In Figure 3, the influence of temperature on the dark current in E = 2 $kV/cm$ is displayed. It is obvious, that the temperature dependence of the dark current under the certain electric field follow by exponential curve. At the certain electrical field, the curves of dark current vs temperature are plotted. It is known that the shape of the curve, increasing with temperature increases, which can be due to electrons escaping from the quantum dot by the thermionic emission. It should be mentioned that GaN self-assembled QDIP has a very low dark current in comparison to the structure introduced in Ref [24]. The amount is at room temperature (T = 300°$K$).

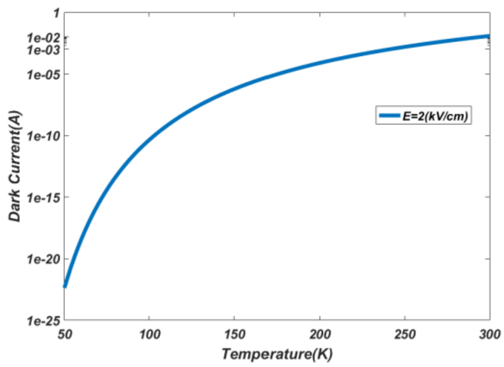


**Fig. 3.** Dark current as function of temperature.

### 3-2-Detectivity

The detectivity is one of the most important factors of a detector. This quantity determines how small the incoming light can be detected, and is actually a quantity for signal-to-noise measurements. Figure 4 shows the dependence of detectivity on temperature plotted for fixed applied electric field. Moreover, shows the detectivity decreases with the increase of the temperature at certain applied electric field, for example, at the E = 4 $kV/cm$ , when the temperature increases from 50$K$ to 300$K$, corresponding detectivity rapidly decrease from $2 \times 10^{19}\, cm\sqrt{Hz}/W$ to $4 \times 10^{9}\, cm\sqrt{Hz}/W$, respectively. The reasons for the decrease of the detectivity are as follows: when the temperature is increased, the thermal emission will be enhanced, and thus more and more electrons can easily capture out of the quantum dot to form the dark current and the noise, which ultimately leads to the decrease of the detectivity.

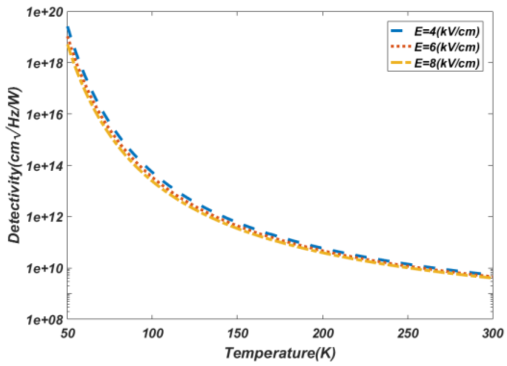


**Fig. 4.** Detectivity (at $\lambda$=10 $\mu m$) as function of temperature with different applied electric field.

## 4-Conclusion

As discussed in this paper and explained in numerous publications, according to the unique properties of nitride based self-assembled QD, that have the potential for superior performance as infrared detectors in the LWIR. We report in this paper on the superior properties of QDIPs based on nitride materials. The amount of dark current and the amount of detectivity at room temperature promise the use of these detectors without the need for a cooling system. Therefore, the proposed self-assembled QDs will be considered a proper alternative to the mature technologies that have been widely deployed.

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