Invited paper

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Quantum dot infrared photodetector

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This paper discusses key issues related to the quantum dot infrared photodetector (QDIP). These are the normal incidence response, the dark current, and the responsivity and detectivity. We attempt to address the following questions of what is QDIP's potential, what is lacking, and what is needed to make the device interesting for practical applications. It is argued that so far the present QDIP devices have not fully demonstrated the potential advantages. Representative experimental results are compared with characteristics of quantum well infrared photodetectors. Areas that need improvements are pointed out.

Keywords: quantum dot, infrared, photodetector, normal incidence, dark current, responsivity.

1. Introduction

The area of research on infrared detectors utilizing semiconductor quantum or nanostructures has been an active one. Drawing a similarity to the success of the quantum well infrared photodetector (QWIP) [1,2], the quantum dot infrared photodetector (QDIP) has attracted a lot of interests in recent years [3–13]. QWIPs, especially those made of GaAs/AlGaAs epitaxial materials, have been successful because they are based on the mature GaAs materials and fabrication technologies. Presently QWIPs are being commercialised for infrared imaging applications. Other areas such as high-speed detection [14–16] may also find practical applications. An ideal QDIP is expected to be substantially superior than QWIP. The area of QDIP research is therefore very active in the last a few years.

Generically, QDIPs are similar to QWIPs with the quantum wells replaced by quantum dots. Quantum dots discussed here are those having size confinement in all spatial directions. A schematic of the layered structures of a QWIP and a (ideal) QDIP is shown in Fig. 1. The most widely studied QDIPs are made of self-assembled InAs dots on GaAs substrates. For these dots there is commonly a thin wetting layer of InAs, however, in the discussion here we neglect any explicit effects of the wetting layer. The detection mechanism in both QWIPs and QDIPs relies on the intraband photoexcitation of electrons from confined states in the conduction band wells or dots into the continuum. If one draws the potential (bandedge) profile along the growth direction, QWIPs and QDIPs would have a similar shape shown in Fig. 2. If the dots are aligned in the growth direction, the potential profile would be exactly the same. However, because the barriers are usually wide to suppress dark current, dots are not correlated between layers. All discussions and estimates here are independent of the position correlation among the dots. We assume that barriers between any adjacent dots are sufficiently wide so that tunnelling can be neglected.

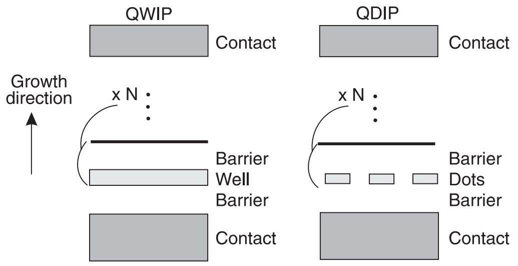

Fig. 1: Schematic layers of a QWIP (left) and QDIP (right). In the QDIP case, the dot cross-section is shown as rectangular, approximating the shape of our dots. The wetting layer is neglected.

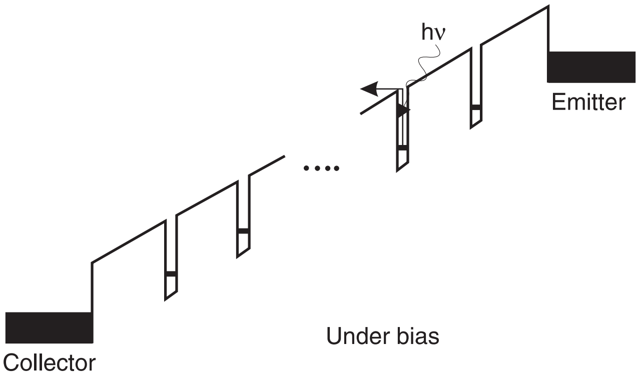

Fig. 2: Schematic potential profile for both QWIPs and QDIPs. The detection mechanism in both devices is by intraband photoexcitation.

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This paper discusses the potential advantages of QDIP over QWIP, compares preliminary experimental results on QDIPs with standard QWIPs, and points out areas that need improvements. We attempt to give an analytical and intuitive model to address the key physics.

2. Anticipated advantages and current status

One of the major selling points is that "QDIPs allow normal incidence". That is, the incident light normal to the wafer along the growth direction is expected to cause intraband absorption unlike the standard n-type QWIPs [17]. The normal incidence property is advantageous because it avoids the need of fabricating a grating coupler in the standard QWIP imaging arrays [2]. The grating coupler not only adds at least one extra fabrication step but also causes difficulties in realizing a wide and multiple wavelength coverage because of its spectrally peaked nature and in fabricating a short wavelength coupler because of the required small grating features. Indeed, normal incidence response in QDIPs has been reported in several publications [3,5,7,10,13]. Unfortunately most publications do not show polarization dependence of the photocurrent spectra, and some [6,8,11] show dominant P-polarised response in the 45-degree facet geometry, very similar to QWIPs measured in the same geometry under flood illumination. In one publication [18] on absorption measurements clear evidence of absorption features due to in-plane confined quantum dot levels was reported. It seems that a dominant normal incident response in present QDIPs has not been achieved. This is also the conclusion of our recent experiments on a number of QDIPs where the dominant response comes from light polarized in the growth direction. Figure 3 shows spectra of two of our samples under both P and S-polarized lights in the 45-degree facet geometry. Clearly the P-polarized response is much stronger than that for S.

The problem is believed to be due to the fact that self-assembled quantum dots grown so far for QDIPs are wide in the in-plane direction (~20 nm) and narrow in the growth direction (~3 nm). The strong confinement is therefore in the growth direction; while the in-plane confinement is weak, resulting in several levels in the dots. The transitions between in-plane confined levels give rise to the normal incidence response. From the ground state, the transition oscillator strength reduces for higher final states. In other words, the transitions within the dots (which do not result in a detection photocurrent because the excited electrons cannot escape) exhaust most of the in-plane oscillator strength. In contrast, in the growth direction, the high oscillator strength transition is the one going into the continuum resulting in the dominant photocurrent. This point is illustrated in Fig. 4. The strong confinement in the growth direction is represented by a narrow well; whereas the in-plane weak confinement leads to several states. For conceptual simplicity, the confinement potentials are represented by one-dimensional wells separately in z and x–y directions.

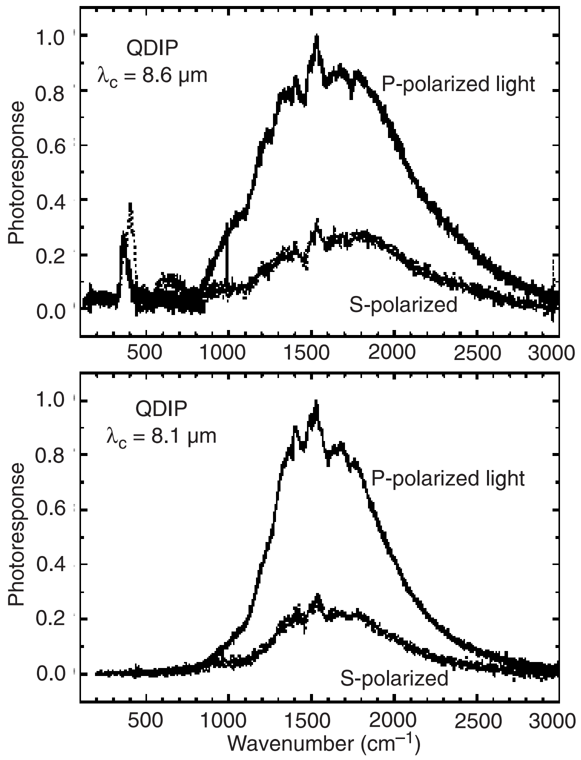

Fig. 3: P- and S-polarized spectral response curves in the 45-degree facet detector geometry. The QDIPs have 50 layers of InAs dots separated by 30-nm GaAs barriers. The dot density is about 5×10^9 cm^{-2}. The number of electrons is estimated to be (for the top panel) six per dot, due to the delta-modulation Si doping in the barriers; and (for the bottom panel) one per dot, due to the background doping. The cutoff wavelength λ_c (defined as the 50% response point) is indicated. The spectra in the top panel show small features (some mainly S polarized) in 300–800 cm^{-1} region, which are believed to be caused by the inter-lateral-level transitions and are presently under further investigation.

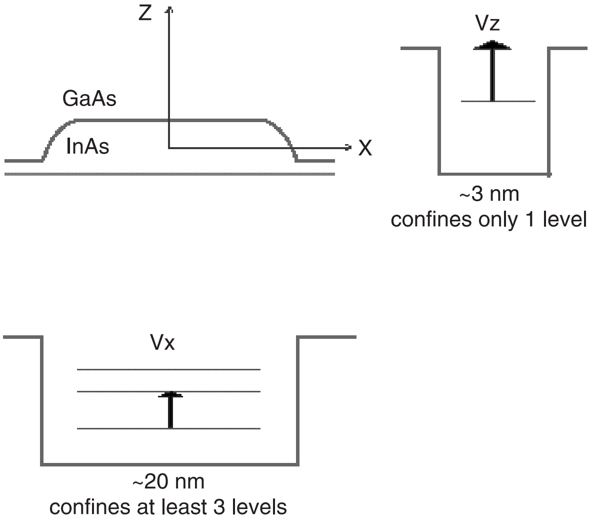

Fig. 4: Illustration of transitions under polarized light in the growth direction (z) or in the in-plane directions (x or y). The strong confinement in the growth direction is represented by a narrow well; whereas the in-plane wide potential well leads to several states. The upward arrows indicate the strongest transitions for z and x polarized lights.

Another potential advantage of QDIPs over QWIPs is that "QDIPs have lower dark currents" [19]. Since dark current causes noise a lower dark current leads to a higher detector sensitivity. The simplest way to estimate dark current is by counting the mobile carrier density in the barrier and then the current is given by multiplying the carrier velocity. We use the following expression [1]

$$j_{dark} = e\upsilon n_{3D}, \tag{1}$$

where υ is the drift velocity and n_{3D} is the three-dimensional (3D) density, both for electrons in the barrier. Equation (1) neglects the diffusion contribution. The electron density can be estimated by [1]

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

where m_b is the barrier effective mass and E_a 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. We have assumed that $E_a/k_BT >> 1$, appropriate for most practical cases. Equation (2) can be easily derived by integrating the 3D density of state and Fermi distribution above the barriers. For similar barriers in a QWIP or a QDIP (i.e., υ and m_b are comparable), the difference in E_a gives rise to a difference in dark current. If we neglect the field induced barrier lowering effect in E_a which makes the estimation valid for low applied fields (but not too lower so that diffusion must be considered), the activation energy relates to detection cut-off wavelength (λ_c) by

$$E_a^{QWIP} = \frac{hc}{\lambda_c} - E_f, \tag{3}$$

for a QWIP with a bound-to-continuum detection scheme, and for QDIP

$$E_a^{QDIP} = \frac{hc}{\lambda_c}, \tag{4}$$

where E_f is the Fermi level in the well. The term E_f in Eq. (3) is due to the subband nature of QWIP quantum wells: intersubband transition is from all electrons in a subband at the same energy whereas the thermal activation energy is from the top of the Fermi sea. Given that the optimal design for a QWIP is having $E_f = 2k_BT$ for maximizing detectivity or $E_f = k_BT$ for maximizing operating temperature [1], the reduction in dark current in QDIPs vs. QWIPs for the same cut-off wavelength and barrier material is only in the range of a factor of about 3–7. This is an ideal expectation.

The devices tested so far are far from ideal and have shown much higher dark currents far from the ideal estimate. Figure 5 shows a comparison of current-voltage characteristics at 77 K. The two QDIPs are the same devices as in Fig. 3. For a "fair" comparison, the chosen QWIP has the same cutoff wavelength of 8.6 µm as one of the QDIPs. Even the shorter wavelength QDIP (λ_c = 8.1 µm) with lower electron occupation has a substantially higher dark current than that for the QWIP. Effects such as ionised dopant induced potential fluctuations could be the cause of the excess dark current [20].

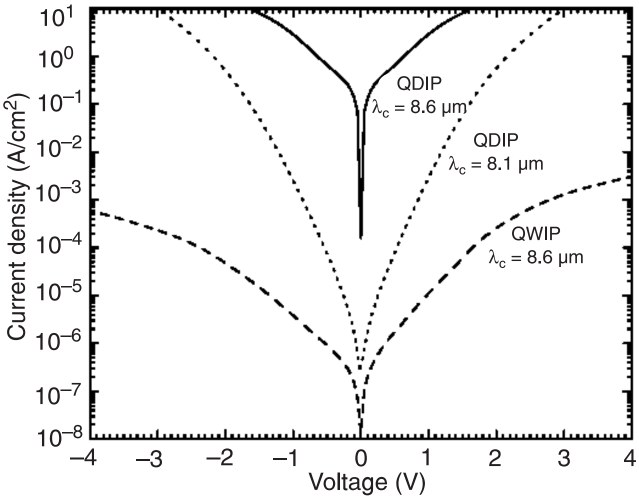

Fig. 5. Dark current characteristics for a QWIP and QDIPs with the same cutoff wavelength. The QWIP has 32 GaAs wells center delta-doped with Si to 5×10^{11} cm^{-2} and undoped AlGaAs barriers, with a total device thickness of 1.58 µm. The QDIPs are the same as in Fig. 3.

The final advantage relates to the potentially long excited electron lifetime τ_{life}. It has been anticipated [21] that the relaxation of electrons is substantially slowed when the inter-level spacing is larger than the phonon energy – "phonon bottleneck". This effect has been investigated extensively [22], and the topic is still under debate and controversial. If the phonon bottleneck can be fully implemented in a QDIP, the long excited electron lifetime directly leads to a higher responsivity, higher operating temperature, and higher dark current limited detectivity. The reason is very simple since a photoconductor responsivity is given by

$$R = \frac{e}{h\nu}\eta g, \tag{5}$$

where ν is the photon frequency, η is the absorption efficiency, and g is the photoconductive gain

$$g = \frac{\tau_{life}}{\tau_{trans}}, \tag{6}$$

where τ_{trans} is the transit time across the device. A long τ_{life} directly translates into a large R. High operating temperature and high detectivity are immediate consequences. Ryzhii *et al.* [23] recently analysed the detectivity and made comparisons between QWIPs and QDIPs having the same ground state ionisation energy (not the same cut-off wavelength). Their main conclusions are similar to those reached here.

Experimentally, the situation is very encouraging in the measured magnitude of the infrared responsivity, often comparable to that for a QWIP. This is an indirect evidence of the long lifetime: the high measured responsivity [10,13] despite the small absorption efficiency very often not directly measurable.

3. Areas of improvement

To realize a strong and dominant normal incident response, first and foremost is to make the dots small so that the in-plane confinement leads to one or two bound states. In the latter case, the second state should be very close to the top of the barrier. This will allow strong and dominant normal incidence absorption. If a broader response spectrum is desired, one could have two or more states in the dots, all occupied with electrons; but no unoccupied states should exist, which are deep in the dot potential.

To have a good detector, the absorption efficiency must be high. This requires a high dot density. To have a comparable absorption as in QWIPs, the electron density per layer of dots should in the range of $(2–10)\times10^{11}$ cm^{-2}. If there are two electrons occupying every dot, the dot density should be in the range of $(1–5)\times10^{11}$ cm^{-2}. For six electrons per dot, the density reduces to $(3–17)\times10^{10}$ cm^{-2}. The dot densities commonly achieved are in the range of $(0.01–1)\times10^{10}$ cm^{-2}. Some improvement in this area is therefore needed. The desired high dot density necessarily requires small dot size. For example of the extreme case, for a dot density of 5×10^{11} cm^{-2}, the dot size must be smaller than 14 nm in diameter.

To populate dots with electrons one needs doping. In a QWIP, this can be simply done by directly doping the wells. Since the doping density is high and degenerate, the effect of random dopant distribution is minor and is expected to only lead to a broadening in the absorption linewidth. In a QDIP, however, if the doping is done in the same layer as the dots, the random distribution could lead to a significant potential fluctuation. Moreover, if the doping is done in the barriers (modulation doping), the random distribution of the ionised dopants could lead to leakage current path. Similarly, ionised dopants in the wetting layers could also lead to leakage path. Detailed modelling and doping control are needed to fully account for the effect of doping and realize the lower dark current.

There are alternative designs of QDIPs to further enhance the photoconductive gain such as those in Refs. 24, 25, and 26. These are interesting directions (not available to QWIPs) that explore the uniqueness of quantum dots.

In conclusion, we are still far from realizing all the projected advantages. QDIPs have very attractive potentials if the growth/fabrication technology delivers the design requirements. The key areas of improvements are making the dots smaller and denser, and having better doping controls.

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