Insight on quantum dot infrared photodetectors

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Abstract. The paper presents possible future developments of quantum dot infrared photodetectors (QDIPs). At the beginning the fundamental properties of QDIPs are summarized. Next, investigations of the performance of QDIPs, as compared to other types of infrared photodetectors, are presented. Theoretical predictions indicate that only type II superlattice photodiodes and QDIPs are expected to compete with HgCdTe photodiodes. QDIPs theoretically have several advantages compared with QWIPs including the normal incidence response, lower dark current, higher operating temperature, higher responsivity and detectivity. The operating temperature for HgCdTe detectors is higher than for other types of photon detectors. Comparison of QDIP performance with HgCdTe detectors gives evidence that the QDIP is suitable for high operation temperature. It can be expected that an improvement in technology and design of QDIP detectors will make it possible to achieve both high sensitivity and fast response useful for practical application at room temperature focal plane arrays. However, so far the QDIP devices have not fully demonstrated their potential advantages.

1. Introduction
Since the initial proposal by Esaki and Tsu in 1970 and the advent of molecular beam epitaxy (MBE), the interest in semiconductor low-dimensional solids has increased continuously over the years, driven by technological challenges, new physical concepts and phenomena as well as promising applications. A new class of materials with unique optoelectronic properties has been developed.

First observations of intersublevel transitions in the far infrared were reported in the early 1990s, either in InSb-based electrostatically defined quantum dots or in structured two-dimensional (2-D) electron gas. The first QDIP was demonstrated in 1998. Ever since, a great progress has been made in their development and performance characteristics and in their applications to thermal imaging focal plane arrays (FPAs).

The beginning of the interest in quantum dot research can be traced back to a suggestion by Arakawa and Sakaki in 1982 that the performance of semiconductor lasers could be improved by reducing the dimensionality of the active regions of these devices. Initial efforts at reducing the dimensionality of the active regions focused on using ultrafine lithography coupled with wet or dry chemical etching to form 3-D structures. It was soon realized, however, that this approach introduced defects (high density of surface states) that greatly limited the performance of such quantum dots. In 1993, the first epitaxial growth of defect-free quantum-dot nanostructures was achieved by using MBE. Most of the practical quantum-dot structures today are synthesized both by the MBE and MOCVD.
Under certain growth conditions, when the thickness of the film with the larger lattice constant exceeds a certain critical thickness, the compressive strain within the film is relieved by the formation of coherent island. These islands may be quantum dots. Coherent quantum-dot islands are generally formed only when the growth proceeds in what is known as the Stranski-Krastanow growth model. The onset of the transformation of the growth process, from a 2-D layer-by-layer growth mode to a 3-D island growth mode, results in a spotty RHEED pattern. This is, in contrast to the conventional streaky pattern, generally observed for the layer-by-layer growth mode. The transition typically occurs after the deposition of a certain number of monolayers. For InAs on GaAs, this transition occurs after about 1.7 monolayers of InAs have been grown; this is the onset of islanding and, hence, quantum-dot formation.

The most advanced III-V infrared detectors, which utilize intersubband or subband to continuum transitions in quantum wells, are GaAs/AlGaAs quantum well infrared photodetectors (QWIPs). The imaging performance of focal plane arrays fabricated with this material system is comparable to the state of the art of HgCdTe.10

The goal of this paper is to compare the potential QDIP performance with different material systems used in infrared detector technology. Our intention is to concentrate on the fundamental phenomena and minimize any confusion that might exist within the minds of scientists.

2. Anticipated advantages of QDIPs
The success of quantum well structures for infrared detection applications has stimulated the development of QDIPs. In general, QDIPs are similar to QWIPs but with the quantum wells replaced by quantum dots, which have size confinement in all spatial directions.

Two types of QDIP structures have been proposed: a conventional structure (vertical) and a lateral structure. In a vertical QDIP, the photocurrent is collected through the vertical transport of carriers between top and bottom contacts (see Fig. 1). The device heterostructure comprises repeated InAs QD layers buried between GaAs barriers with top and bottom contact layers at active region boundaries. The mesa height can vary from 1 to 4 µm, depending on the device heterostructure. The quantum dots are directly doped (usually with silicon) in order to provide free carriers during photoexcitation, and an AlGaAs barrier can be included in the vertical device heterostructure in order to block dark current created by thermionic emission.

Figure 1. Schematic diagram of conventional (a) and lateral (b) quantum dot detector structures.

In addition to the standard InAs/GaAs QDIP, several other heterostructure designs have been investigated for the use as IR photodetectors. An example is InAs QDs embedded in a strain-relieving InGaAs quantum well which are known as dot-in-a-wall (DWELL) heterostructures.11 This device offers two advantages: challenges in wavelength tuning through a dot-size control can be compensated in part by engineering the quantum well sizes and quantum wells facilitate ground state refilling.
The lateral QDIP collects photocurrent through transport of carriers across a high-mobility channel between two top contacts, operating much like a field-effect transistor. As previously, again AlGaAs barriers are present, but instead of blocking the dark current, these barriers are used to both modulation-dope the quantum dots and to provide the high-mobility channel. Lateral QDIPs have demonstrated lower dark currents and higher operating temperatures than vertical QDIPs since the major components of the dark current arise from interdot tunnelling and hopping conduction. However, these devices will be difficult to incorporate into a FPA hybrid-bump bonded to a silicon read-out circuit.

The potential advantages in using QDIPs over quantum wells are as follows:

- Intersubband absorption may be allowed at normal incidence (for n-type material). In QWIPs, only transitions polarized perpendicularly to the growth direction are allowed, due to the absorption selection rules. The selection rules in QDIPs are inherently different, and normal incidence absorption is observed.

- Thermal generation of electrons is significantly reduced as a result of the energy quantization in all three dimensions. As a result, the electron relaxation time from excited states increases due to phonon bottleneck. Generation by LO phonons is prohibited unless the gap between the discrete energy levels equals exactly to that of the phonon. Thus, it is expected that S/N ratio in QDIPs will be significantly larger than that of QWIPs.

- Lower dark current of QDIPs is expected than that of HgCdTe detectors and QWIPs due to 3-D quantum confinement of the electron wavefunction.

Both the increased electron lifetime and the reduced dark current indicate that QDIPs should be able to provide high temperature operation. In practice, however, it has been a challenge to meet all of above expectations.

Carrier relaxation times in QDs are longer than the typical 1–10 ps measured for quantum wells. It is predicted that the carrier relaxation time in QDs is limited by electron-hole scattering, rather than phonon scattering. For QDIPs, the lifetime is expected to be even larger, longer than 1 ns, since the QDIPs are the majority carrier devices because of the absence of holes.

The main disadvantage of the QDIP is the large inhomogeneous linewidth of the quantum-dot ensemble variation of a dot size in the Stranski-Krastanow growth mode. As a result, the absorption coefficient is reduced, since it is inversely proportional to the ensemble linewidth. Subsequently, the quantum efficiency of QD devices tend to be lower than what is predicted theoretically. As in other type of detectors, also nonuniform dopant incorporation adversely affects the performance of the QDIP. Therefore, improving the QD uniformity is a key issue in the increasing absorption coefficient and improving the performance. Thus, the growth and design of unique QD heterostructure is one of the most important issues related to achievement of state-of-the art QDIP performance.

3. Performance limits of QDIPs

In further considerations, a simple QDIP model developed by Ryzhii et al. is adapted. The QDIP consists of a stack of QD layers separated by a wide-gap material layers. Each QD layer includes periodically distributed identical QDs with the density $\Sigma_{QD}$ and sheet density of doping donors equal to $\Sigma_D$. It is assumed that the lateral size of QDs, $a_{QD}$, is sufficiently large in comparison with transverse size, $l_{QD}$. Consequently, a single energy level associated with the quantization in the transverse direction exists. The excited state coincides with the barrier conduction band minimum. Relatively sufficient large lateral size, $l_{QD}$, causes a large number of bound states in dots and, consequently, is capable of accepting a large number of electrons. Instead, the transverse size is small in comparison with the spacing between the QD layers, $L$. The QDIP active region (the stack of QD arrays) is sandwiched between two heavily doped regions which serve as the emitter and collector contacts.

Material parameters that are used for QDIP calculations are listed in Table 1. They are representative for self-assembled InAs/GaAs quantum dots reported in the literature.
Table 1. Material parameters of quantum dots in QDIP calculations

| \(a_{QD} \) | \( \Sigma_{QD} \) | \( \Sigma_D \) | \( L \) | \( K \) | \( N_{QD} \) | \( \varepsilon_r \) | \( m^*/m \) |
|-----------|-------------|-------------|------|------|----------|---------|--------|
| 15 nm     | \( 10^{11} \) cm\(^{-2} \) | \( 6 \times 10^{10} \) cm\(^{-2} \) | 100 nm | 10   | 6        | 12      | 0.023  |

Figure 2 compares the thermal detectivities of various photodetectors with cutoff wavelength in MWIR (\( \lambda_c = 5 \mu m \)) and LWIR (\( \lambda_c = 10 \mu m \)) regions. In the calculations, carried out for different material systems we have followed the procedures described in details in Refs. 17 and 18. The assumed typical quantum efficiencies are indicated in the figure. Theoretical estimations for QDIPs are carried out assuming low quantum efficiency \( \approx 2\% \) (often measured in practice) and 67\%. The last value is typical for HgCdTe photodiodes (without antireflection coating). It should be noticed, however, that a rapid progress has recently been made in the performance of QDIP devices, especially at near room temperature. Lim et al. have announced a quantum efficiency of 35\% for detectors with peak detection wavelength around 4.1 \( \mu m \).\(^{19}\)

![Figure 2](image-url)

**Figure 2.** The predicted thermal detectivity versus temperature for various MWIR (\( \lambda_c = 5 \mu m \)) (a) and LWIR (\( \lambda_c = 5 \mu m \)) (b) photodetectors. The assumed quantum efficiencies are indicated.

Estimation of detectivity for InAs/GaInSb strained layer superlattices (SLSs) are based on several theoretical papers. Early calculations showed that a LWIR type-II InAs/GaInSb SLS should have an absorption coefficient comparable to an HgCdTe alloy with the same cutoff wavelength.\(^{20}\) Figure 2(b) predicts that type-II superlattices are the most efficient detector of IR radiation in long wavelength region. It is even a better material than HgCdTe; it is characterized by high absorption coefficient and relatively low thermal generation rate. However, hitherto, this theoretical prediction has not been confirmed by experimental data. The main reason of that is an influence of Schockley-Read generation-recombination mechanism, which causes lower carrier lifetime (higher thermal generation rate). It is clear from this analysis that the fundamental performance limitation of QWIPs is unlikely to rival HgCdTe photodetectors. However, the performance of a very uniform QDIP is predicted to rival with HgCdTe.

4. Experimental verification

4.1. Detectivity at 78 K

A useful figure of merit, for comparing detector performance, is thermally limited detectivity. Figure 3 compares the highest measurable detectivities at 77 K of QDIPs found in literature with the predicted detectivities of P-on-n HgCdTe and type II InAs/GaInSb SLS photodiodes. The solid lines are...
theoretical thermal limited detectivities for HgCdTe photodiodes, calculated using a 1-D model that assumes the diffusion current from a narrower band gap n-side to be dominant and decisive contribution of the minority carrier recombination via Auger and radiative process. In calculations of typical values for the p-side donor concentration ($N_d = 1 \times 10^{15} \text{ cm}^{-3}$), the narrow bandgap active layer thickness (10 µm), and quantum efficiency (60%) have been used. It should be insisted, that for HgCdTe photodiodes, theoretically predicted curves for temperature range between 50 and 100 K coincide very well with experimental data (not shown in Fig. 3). The predicted thermally limited detectivities of the type II SLS are larger than those for HgCdTe.\textsuperscript{21}

![Graph](image-url)

**Figure 3.** The predicted detectivity of P-on-n HgCdTe and type II InAs/GaInSb SLS photodiodes, compared with measured QDIP detectivities at 77 K (after Ref. 17).

The measured value of QDIPs’ detectivities at 77 K gathered in Fig. 3 indicate that QD device detectivities are as yet considerably inferior to the current HgCdTe detector performance. In LWIR region, the upper experimental QDIP data at 77 K coincide with HgCdTe ones at a temperature 100 K.

4.2. Performance at higher temperatures

One of the main potential advantages of QDIPs is the low dark current. In particular, the lower dark currents enable higher operating temperatures. Up till now, however, most of the QDIP devices reported in the literature have been working in the temperature range from 77 to 200 K. On account of this fact, it is interesting to insight on achievable QDIP performance in temperature range of above 200 K in comparison with other type of detectors.

Most modern infrared devices are fabricated from two pieces of material – a detector array made from compound semiconductor materials and a silicon signal processing chip called a readout integrated circuit (ROIC).

To receive high injection efficiency, the input impedance of the readout MOSFET must be much lower than the internal dynamic resistance of the detector at its operating point, and the following condition should be fulfilled

$$IR_d \gg \frac{nkT}{q},$$

where $R_d$ is the dynamic impedance of the detector and $I$ is the total injected detector current (the sum of the photocurrent and the dark current) equal to the photocurrent, $I_{ph}$, in the background-limited case. $n$ is the ideality factor that can vary with temperature and geometry of the transistor and usually it is in the range 1–2.
Generally, it is not a problem to fulfil this inequality for short wavelength infrared (SWIR) and middle wavelength infrared (MWIR) focal plane arrays (FPAs) where the dynamic resistance of detector $R_d$ is large, but it is very important for LWIR designs where $R_d$ is low. There are more complex injection circuits that effectively reduce the input impedance and allow lower detector resistance to be used.

The above requirement is especially critical for near-room temperature HgCdTe photodetectors operating in the LWIR region. Their resistance is very low due to a high thermal generation. In materials with a high electron to hole ratio such as HgCdTe, the resistance is additionally reduced by ambipolar effects. Small size uncooled 10.6-μm photodiodes (50×50 µm²) exhibit less than 1 Ω zero bias junction resistances which are well below the series resistance of a diode. As a result, the performance of conventional devices is very poor, so they are not useful for practical applications. To fulfil inequality (1) to effectively couple the detector with silicon readout, the detector incremental resistance should be $R_d >> 2 \Omega$. As Figure 4 shows, the saturation current for 10-μm photodiode achieves 1000 A/cm² and it is by four orders of magnitude larger than the photocurrent due to the 300 K background radiation. The potential advantages of QDIPs are a considerably lower dark current and higher $R_oA$ product in comparison with HgCdTe photodiodes (see Figure 5).

![Figure 4](image1.png)

**Figure 4.** Dark current density of HgCdTe photodiodes and QDIPs, and background-generated photocurrent as a function of wavelength. The calculations for HgCdTe photodiodes have been performed for the optimized doping concentration.

![Figure 5](image2.png)

**Figure 5.** $R_oA$ product of HgCdTe photodiodes and QDIPs as a function of wavelength. The calculations for HgCdTe photodiodes have been performed for the optimized doping concentration.

Figure 6 compares the calculated thermal detectivity of HgCdTe photodiodes and QDIPs as a function of wavelength and operating temperature with the experimental data of uncooled HgCdTe and type-II InAs/GaInSb SLS detectors. The Auger mechanism is likely to impose fundamental limitations to the LWIR HgCdTe detector performance. The experimental data for QDIPs are gathered from the literature for detectors operating at 200 and 300 K.

Uncooled LWIR HgCdTe photodetectors are commercially available and they are manufactured in significant quantities, mostly as single-element devices. The results presented in Figure 6 confirm that the type-II superlattice is a good candidate for IR detectors operating in the spectral range from the mid-wavelength to the very long-wavelength IR. The comparison of QDIP performance both with HgCdTe and type II superlattice detectors gives clear evidence that the QDIP is suitable for high temperature. Especially encouraging results have been achieved for very long-wavelength QDIP devices with a double-barrier resonant tunnelling filter with each quantum-dot layer in the absorption
In this type of devices, photoelectrons are selectively collected from the QDs by resonant tunnelling, while the same tunnel barriers block electrons of dark current due to their broad energy distribution. For the 17-µm detector, a peak detectivity of $8.5 \times 10^6$ cmHz$^{1/2}$/W has been measured. Up till now, this novel device demonstrates the highest performance of room-temperature photodetectors.

![Figure 6. Calculated performance of Auger generation-recombination limited HgCdTe photodetectors as a function of wavelength and operating temperature. BLIP detectivity has been calculated for $2\pi$ FOV, the background temperature is $T_{BLIP} = 300$ K, and the quantum efficiency $\eta = 1$. The experimental data is taken for commercially available uncooled HgCdTe photoconductors (produced by Vigo System) and uncooled type-II detectors at the Center for Quantum Devices, Northwestern University (U.S.). The experimental data for QDIPs are gathered from the marked literature for detectors operating at 200 and 300 K (after Ref. 17).](image)

The room-temperature operation of thermal detectors makes them lightweight, rugged, reliable, and convenient to use. However, their performance is modest, and they suffer from slow response. Because they are nonselective detectors, their imaging systems contain very broadband optics, which provide impressive sensitivity at a short range in good atmospheres.

Thermal detectors seem to be unsuitable for the next generation of IR thermal imaging systems, which are moving toward faster frame rates and multispectral operation. A response time, much shorter than that achievable with thermal detectors, is required for many nonimaging applications. Improvement in technology and design of QDIP detectors make it possible to achieve both high sensitivity and fast response at room temperature.

5. Conclusions

At present, HgCdTe is the most widely used variable-gap semiconductor that has a privileged position both in the MWIR as well as LWIR spectral ranges. Theoretical predictions indicate that only the type II superlattice photodiodes and QDIPs are expected to compete with the HgCdTe photodiodes. However, the measured values of QDIPs’ detectivities at 77 K are considerably inferior to the current HgCdTe detector performance. Improving QD uniformity is a key issue in the increasing absorption coefficient and improving the performance.

The comparison of QDIP performance both with HgCdTe and type II superlattice detectors gave clear evidence that the QDIP is suitable for high operation temperature. Due to the fact that conventional HgCdTe photodiodes are not usable for room temperature FPA applications, it can be expected that improvement in technology and design of QDIP detectors will make it possible to achieve both high sensitivity and fast response useful for practical application in room temperature operations.
FPAs. Larger operating speed of QDIP and multispectral capability are considerable advantages in comparison with thermal detectors.

Optimization of the QDIP architecture is still an open area. Since some of the design parameters depend on a device structure, the performance is still being improved.

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