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Infrared Quantum Dot Detectors

Devendra Kumar Rana ARSD College, University of Delhi, Delhi-110021

Kuldeep Kumar SGTB Khalsa College, University of Delhi, Delhi- 110007

ABSTRACT *In this article, we were trying to report the available review of literature of Infrared Quantum Dots. The advanced quantum dot based IR-sensors were explained in detailed.*

KEYWORDS : Infrared, Sensors, Quantum dot, Photo-detector

Introduction

An infrared detector is a transducer of radiant energy; it converts radiant energy in the infrared into a measurable form. Infrared detectors can be used for a variety of applications in the military, scientific, industrial, medical, security and automotive arenas. Main application of IR Detectors is in military to detect and track hot objects at long range, for passive night vision and also to assist in day time vision when the atmospheric transmission in the visible is poor due to smoke or mist. Infrared detectors are the eyes of digital battlefield. In addition to many applications of IR systems in military such as target acquisition, missile seekers guidance, search and track, there is a great importance for IR systems in commercial market. IR systems have improved medical diagnosis, automobile and aircraft safety manufacturing quality and control. [9]

In the spectral range 0.78-3µm IR detectors found applications in fiber optics communications, agricultural sorting, chemical analysis, environmental monitoring. In IR region 2.-5µm IR detectors are used in gas analysis for pollution control, in thermal imaging and in non contact temperature sensing. IR region 3-5µm is used mainly for hotter objects. There are three specific atmospheric windows for transmission are 1-3 µm (near infrared), 3-5 µm (middle infrared) and 8-14 µm (LWIR). IR is transmitted well only through these three windows and the rest of the IR radiation is absorbed by the molecules of CO_2, O_3, water vapor, oxygen etc. present in the atmosphere. Usually infrared imaging is performed in two different atmospheric transmission windows 3-5µm medium wavelength infrared (MWIR), or the 8-12 µm long wavelength infrared (LWIR). In these windows atmospheric transmission is highest or equivalently the absorption is lowest.

Infrared radiation offers the possibility of seeing in the dark or through obscured conditions by detecting the infrared energy emitted by objects; it does not rely on visible light. The detected energy is translated into imagery showing the energy differences between objects thus allowing an otherwise obscured scene to be seen. Under infrared light the features are revealed that are not apparent under regular visible light. People and animals are easily seen in total darkness, weaknesses are revealed in structures, components close to failure glow brighter, visibility is improved in adverse condition such as smoke or fog.

The Infrared (IR) region is located in-between the visible and microwave spectral regions i.e. 0.78µm to 1000µm. In this region, every object having non-zero temperature emits "thermal radiation" The characteristics of radiation emitted depends on the temperature and the wavelength. Human eye responds well only to the visible light but very poorly to infrared radiation, the human eyes do not directly detect almost all the information encoded in the infrared radiation. Therefore, it was necessary to develop a device if thermal radiation is to be detected and such device is called as detector. Detector main function is the conversion of the radiation falling on it into an electrical signal for further investigation. It can be done using many different physical phenomena. We can say that all physical phenomena in the range of about 0.1-1ev can be proposed for IR detectors. Detectors can be classified between photon and thermal detectors. Thermal detectors such as thermopiles, golay cells, resistance bolometer and pyroelectric detectors, when incident with IR radiation, radiation heats the detection element causes to change some physical properties of detectors material such as resistance, polarization, voltage etc. These detectors have the advantage that they operate at ambient temperature and can often use cheap materials but their main disadvantage was that they are relatively insensitive and slow. These disadvantages concentrated the research and development efforts onto the alternative photon detectors.

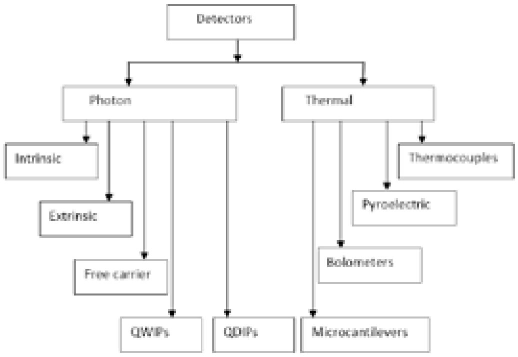


Fig: classification of IR detectors

In Photon detectors, the incoming radiation is absorbed to change the free carrier density in the material and this change in carrier density is measured. These detectors are very sensitive and fast but they require cooling to cryogenic temperatures especially at longer wavelength. A large number of photon detectors were developed for operation in infrared spectrum. These detectors have very high sensitivity, high frequency range of many GHz. These detectors have many applications industrial as well as scientific in remote temperature sensors, in spectrometers and in infrared systems. The development of IR detectors comes in three phases, Photon detector dominated the first two and Thermal detectors had a strong resurgence in the third. In first phase emphasis was on discovery and development of semiconductor materials to provide single element or very small arrays of detectors for wavelength of interest (for 3-5µm and 8-12µm atmospheric windows). Infrared technology progress is connected to semiconductor infrared detectors, which are included in the class of photon detectors. IR detectors made possible to image objects in darkness, or carry out contact less temperature measurement. Further research efforts move to Quantum well Photodetectors (QWIP) and Quantum Dot Photodetectors [3].

1.1 Quantum Well Infrared Photo detector (QWIP):

The concept of light detection by using quantum wells has been studied extensively by many researchers. The earliest studies were on two dimensional electron systems in metal-oxide-semiconductor inversion layer that has triangular barrier. The idea of using artificially structured semiconductors with quantum well for photo detection was first purposed by Esaki and Sakaki [5]. The first experiment on making use of quantum wells for IR detection was reported by Smith *et al*. [6]. Their device operation was based on the absorption of the IR radiation by the free carriers which are trapped in the wells formed by GaAs/AlGaAs hetrojunctions material systems. Quantum wells are constructed by growing a lower bandgap material (i.e. GaAs) between two larger bandgap materials (i.e. AlGaAs); the larger bandgap material serves as a barrier while the small bandgap material serves as a well. When the width of the well is small enough, discrete energy levels are created in the well. Intersubband transition in the wells is the base of modern quantum well infrared detectors. The first observation of Intersubband transition in quantum wells was reported by West and Eglash [16]. The first demonstration of quantum well infrared Photodetectors (QWIPs) was made by Levine et al. [17]. Since then tremendous progress has been made on both experimental and theoretical considerations about QWIPs and can be found in the literature [18, 19].

QWIPs devices offer excellent performance in the mid infrared (3 -5μm) and long-wavelength Infrared region (8–14μm). In terms of quantum efficiency and responsivity these were inferior to bulk detector fabricated from a direct bandgap semiconductor such as HgCdTe. In QWIP intersubband transition are allowed only for light propagating in the plane of quantum well. At the present time, HgCdTe (MCT) interband IR detectors lead the technology [20, 21]. However, there are difficulties in epitaxial growth of HgCdTe based materials due to the presence of large interface instabilities, etch-pit and void defect densities and because of it there are high uncertainties and fluctuations in the value of D* in QWIPs [22]. QWIPs require lower temperatures than MCT based IR devices because of a very large rate of thermionic emission of photo-excited electrons from the quantum wells. Another disadvantage is that; QWIPs cannot detect normally incident light due to polarization selection rules. Because of these shortcomings, alternative technologies are being investigated.

1.2 Quantum Dot Infrared Photo detector (QDIPs):

QDIPs are based on quantum dots; hence Quantum dots (QDs) are explained in this article. A QD is described as a small semiconductor box with a dimension less than 100nm incorporated into a semiconductor matrix of different material. QD is similar to an atom and sometime it is referred to as artificial atom. Wave like nature of electrons allows them to exist in discrete state in an atom. In QD electrons are confined in all the three directions due to small band gap of QDs compared to surrounding matrix. QD can consists large number of atoms and differ from an atom only in size. The main driving force behind the extensive studies and development of QDs is the possibility of tuning them to quantum and many body effects by changing the size of the dots and the number of electrons in the dots. By changing the size of the dots electronic structure inside the dot could be changed and by varying the number of electrons in the dots atomic like structure can be changed [7]. Quantum dots are made out of semiconductor material and the electrons in quantum dots have a range of energies. The concepts of energy levels, band gap, conduction band and valence band are applicable to Quantum dots. But the main difference is that the exciton (electron-hole pair) has an average physical separation between the electron and hole known as the exciton Bohr radius and this physical distance is different for each material.

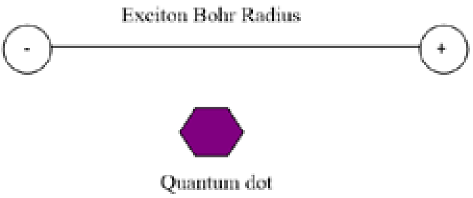


Fig 1.4: Quantum dots and Bohr radius

In bulk material, the dimensions of the semiconductor crystal are much larger than the exciton Bohr radius and due to this, the exciton extend to its natural limit. If the size of a semiconductor crystal becomes small enough that it approaches the size of the material's exciton Bohr radius, then the electron energy levels are not continuous, now they may be treated as discrete. This condition of discrete energy levels is called quantum confinement and under these conditions the semiconductor material different from bulk and can be called a quantum dot.

QD may consist of a few hundreds to few millions of atoms, only with small number of free electrons. QDs are special class of semiconductors nanocrystals, these are composed of periodic groups of II-VI, III-V, or IV-VI materials. Quantum dots show very high sensitivity to dot's size and composition, and this can be controlled. In Quantum dots, the band gap can be tuned hence the emission wavelength or the color in QDIPs. QDs are structures strongly confined to zero dimensional systems within a semiconductor matrix. Their property of discrete electronic levels with transitions in the mid- and far-infrared region is of great importance, especially for infrared photo detectors. Interest in QDs is based on the favorable energy spacing of their bound electronic states and the great potential to adjust these properties.

QD structures show higher photocurrents and lower dark currents than quantum well structures because of the longer lifetime of the excited states. Depending upon the electronic confinement QDs are classified as planer, vertical and self assembled QDs.

Quantum dots formation generally depends on the growth condition as substrate temperature and constituent material flux these parameter control the deposition of layers on substrate. The main difficulty with quantum dots is their random size distribution and the location of quantum dots in an array is very stochastic this has limited the potential performance of quantum dots devices. The nominal lateral dimension of dots grown is 30-50nm and vertical dimension is 5-12nm. Dots shape depends upon the number of parameter, growth condition and initial substrate surface. Most general shape of dots is pyramidal and Plano lens shape.

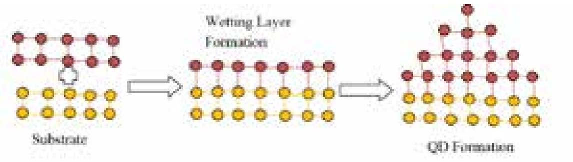


Fig1.10 Showing the Quantum dot formation.

A promising device that has emerged in the recent past is the quantum dot infrared photodetector (QDIP), which is based on optical transitions between bound states in the conduction (valence) band in quantum dots. Also they benefit from a mature technology with large-bandgap semiconductors. There are many advantages offered by QD detectors. First, QDs inherently allow sensitivity to normal excitation. The electron relaxation times between the discrete bound states (separated by 50-70 meV) are larger than in quantum wells due to a phonon bottleneck. This promises high temperature operation of QDIP. The three-dimensional confinement of carriers results in decreased thermionic emission and a lower dark current. Uncooled IR detectors will significantly reduce the size and operating costs of arrays and imaging systems for a variety of applications. This section presents intersubband QD detectors as a promising technology for tunable and multi-wavelength IR detection.

1.4 Why QDIPs for IR Detection?

1. A limitation of QWIPs is that they are not sensitive to normally incident light and they have only a narrow response range in the infrared. "QDIPs do not suffer from this normal-incidence limitation because of the geometry with the carrier confinement in all three directions. The normal incidence property is advantageous in QDIPs because it avoids the need of fabricating a grating coupler in the standard QDIPs imaging arrays. Also QDIPs can have a broader infrared response range because the self assembled dots have several discrete states.
2. Another potential advantage of QDIPs over QWIPs is the theoretical prediction of lower dark currents in QDIPs [32]. The simplest way to estimate the dark current is by the following expression [34]

$$j_{dark} = e v_d n_{3D} \qquad (1.1)$$

Where, υ_d is the drift velocity for the electrons in the barrier and n_{3D} *is* the three dimensional electron density in the barrier. The diffusion is neglected in Eq. (1.1). The electron density can be estimated by [1.2]

$$n_{3D} = 2\left(\frac{m_b k_B T}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\frac{E_a}{k_B T}\right) \qquad (1.2)$$

Where m_b is the barrier effective mass and *Ea* is the thermal activation energy which equals the energy difference between the top of the barrier and the Fermi level in the well or dot. The difference in the dark current for similar barriers in a QWIP and a QDIP (i.e. υ and m_b are comparable) is then determined by the difference in *Ea*. If the field induced barrier lowering effect in *Ea* is neglected (applicable for low applied fields), the activation energy relates to detection scheme by

for QWIPs $$E_a^{QWIP} = \frac{hc}{\lambda} \qquad (1.3)$$

for QDIPs

$$E_a^{QDIP} = \frac{hc}{\lambda} \qquad (1.4)$$

Where; E_F is the Fermi level in the well. Thus it can be seen from the Eq. (1.3) and Eq. (1.4) that for the same cut-off wavelength and barrier material there is a reduction in the dark current in QDIPs in comparison of QWIPs.

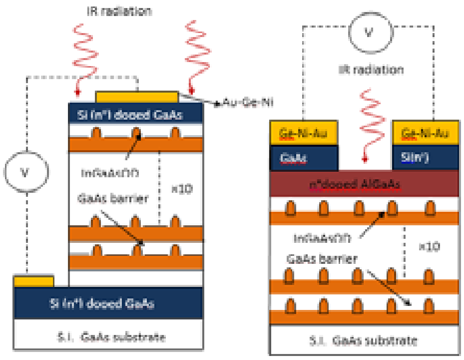
3. It relates to potentially long excited electron lifetime, τ_{life}. It has been anticipated [36] that the relaxation of electrons is substantially slowed when the inter-level spacing is larger than phonon energy – "phonon bottleneck". If the phonon bottleneck can be implemented in a QDIP, the higher responsivity values are obtained because photoconductor responsivity is given by

$$R = \frac{e}{h\nu}\eta g \qquad (1.5)$$

Where η is the absorption efficiency and *g* is the photoconductive gain given by equation (1.6)

$$g = \frac{\tau_{life}}{\tau_{trans}} \qquad (1.6)$$

where τ_{trans} is the transit time across the device. Thus, a long τ_{life} directly drives the higher Responsivity *R*



(a) (b)

Fig 1.17 Cross-sectional schematic diagram of a ten layer QDIP, InGaAs/GaAs, two basic quantum dot detector structures (a) vertical transport through the stack of self assembled quantum dot layers of photo excited carriers upwards to reach the external circuit for current conduction (b) lateral transport of carriers [8]

A promising device in the series IR detectors that has emerged in the recent past is the quantum dot IR Photodetector (QDIP) [38], based on optical transitions between bound states in the conduction (valence) band in quantum dots as in QWIPs. Also they benefit from a mature technology with large-band gap semiconductors. Currently self-assembled quantum dots are realized utilizing the Stranski-Krastanow growth mode of strained hetero structures and several groups have demonstrated QDIPs with promising results [39, 40]. Quantum dot infrared Photodetectors are advanced devices made from several stacked layers of quantum dots grown on a GaAs substrate. There are two basic device structures for intersubband QDIPs described by the direction in which the photo-excited carriers move relative to the substrate plane. These are the vertical and lateral QDIP structures as shown in figures 1.17(a), (b). In both structures, electrons are used as carriers due to their higher mobility.

These structures are typically made from more than 5 layers of quantum dots, and QDIPs with up to 70 layers have been reported Chakrabarti et al. 2004, [37]. In vertical transport structure photoelectrons move along the growth direction under a static electric field applied normal to the plane of quantum dot layers. In second kind of device structure the electron move laterally along the growth plane. These type of structure shows potential for better performance because in these structures electron can move readily in a plane parallel to the dot layer s than in perpendicular direction. Lateral device structure can be operated at temperature as high as 190ºK also in FPA the lateral device structure implementation is rather cumbersome.

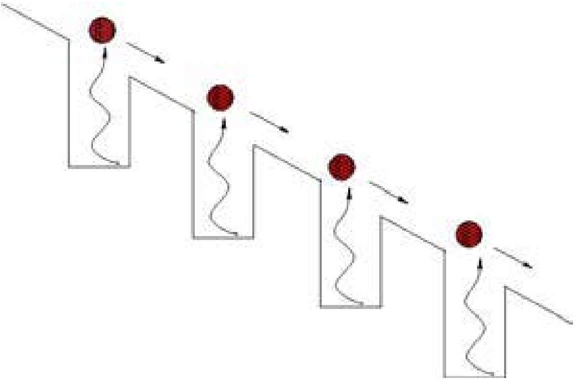


Fig: 1.18: Schematic energy band diagram of a QDIP operating under an electric field

Lateral QDIPs are believed to have the potential for better performance than vertical structures since the carriers have a higher mobility in the plane parallel to the quantum dot layers, Towe & Pan 2000[10]. However, vertical QDIPs remain the most popular for research, Stiff et al. 2001, Stiff-Roberts et al. 2002, [41] since the design is easier to fabricate into focal plane arrays (FPAs) so vertical QDIPs is preferred. Based on the direction in which the carriers move two kinds of device structures is possible. [8]. These Uncooled IR detectors will significantly reduce the size and operating costs of arrays and imaging systems used for a variety of applications. We have gone through various aspects of QDIPs; their fabrication and characterization Technology. Quantum dot detectors has established a promising technology for tunable and multi wavelength IR detection

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