Quantum Dot Infrared Photodetector
as an Element for Free-Space Optics Communication Systems

Milan Maksimović,
IHTM-Institute of Microelectronic Technologies And Single Crystals, Belgrade

1. INTRODUCTION

Infrared detection has many applications in a variety of fields such as: military targeting and tracking, firefighting, environmental monitoring, fiber-optic and free-space optics communication systems. Optically induced transitions in photodetectors, based on quantum-confinement structures, involve subband to subband or subband to continuum absorption [1]. Devices which use intersubband transitions in quantum wells led to development of QWIP (Quantum Well Infrared Photodetector) detector which demonstrated good performances and had been successfully commercialized for IR detection. Substitution of QW (Quantum Well) by QD (Quantum Dot) arrays which play the role of a photosensitive base led to development of the QDIP (Quantum Dot Infrared Photodetector) [2]. The main advantages of QDIPs are sensitivity to normal incidence photoexcitation, broader IR response, high photocurrent, increased extraction efficiency, lower dark currents and increased operating temperatures [2, 3]. By controlling material composition and QD sizes it is possible to control the spectral response of QDIP in broad range through IR. Most of the realizations of QDIP are using III-V materials which have the advantages of mature epitaxial and fabrication technologies and a generally lower cost. Much investigation is dedicated to Ge/Si QDs based QDIPs which would have the advantage of far-infrared response and compatibility with Si read out circuitry [4], [5].

FSO is fixed wireless communication technologies that is capable of delivering ultra broadband services over the air. FSO systems can quickly deliver a gigabit of capacity, over the last mile, without the time and costs associated with trenching to install fiber. Additionally, this technologies is unlicensed [6,7].

A goal of this paper is to estimate the performance of the QDIP as an element of FSO communication system and to compare the available solutions against the requirements of an FSO communication system. Also it will discuss some important parameters of QDIP which have to be optimized in order to improve their characteristics. The QDIP parameters have been estimated through present theoretical models and experimental data from literature. Also a relation is proposed for the carrier capture limited modulation bandwidth of QDIP, in light of diffusion limited carrier capture, through model proposed recently in literature [8].

2. QDIP PRINCIPLE OF OPERATION AND DESIGN

QDIP detects radiation through intraband transitions in the conduction band. The absorption of IR radiation is associated with the electron bound-to-continuum or bound-to-quasibound transitions which result in photoionization of QDs and the appearance of free electrons. A QDIP device consists of a multiple two-dimensional array of QDs separated by barrier layers and sandwiched between two heavily doped layers: emitter and collector (which serve as a reservoir of carriers). There are two mostly studied QDIP device structures: the vertical QDIP (which collects electrons by vertical transport between the emitter and the collector) [9] and the lateral QDIP (which collects electrons through lateral transport of electrons across a high-mobility channel between the contacts) [10]. The electrons are injected from the emitter in the active region with QDs were electrons could be captured by QDs or drift toward collector. After photoexcitation by IR photon the emitted electrons drift toward collector in electric field provided by the applied bias, and creates photocurrent [2, 10]. Bound electrons accumulated in QDs create a significant space charge which modifies the electric field distribution in the active region. The process of photoionization of QDs under IR illumination results in a redistribution of electric field in the active region which gives rise to a change of the injected current. The total current across the photodetector includes the current caused by electrons emitted from QDs (by thermoemission or photoemission) and the injected current from the emitter. The QDIP operation is associated with the current across the device active region limited by the bound space charge which is controlled by incident IR radiation [11].

Figure 1: QDIPs principle operation scheme

3. QDIP PARAMETERS

Absorption: Intraband absorption of IR radiation is the main process in the QDIP operation. The shape and dimensions of QDs as well as the barrier materials are chosen in dependence on the desired operating wavelength range [9]. The absorption coefficient profile is associated with the electron density of states in the QDs. Because of the presence of the fluctuations of dot sizes and shape, the electron density of states in the QDs has the Gaussian shape and inhomogeneously broadening areas, which leads to a wide spectral response. The polarization dependence of the
absorption spectra has been established by theoretical models and experiment [12]. The strong normal incidence absorption is connected with the QDs size, and the conclusion is that the QDs have to be small in the lateral and in the growth direction [12].

A good performance detector must have high absorption efficiency and requires a high dot density. For the highest possible absorption QDs the ground states have to be filled with electrons, so it is customary to use the modulation doping of the structure. The QDIPs with a bound-to-continuum detection scheme have a cut-off frequency defined by relationship [3]:

$$E_c^{QDIP} = \frac{hc}{\lambda_c}$$

(1)

where $E_c$ is the activation energy and equals the difference between the top of the barrier and the Fermi level in the QD, $h$ is Planck constant and $c$ is the speed of light. Another noticeable feature of the detection response spectra is the broad line width $\Delta \lambda/\lambda$ which is much greater than in the case of QWIPs [2]. This aspect is useful for FSO applications because of the wavelength shift caused by the scattering events during propagation through air.

Dark current: The dark current in photodetector is defined as the current which flows across the device without illumination. In QDIPs it has generation-recombination origin in the carrier trapping and thermionic emission from QDs and thermionic emission from emitter in the active region of device [2]. QDIPs are expected to have lower dark currents due to the decrease of thermionic emission which is associated with the effects on carrier capturing probability and the effective lifetime of carriers and effects such as: phonon bottleneck in electron capture (interlevel spacing in QDs is larger than the phonon energy), limitation in capturing process due to the Paulie principle, the presence of repulsive potential barriers surrounding the charged QDs and QDs sizes. The relationship which provides an estimate of the thermal dark current is [11]

$$j_n \approx \frac{eG_{th}}{p_c}$$

(2)

where $e$ is the electron charge, $G_{th}$ is the rate of thermoemission per unit area of QDs layer and $p_c$ is the average capture probability for free electrons passing above a QD. A detailed theoretical consideration of dark current in QDIP leads to the conclusion that the dark current optimization depends on the following parameters: density of QDs in QD layer, doping level of the active region, and applied bias [13].

Photocurrent and photoconductive gain: If QDIP is under IR illumination, which causes the photoexcitation of QDs due to the bound-to-continuum transitions, the photoemission dominates thermoemission and gives rise to the photocurrent which is estimated by the expression [11]

$$j_{ph} = \frac{eG_{ph}}{p_c} = \frac{e\sigma_{QD} < n > \Phi}{p_c}$$

(3)

or

$$j_{ph} \propto e\sigma_{QD} < n > \Phi g$$

(4)

where $G_{ph}$ is the rate of photoemission per unit area of the QD layer, $\sigma_{QD}$ is the photoemission cross section (which equals the absorption cross section under the principle of detailed balance!), $<n>$ is the average sheet density of electrons in the QD layer, $\Phi$ is the incident photons flux and $g$ is the photoconductive gain. A very important parameter of the QDIP is the photoconductive gain defined as the ratio of the total flux of injected electrons to the total rate of thermoemission (under dark conditions) or photoemission (under illumination) from all QDs. Under this definition we have an expression, similar to those developed for QWIPs, in the form [12,14]:

$$g \approx \frac{1}{MFp_c(1+p_c)}$$

(5)

where $M$ is the number of QD layers, $F$ is the filling factor determining the portion of the covering area of the QD layer by QDs. This expression is valid under the condition $p_c \ll 1$, which is true in QDs. The physical mechanism under the photoconductive gain may be understood as the maintenance of the charge neutrality in the active region by the balance between the charge in the bound states of the QDs and the donor atoms. Also we can express the photoconductive gain through the expression [12]:

$$g = \frac{\tau_{off}}{\tau_{tr}}$$

(6)

$\tau_{off}$ is the effective carrier lifetime and $\tau_{tr}$ is the carrier transit time across the active region. From the expression (6) it can be seen that increasing the effective lifetime of carriers lead to increasing of the photoconductive gain.

Responsivity: Responsivity is used as a figure of merit for detector performance and is defined as the photocurrent per unit watt of incident light. If photoemission is much stronger than thermoemission, the QDIP responsivity can be expressed by [11]

$$R = \frac{j_{ph} - j_{th}}{\hbar\omega\Phi} \approx \frac{e\sigma_{QD} < n >}{\hbar\omega p_c}$$

(7)

where $\hbar\omega$ is the energy of incident photon. Responsivity of QDIP can be as large as several $\Lambda/W$ [11]. But it is important that although the responsivity is high and rises with bias voltage, we also have an increase of the dark current, so this is an issue for further optimization.

Detectivity: Detectivity is a measure of SNR (signal-to-noise-ratio) and it can be expressed by relation [2]:

$$D^* = \frac{R \sqrt{A\Delta f}}{I_n} = \frac{R \sqrt{A\Delta f}}{4eg\Delta I_i \Delta f}$$

(8)

where $A$ is the detector active area, $\Delta f$ is the measurement bandwidth, $I_n$ is noise current (which is in photoconductive mode expressed through shot noise). We can see that lowering dark current leads to increase of detectivity. However, if we express detectivity in terms of total thermoemission $G_{th}$ and photoemission $G_{ph}$ rates [11]:

$$D^* = \frac{G_{ph}}{\hbar\omega\Phi \sqrt{G_{th}}} \times \sqrt{N} \sigma_{QD} \sqrt{N_{QD} < n >} \exp \left( \frac{e\phi}{kT} \right)$$

(9)
where $N_{QD}$ is density of QDs per unit area. From relation (9) it can be seen that the condition for high detectivity means a high QD density per unit area, a large number of QD layers and QDs with small dimensions. Some characteristic values obtained in laboratory conditions are [5, 15]

- for Ge/Si QDIPS responsivity is $R \approx 1.4^{+1}_{-0.8} A/W$,
detectivity is $D^* = 2 \times 5 \times 10^{15} \text{cmHz}^{1/2} W$,
range $\lambda = 1.6 \pm 0.2 \mu m$ at temperatures $T \leq 40K$

- for InAs/GaAs QDIPS responsivity is $R \approx 0.1 A/W$,
detectivity is $D^* = 10^9 \times 10^{10} \text{cmHz}^{1/2} W$,
spectral range is $\lambda = 1.3 \pm 3 \mu m$ for temperatures $T \leq 60K$

For most of the investigated QDIPS dark current is about $1 \pm 2 \mu A$ for temperatures below 100 K. These values are comparable with the existing IR detectors and promise a wide application area for QDIPS. Among other features is tuneability of the spectral response with applied bias, which results from the mechanisms of photoemission or emission by tunneling through barriers. That is the key advantage against other types of detectors. The temperature dependence of QDIP parameters is the main issue for improvement in further device realizations, and reaching higher operating temperatures will make QDIPS more competitive in comparison to other detectors.

### 4. FSO RECEIVER SUBSYSTEM CHARACTERISTICS

An FSO communication system includes three major subsystems: transmitter, receiver and tracking system. Due to the atmospheric attenuation only a small portion of the emitted power arrives to the receiver subsystem. On the receiving side the most important aspects are the receiving optics aperture size and the detector field of view. The receive detector is coupled to the receive aperture through the air or a fiber [7]. Detector choices are limited by requirements in such aspects as: wide response spectra range, large detector active area, high sensitivity and detection bandwidth. The most commonly used detectors are PIN diodes and avalanche photodetectors (APD). Especially the APD is in use because of its internal gain which is necessary due to low level of the signals coming to detector. The presently available FSO systems operate in near-IR range for $\lambda = 0.78 \pm 0.85 \mu m$, because commercial detectors and sources are well designed and cost-effective [7]. In this spectral range Si PIN and Si APD detectors are used because of mature technology, high responsivity and gain (for APD) and generally very high bandwidth. (there are applications of $10^{\frac{Gb}{s}}$ systems in the market [7]). These detectors can be large and still operate at high bandwidths, which is useful to minimize losses when light is focused on the detector. In the IR region for $\lambda = 1.5 \pm 1.0 \mu m$ the commonly used detector material is InGaAs, offering a good sensitivity and bandwidth performance, but these detectors are small, which makes light coupling process more challenging. Atmospheric attenuation is independent on wavelength to all above $10 \mu m$ range. This long wavelength range of about $11.5 \mu m$ has better fog transmission characteristics [6]. In this spectral range the common detectors are based on HgCdTe material and have good performances comparable with detectors for other ranges. If we compare the data for detector performance between the presently available FSO detectors [7] and QDIPs characteristics, we can see that all the characteristics are comparable or better in the QDIPS case. Only one feature remains worse for QDIPS, the operating temperatures which are very low [1]. This requires an improvement through QDIP design until it reaches commercial detectors performance. But among different detectors the QDIPS as elements for FSO systems have advantages. An unknown feature of QDIPS is their dynamical behavior and the properties of device under high modulation rates. This is a very important issue for communication applications and may be the main restrictive factor for using QDIPS in FSO systems.

![Figure 2: FSO receiving subsystem](image)

### 5. QDIP HIGH-SPEED OPERATION PROPERTIES

There is a need for photodetectors with large modulation bandwidths that could be used in FSO systems for high-speed detection [7]. The key for determining QDIPs modulation characteristics is proper understanding of carrier dynamics during carrier trapping and emission process form QDs. The classical limitation to modulation bandwidth in QWs is associated with the capture time limit, quantified as [13]:

$$f = (\frac{2\pi}{\tau_c})^{-1}$$

where $\tau_c$ is the carrier capture time. This limitation can be understood as the upper limit for the frequency response in the case of QDIPS. In the QWIPs case it is observed that the transient response consists of two parts: the fast and the slow transient. The fast transient’s photocurrent is due to electrons which drift toward the collector, directly photoexcited from the QW, while the emitter contact behaves as a blocking contact. The time constant of the fast transient is equal to the minimum of the carrier capture time and transit time across device. During slow transient, QWs are recharged, so the photocurrent increases to reach its steady state value. The time constant of slow transient is determined by the differential conductivity of the emitter contact. According to the analysis in literature [16] the slow transient, associated with the emitter-contact injection properties, can limit the QWIP speed of operation. This conclusion might be applicable in the QDIP case, because there is much similarity in device structures and models. In paper [15] a diffusion limited carrier capture model has been proposed. This model predicts photoelectron lifetime (and capture time) determined by electron diffusion in interdot space. So we can estimate capture time limited bandwidth as from (10) and [15] as:

$$f = (\frac{N \sigma_{QD}}{\lambda})^{-1}$$

or
\[ f = \frac{MN_{QD}}{L}N_{QD} \exp\left( -\frac{eV(a)}{kT} \right) \]  
(12)

where \( N = \frac{MN_{QD}}{L} \) is QD concentration in active region, \( L \) is the active region length, \( \bar{a} \) is the mean size of QDs, \( \bar{v} \) is thermal velocity of carriers (or it can be interpreted as the drift velocity in low-field approximation), \( k \) is the Boltzmann constant, \( T \) is temperature and \( V(a) \) is potential at the QDs critical boundary where carriers are trapped. Therefore, large bandwidth is associated with capture time and equilibration process of carrier distribution which comes from transferring carriers between dots. It is important to notify that in the QDs case there is an intrinsic nonequilibrium carrier distribution, especially at low temperatures [16]. Thus, it is needed to properly understand and model the process of carrier distribution and dynamical behavior of QDIP. From the data available in literature [12] we can see that for capturing times \( \tau_c = 10 \pm 30 \) ps, we have \( f \leq 20 \) GHz which is a respectable value.

6 CONCLUSION AND FURTHER WORK

In this paper it is shown that QDIPs characteristics are very promising for FSO communications. The intention is to identify important features for further investigations and the conclusion is that the dynamical behavior of QDIP is poorly understood and needs better models. An answer to the question of modulation bandwidth for QDIP is the key of determining if it satisfies the criteria for modern optical communication systems such as FSO. The conventional rate equation lumped model does not correctly describe carrier dynamics in QDs and the intention is to analyze the random populations models based on microstate models [17,18] or to modify the rate equation model in such a way to meet the proper carrier dynamic behavior in QDs. Our further work will also include the investigation of applicability of the concept of resonant cavity enhancement for quantum dots and the modeling such a kind of QDIP, as proposed in [19].

LITERATURE:


Abstract: In this paper an estimation for the performance of QDIP as an element of FSO communication system is given and available solutions are compared against the requirements of FSO communication systems. A discussion of QDIP parameters has been presented through theoretical models and experimental data from literature. A relation is proposed for QDIP carrier capture limited modulation bandwidth and some further investigation lines of QDIP dynamic properties are suggested.

Quantum Dot Infrared Photodetector as an Element For Free-Space Optics Communication Systems, Milan Maksimović