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REVIEW

Progress and Prospects for Quantum Dots in a Well Infrared Photodetectors*

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Over the past fifteen years, there has been significant interest in developing intersubband quantum dot (QD) detectors for the mid-(MWIR) and long-wave infrared (LWIR) regimes. This class of detectors is generally referred to as quantum dot infrared photodetectors, or QDIPs. At present, one of the leading technologies is that of the quantum dots-in-a-well infrared photodetector, called a DWELL-IP or just a DWELL detector. The DWELL name comes from the active region's structure, which consists of a layer of quantum dots imbedded in (or in some cases grown on) a quantum well. This dot/well combination is similarly surrounded by a barrier material. Here, we identify the major players and their contributions to the evolution of the DWELL-IP. While this dot/well/barrier material combination originally consisted of InAs/InGaAs/GaAs, the materials used has widened in recent years. This paper reviews the progress to date for this quickly advancing field. Some of these advancements have come from the additional focus that has been brought to bear on the physical understanding and experimental mechanics of the structure itself. Explorations into the multi-spectral nature of these detectors have also created unique applications for these detectors. This type of QDIP is now becoming the dominant detector of its class and is quickly heading for parity with quantum well infrared photodetectors (QWIPs) that are presently commercially dominant. Given the potential utility of the infrared spectrum for applications in medicine, military, industrial, and academic fields the DWELL-IPs potential to be an inexpensive, versatile, multi-spectral, infrared detector indicates it has a bright future.

Keywords: Quantum Dot, III–V, Photodetector, Infrared, DWELL, Semiconductor, Quantum Well.

CONTENTS

1. INTRODUCTION

There has been a lot of interest in realizing infrared (3–25 μm) detectors based on intersubband transitions in quantum dots in the past decade. Early theoretical work[1] was followed by the observation of mid infrared photoconductivity in quantum dots.[2–6] The main reasons that the quantum dots have generated a lot of interest are due to three key factors. Firstly, the quantum dots are expected to show normal incidence operation unlike their quantum well counterparts, (Quantum Well Infrared Photodetectors, QWIPs), which are restricted by polarization selection rules that limits absorption for light that has an electric field in the direction of the quantum well confinement. The second reason that the QDIPs have generated

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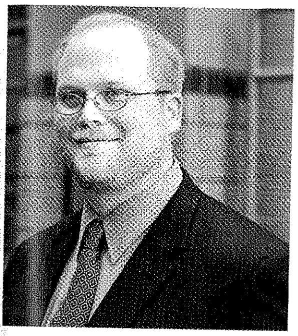
a lot of interest is due to the possibility of obtaining an increased carrier lifetime because of the suppression of Phonon scattering. This phenomenon, also referred to as a "Phonon Bottleneck," is expected to increase the signal to noise ratio of the infrared detector. Thirdly, quantum dots are expected to have a lower dark current due to three dimensional confinement, which would lead to an increased operation temperature of these detectors. However, in spite of active research, the QD based devices have not been able to live up to their potential. For example, there is considerable dispute in the literature about the presence of a phonon bottleneck in the existing Stranski-Krastonow (SK) dots.

One interesting variation of the QDIPs that has been explored is the quantum dots in a well heterostructure that is discussed in detail in the next few sections. In this architecture, quantum dots are placed in quantum wells to engineer transitions from the ground state in the dot to a state in the well. This leads to more reproducible control in the operating wavelength and enhanced quantum confined Stark effect (QCSE) that leads to bias tunable spectral response. Thus the DWELL design is expected to combine the advantages of the QWIPs such as good "dial-in-recipes" with the advantages for the QDIPs such as lower dark current and normal incidence operation.

2. UNIVERSITY OF NEW MEXICO GROUP

As the progenitors of DWELL detectors it is not surprising that the work by the Krishna group at The Center for High Technology Materials (CHTM) at the University of New Mexico (UNM) is probably the most all encompassing. They work with single pixel devices and focal plane arrays (FPAs). In addition to trying to improve the basic key parameters of the detectors (QE, noise/temperature of operation, spectral sensitivity, etc.), they work on modeling



Thomas E. Vandervelde (M'03) earned two B.S. degrees from the University of Massachusetts, Amherst, one in physics and the other in astronomy, both in 1999, his M.A. and Ph.D. degrees in Physics at the University of Virginia, Charlottesville, in 2001 and 2004, respectively. He is the John Adams Endowed Chair Professor in the Electrical and Computer Engineering Department at Tufts University. He joined the faculty at Tufts as an assistant professor in 2008. He joined CHTM as a research assistant professor in 2007. Prior to his present employment, he was a Research Assistant Professor at the Center for High Technology Materials at the University of New Mexico and a Post-Doctoral Fellow at University of New Mexico with Sanjay Krishna in 2007, University of Illinois Urbana-Champaign with Milton Feng in 2005–2006, and University of Virginia with Michael Skrutskie in 2004–2005. Additionally, he also was a Visiting Assistant Professor of Physics at Washington and Lee University in 2004–2005. He has authored/co-authored over 30 peer-reviewed journal articles, over 30 conference presentations, three book chapters, and has one provisional patent. His current and previous research interests are group IV and III–V materials for photodetectors, photovoltaics/thermophotovoltiacs, nanophysics/devices, and hetero-integrated circuits. Professor Vandervelde was recently on the executive committee for the local IEEE LEOS chapter in Albuquerque and in addition to IEEE and IEEE-LEOS, he is a member of APS, SPS, AAS, Eta Kappa Nu, Sigma Xi, MRS, TMS, AVS, and AAAS.

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the DWELL designs and running fundamental experiments to understand how the DWELL works. They work on improving the material that makes up the DWELL, how it is deposited, how it is processed, and how the devices are utilized to optimize the performance. The results for each of these efforts are detailed below.

2.1. The Classic DWELL

The classic or standard DWELL detector, to which we will refer throughout this article is the one used by the CHTM group initially.[7–10] As discussed in the above, this structure consists of InAs QDs in a 15% InGaAs QW. This well is then surrounded by GaAs barriers. The width of this well is tuned such that the transition from the QD to the QW is in the 8–12 micron range. In addition to this transition, there is also a transition from the QD to the continuum that falls in the 4–6 micron range.[10]

2.2. Fundamental Experiments

While most of the other groups have been focused primarily on monochromatic response for their DWELL FPAs, the group at UNM has been focused on bringing color to the infrared spectrum from the beginning.[11–14] As mentioned above, most designs, therefore, have two strong responses, one in the MWIR and one in the LWIR. This single bump, multicolor, technique provides enhanced utility for the detector in the applications mentioned in the introduction. For example, being able to examine a scene at two wavelengths removes the ambiguity generated by objects having different emissivity. This ability to differentiate objects is also the beginning of spectroscopy, enabling the fine differentiation between chemicals, biological agents, or types of tissues for medical and security applications.[10]

Additional fundamental experiments were carried out during this period as well. These studies included characterizing the effects of critical processing steps such as rapid thermal annealing, theoretical modeling, and the empirical effects of varying different growth parameters.[15–30] These types of experiments are nearly infinite in variety and each can yield new information, so they are still ongoing at CHTM and have been repeated and expanded upon by other groups (detailed below).

2.2.1. RTA

A common element in the fabrication process of photodetectors involves an annealing step for the creation of ohmic contacts. To determine what effect this process had, an extensive study was performed using a rapid thermal annealer (RTA).[15] It was observed that as RTA process temperatures and duration were increased the degree of blue-shifting observed also increased. The shift, however, was not enough to present serious problems and could be minimized while maintaining high contact quality. It was concluded that since the QDs are a metastable phenomena, the blue-shifting represented intermixing of the QD material with the surrounding matrix.

2.2.2. Structural Variations

Once the standard DWELL design was shown to have a great deal of promise, the CHTM group set about optimizing its structure and testing alternate designs. The first alternate design was an increase in barrier height to decrease dark current. To accomplish this within the structure AlGaAs blocking layers were introduced.[16] This was successful and reduced the dark current significantly, however, it also reduced the responsivity as well. This decrease was determined to be partially due to lack of optimization and continued work led to dots-in-a-double-well (DDWELL) design among others detailed below. In addition to barrier height, well width and general layer thicknesses were also optimized.[17–18] Here, the CHTM group found a maximal response with an 11 nm wide well. The asymmetric well also exhibited a difference in response between forward and reverse bias, which was concluded to be due to quantum confined stark effect (QCSE).

2.2.3. Doping

Issues of optimal doping profiles and carrier dynamics were also explored by the CHTM group.[19–23] Experiments were conducted to determine if it was best to dope the wells and leave the QDs intrinsic or vice versa and what level of doping would yield the best result. These experiments determined a maximal result for the doping of the QD at a level of one electron per QD. This was accomplished by growing an undoped wetting layer and then doped QD-layer. With this growth technique it was presumed that the doping was preferentially locating in the QDs and not in the wetting layer.

2.2.4. Modeling

The CHTM group also began a collaboration, which is discussed in more detail below, to model the performance of DWELL detectors.[24–25] Using a Greene's Theorem approach they were able to develop a model with high degree of fit when comparing to experimental results. This marks the beginning in the development of a theoretical toolbox to be used for quickly modeling variant structures and designs saving considerable time and resources over the present empirical methods.

2.2.5. FPAs

While the CHTM group performs its leading edge experimentation on single pixel devices they incorporated the successful designs into full FPAs.[26–30] In

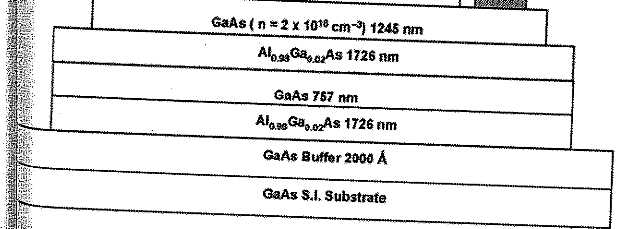
FPA designs were 320 × 256 pixels. Since those initial designs, 640 × 512 designs were created in conjunction with NASA–JPL (detailed below). Greater responsivity and detectivity as well as improved spectral response have characterized each successive generation of FPAs produced by the CHTM group. At present, their best result is NETD = 70 mK at 70 K.

2.3. Resonant Cavity

One of the techniques explored by the CHTM group to improve DWELL performance was to create a resonant cavity to increase the number of passes incident photons make through the active region and, therefore, enhance the quantum efficiency.[31] The resonant cavity (RC) is formed using a DBR at the bottom of the stack; the natural semiconductor-air interface is all that is used at the top for this design, Figure 1. This RC-DWELL was designed to enhance the LWIR signal, which does enhance by approximately a factor of 3, Figure 2.[31]

2.4. Dots-in-a-Double-Well (DDWELL)

As mentioned above, the experimentation with AlGaAs barriers lead to a variant design. This included the use of a double-well.[32–35] In this structure the GaAs barriers are replaced with AlGaAs barriers and the role of the primary well is played by a GaAs layer, see Figure 3. Here, the InGaAs layer thicknesses, which constitute the second well, are reduced to a minimum and, therefore, the strain due to lattice mismatch with the GaAs substrate is also minimized. This enables larger stacks to be grown (30–80 repetitions of the active region). FPAs of this design are detailed below.



g. 1. A schematic of the structure for a processed resonant cavity C) DWELL, by adding the DBR at the bottom of the stack the indecent ht will make multiple passes through the active region enhancing QE. printed with permission from [31], R. S. Attaluri et al., *J. Vac. Sci. hnol. B* 25, 1186 (**2007**). © 2007, American Institute of Physics.

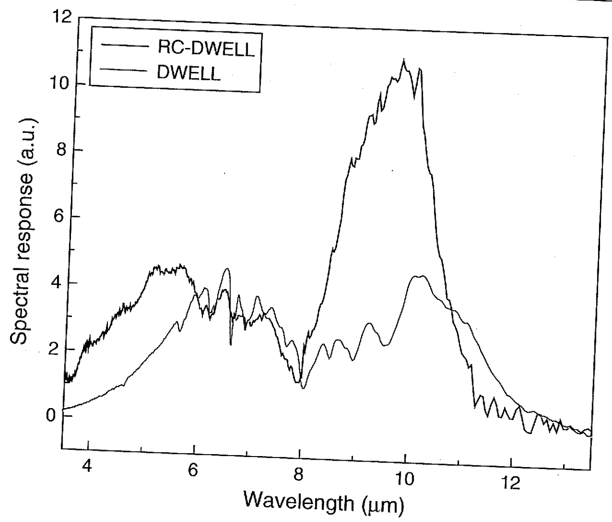


Fig. 2. Spectral response data for the RC-DWELL (upper curve) and the standard DWELL (lower curve) samples. All the spectra were taken at $T = 30$ K at a bias of $V_b = -1.8$ V. Reprinted with permission from [31], R. S. Attaluri et al., *J. Vac. Sci. Technol. B* 25, 1186 (**2007**). © 2007, American Institute of Physics.

With this alternate design, the CHTM group has been able to increase the temperature of operation (see below) as well as significantly decrease the dark current along with an order of magnitude increase in detectivity.[35] This design holds a great deal of promise and is presently being optimized for additional exploitation.

2.5. High Operating Temperature

No matter how good a photodetector may be, if it only works at cryogenic temperatures there are many potential applications that will not be possible. If a photodetector can be used above 150 K, then its field utility increases dramatically. This is the point at which a small inexpensive sterling cooler can take care of the cooling needs. The CHTM group has been exploring techniques to improve

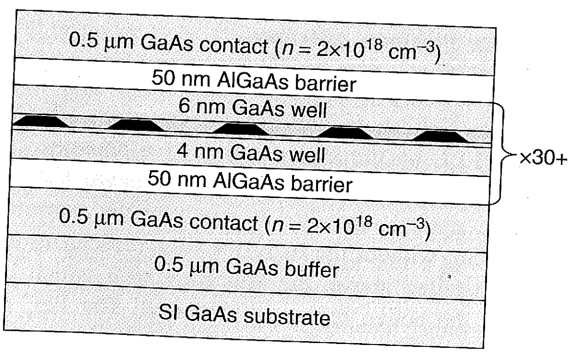


Fig. 3. A schematic for the structure of a low-strain DWELL, specifically a double DWELL or a DDWELL design. Here, a GaAs well acts as a primary well, surrounded by AlGaAs barriers. Inside the GaAs well, lies a minimized InGaAs well surrounding the InAs QDs. Reprinted with permission from [34], W.-Y. Jang et al., *IEEE Journal of Quantum Electronics* 45, 6 (**2009**). © 2009, Institute of Electrical and Electronics Engineers.

the operation temperature.[36–38] The DDWELL, detailed above, was able to operate at 140 K and with continued optimization is predicted to reach higher temperatures.

An alternate design was also created by the CHTM group specifically for the purpose of high temperature operation. This design utilized a new material option for the quantum well. Here, the QW was made of $In_{0.15}Ga_{0.65}Al_{0.1}As$ and the barriers were correspondingly raised to 10–30% AlGaAs. The downside of this new design is that it decreased the wavelength of operation by eliminating the longer wavelength response. As discussed in more detail below for the Northwestern Group's results, the dark current is automatically lower for shorter wavelengths, making high temperature operation easier. This design by CHTM raised temperature of operation to 250 K.[38]

2.6. Resonant Tunneling

Taking a page from some of the QDIP work performed at The University of Michigan Bhattacharya group,[39–43] the CHTM has recently begun efforts to use resonant tunneling (RT) barriers in an attempt to decrease the dark current.[44] The CHTM group focused on the LWIR peak and added a RT barrier to enhance it. This addition decreased the dark current by two to four orders of magnitude when compared to a control sample. Careful analysis of spectral response clearly demonstrates the effect of RT in these devices. Peak specific detectivity of $\sim 3.6 \times 10^9$ cm $Hz^{1/2}W^{-1}$ at 77 K, at a peak wavelength of 11 μm, for RT-DWELL device shows a factor of 5 improvement over the control sample, in this unoptimized structure. Reduction in responsivity can be compensated by a larger operating bias range, which is a direct consequence of the reduction in the dark current by RT barriers. The peak responsivity was 2.3 A/W at -2 V bias at 77 K, which gave conversion efficiency of 26%.

2.7. Photonic Crystals and Surface Plasmon Antennas

The CHTM Group also collaborated with the Painter Group from Caltech to enhance the quantum efficiency of the DWELL by the incorporation of a photonic crystal (PhC). Here, a two-dimensional hexagonal PhC was used as an optical resonator to improve the conversion efficiency. So, without the inclusion of a vertical resonant cavity as detailed above, the efficiency with which light couples to the active region is increased. The PhC represents a regular array of holes that is used to modify the local refractive index to provide localized modes in the "photonic" band structure.[45–47] The PhC has a grating effect that "diffracts" the normally incident radiation to the in-plane direction. The in-plane radiation then propagates extremely slowly at the Γ-point of the band structure, resulting in an increased interaction of the incident light with the active region.[48–49] With the inclusion of the PhC, they were able to increase the conversion efficiency from ~8% to 95% for the LWIR peak at a given bias. Since this approach is detector agnostic, it could be applied to any detector and will be improved and applied to future detector designs.

2.8. Algorithmic Spectrometer

As mentioned above, for different applied biases the wavelength response for the asymmetric DWELLs can vary quite widely: shifting by as much a couple microns. This bias dependant tunability can be advantageously applied. By temporally scanning through the biases while imaging a scene, the resultant spectral map of the scene allows for additional offline analysis. The set of images overlapping in spectral range allows one to discern spectral features much finer than the detector could resolve at any one bias.[50–52] This is similar to what the human eye does spatially by having sensors for each color, which are then combined to distinguish each color. The human eye is able to make sine distinctions between colors even though there is an 85% spectral overlap between the various responses. With this technique gas and other material identification becomes possible, turning the broader detector response into a fine tuned spectrometer.

3. SHEFFIELD UNIVERSITY

The Sheffield University group has a strong history of enhancing avalanche photodiodes.[53–58] Recently, they have started to explore the potential of DWELL detectors through collaboration with the CHTM group.[59–60] In this collaboration, they carried out a study on CHTM's DDWELL structure and were able to see a photoluminescent and spectral response from an 80-layer sample, which is the thickest working sample yet.

4. IR NOVA/LINKOPING UNIVERSITY (SWEDEN)

The work of the Swedish group is typified by their pursuit of in-depth understanding of the Q-based photodetectors. This has led them to explore the properties of the DWELL detectors more thoroughly than some groups.[61–62] While this approach has not, as of yet, yielded record breaking detector performance, it has confirmed what many believed to be true, but could not prove and has lit the path for modelers to follow.

Recently, the Swedish group performed an extensive scanning tunneling microscopy investigation of a DWELL structure made of InAs/InGaAs QDs in a GaAs matrix.[63] They were able to determine through XSTM that the Ga interdiffused with the InAs QDs leading to the average stoichiometry of $In_{0.67}Ga_{0.33}As$ in the QDs. As discussed earlier, this intermixing process alters the shape of the dots and is far more pronounced for structures using a pure Ga matrix without InGaAs capping or seeding layers. They describe the resultant structure as, "the shape of the dots is not well defined and can best be described by a broad oval base extending approximately over the bottom half of the InGaAs region and a narrow top region extending over the top half of the InGaAs region. Despite the significant diffusion of Ga into the QDs, no changes of the width of the QW can be observed." This observation adds further weight to the idea that the diffusion process is a localized phenomenon and is driven by interfacial energies; therefore, it should be able to me mitigated by surfactant-based or other diffusion limiting techniques. In addition to the observations on interdiffusion, the IR Nova group was also able to trace some of the defects in the GaAs layers to the Si doping. These results will help to create more realistic models enabling the community to further understand these promising structures.

Also in 2006, the Swedish group confirmed that the photocurrent in the DWELL structures was coming from the transition from the QD's ground-state to an excited level in the QW.[64] This study was conducted using Fourier transform photoluminescence. This further confirmed that the response of the detector could then be altered by changing the size of the QD or virtually dialed-in by simply varying the width of the well.

In 2008, this group went on to confirm the New Mexico results that showed the temperature and bias dependence of the DWELL IP.[65,66] They were able to observe additional transitions associated with states deeper in the well at higher biases. These transitions become available as their tunneling probability increases due to the effective thinning of the confining barrier with increased bias. Additionally, they observed the effects of bias and temperature on the dark current, which increases with the availability of new transitions and effective thinning of the barriers.

Also in 2008, they were also able to repeat CHTM's bias tunability results for their "D-on-WELL" design, which is a standard-DWELL without a strain reducing capping layer.[67] This alternate design increases the intermixing with their GaAs matrix, as noted in relation to their 2006 paper above. With this design they were able to achieve a tunability in the response from 8.4 to 10.3 microns. Detectors with this level of tunability could be of considerable importance for a variety of applications. As mentioned above, this tunability is the basis for being able to resolve fine spectral features as seen in CHTM's algorithm-based spectrometer.

5. AUSTRALIAN NATIONAL UNIVERSITY

The Australian National group has a long history with QDIPs and have consistently used various techniques to improve them. Their common toolbox includes explorations of selective area epitaxy/interdiffusion, implantation of various dopants and the effects of subsequent annealing, as well as more fundamental structural studies.[68–83]

Fig. 4. A schematic depiction of the layer structure for the Australian group's standard DWELL design.

This group primarily focuses their efforts on one of the variant DWELL detector design: AlGaAs barriers, GaAs well, and InGaAs QDs (see Fig. 4 below). They derived this alternative after comparing its response to a DWELL detector with InGaAs QDs and well with a GaAs barrier.[84] Predictably they saw a decrease in dark current and the PL peak was blue-shifted by 92 meV for the higher AlGaAs barrier. They, however, say a decrease in the detectivity and responsivity, which was attributed to the reduced responsivity of the AlGaAs detector are a reduced QD density, larger electron capture probabilities from the AlGaAs barrier layers into the QDs, the reduced electron mobility of the AlGaAs barriers, and different background doping densities of the AlGaAs and GaAs barrier layers. Despite these set-backs the photoresponse at 4.6 μm and the potential for improvement lead them to use this for their standard detector in research to come.

The barrier experiment was followed up by an experiment to optimize the well thickness of the variant detector design.[85] Using the same AlGaAs based variant discussed above they were able to reproduce the strong dot-to-well transitions with a spectral response that had a significant dependence on the QW thickness that had been observed by the CHTM group. This experiment demonstrated that the variant AlGaAs DWELL design also enables the spectral response to be tailored over a wide energy range while maintaining optimized QD growth conditions. They were also able to correlate changes in the QW widths with enhanced responsivity and detectivity. For their conditions this turned out to be a well width of 10 nm, which is similar to the 11 nm determined by the CHTM group for the standard DWELL design. At the conclusion of this test they determined that doping was still a key parameter to be optimized and felt this and the number of active region repetitions to be the most significant factors still limiting their detectivity.

6. McMASTER UNIVERSITY

The McMaster University group is solely focused on the theoretical modeling of the quantum dot structures. They have advanced the models considerably since starting work on the problem.[86–89] The model that they have developed can be used for studying the effect of varying the doping density, barrier separation between QD layers, and number of QD layers on the dark current among other things. One of the nice aspects of this model is its versatility: it can be applied to any QDIP structure to calculate the density of states, electron density, and dark current. This represents the beginning stages of the creation of a theoretical toolbox, which can be used to make quick comparisons between different QDIP structures and between the different design parameters of the same QDIP structure to improve the performance without the laborious experimental iterative techniques.

7. TUFTS UNIVERSITY

The group at Tufts University is a new player in the field of DWELL detectors, but its PI, Vandervelde has a long standing collaboration with the CHTM group[90–94] and an even longer history of maximizing the utility of quantum dots.[95–99] The strong collaboration with CHTM is expected to continue with the Tufts group focusing on low dark current multispectral DWELLs for use in infrared telescopes and general QD optimization issues.

8. NORTHWESTERN UNIVERSITY

The Northwestern University (NWU) group has gained a reputation for making steady remarkable progress in both QE and temperature of operation. A high operating temperature is highly desirable for most of the applications for which DWELLs would be useful. Cryo-coolers significantly increase the initial equipment cost, increase the long-term operational cost, and decrease the field-based utility of the detector. Although the NWU group does not call their structures DWELLs their devices have the same basic architecture: consisting of a QD in a QW surrounded by barriers. Presently, one of the primary differences is the material system with which they are working: Unlike most other DWELL groups, which use the (In, Al, Ga)As material family, the NWU group uses (In, Al)As/InP and grows their material via MOCVD, see Figure 5.[100] This material composition offers several advantages, most significant of which is the ease of strain balancing in the lattice. With each repetition of the active region the barrier can compensate for added strain from the QW and QD. This neutralization of the strain, keeping the average lattice constant equal to the substrate enables the growth of a more extensive active region.

A typical example of a DWELL grown by the NWU group is shown schematically in the figure below. A semi-insulating InP substrate is covered by an undoped buffer layer and then a doped contact layer. Then 25 repetitions of the active region follow. Each repetition consists of

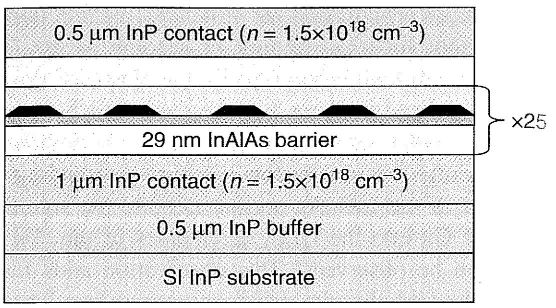


Fig. 5. A schematic for the NWU group crystal structure, consisting of an InP buffer layer followed by an n-doped contact layer grown on top of a InP substrate. The active region is repeated 25 times and contains a 3.5 nm InGaAs quantum well with InAs quantum dots imbedded in the middle of the well. This QW then has in 29 nm of InAlAs on both sides. The entire structure is then capped with 660 nm n-doped GaAs contact layer. Reprinted with permission from [102], H. Lim et al., *Appl. Phys. Lett.* 90, 131112 (**2007**). © 2007, American Institute of Physics.

29 nm of InAlAs barriers surrounding an n-doped 3.5 nm InGaAs QW and 1.8 ML InAs to form the QDs.[100] Following growth a similar basic processing procedure, outlined above was used to fabricate single devices or FPAs.[100,101]

Although the NWU group focused their research in a lower wavelength regime and, therefore, a significantly lower dark current regime, their results are notable. Specifically, their recent high operation temperature results for a 4.1 μm single pixel device and a 4 μm FPA. The 4.1 μm single pixel DWELL detector achieved a detectivity of 6.7×10^7 cm Hz$^{1/2}$/W at room temperature, 300 K; with 2.8×10^{11} cm Hz$^{1/2}$/W at 120 K and 35% QE.[102] Similarly, their FPA was operational at 200 K and achieved a responsivity of 34 mA/W, a conversion efficiency of 1.1%, and a NEDT of 344 mK at an operating temperature of 120 K.[100]

9. WANG GROUP (TAIWAN)

The Taiwan group has a history of enhancing the function of QD detectors by applying a capping material to the QDs[103] and they are now applying these techniques to DWELLs.[104,105] In this case, they apply a 2.5 nm cap consisting of 30% AlGaAs. TEM analysis indicates that the smaller lattice constant AlGaAs settles in the more tensile strained valleys between the dots. This is a significant discovery in itself, since the addition of an AlGaAs cap introduces two competing effects. First, the smaller lattice constant AlGaAs should introduce a higher interfacial energy and, therefore, increase intermixing between the dot and the cap. The results show that the second effect appears to dominate, however. As most crystal growers know and as reported by Zhang et al.,[106] adding aluminum to layers decreases the interdiffusion with indium containing layers. TEM images also indicated that there was not a measureable change in the QDs size by the application of the AlGaAs cap. This implies that the AlGaAs effectively rolls off the dots and settles into the valleys, while the subsequent InGaAs layer then intermixes.

The effect of having this higher band-gap barrier material was similar to what was observed by the New Mexico and UMass groups. The spectral response of the detector blue shifted. This is due to the increased depth of the well or as the Taiwan group chooses to call it "increased confinement." The higher ground state this creates leads to an increase in the dark current (3.82×10^{-4} A/cm^{-2} at -1 V at 77 K for the AlGaAs capped versus 3.3×10^{-5} A/cm^{-2} for a similar uncapped sample), but this is offset by what is assumed to be an increase in quantum efficiency. Note: This could also be due to a decrease in carrier recombination as well. These combined effects lead to a ten-fold increase in their detectivity 1×10^{10} cm Hz$^{0.5}$/W at -0.9 V versus 1×10^{9} cm Hz$^{0.5}$/W at -1.2 V. While increases were similarly observed by New Mexico and UMass, they did not see a ten-fold increase. This is most likely related to their having an initially higher detectivity.

10. NASA JPL

The JPL group has an impressive history working with QW-based detectors (e.g., Refs. [107–116]). Beyond the aptitude of the people involved in this group, their success is partially due to the superior tools available to them at the JPL facility. In 2006 they applied this aptitude and their superior fabrication equipment to the pursuit of DWELL-IPs in a collaboration with the New Mexico group's PI, Krishna. They have quickly become the leaders in creating high-quality large FPAs including their initial 620×512 pixel DWELL FPA.

Recently, Gunapala's group at JPL collaborated with Sanjay Krishna at UNM, to design and create a highly effective 640×512 DWELL FPA grown and fabricated at JPL.[117–125] As discussed above, one of the DWELL structure's primary advantages over typical QDIP structures is the ease of tuning the response by varying the well width; this was aptly demonstrated by the JPL group.

For the DWELL photodetectors each was grown and fabricated in a similar manner to that as was described in the Introduction section above. Minor differences are depicted in Figure 6 and in the InGaAs QW's composition being 12% In rather than the standard 15%. Additionally, the active region was repeated 30 times rather than the standard 10–15 times, which helps to account for the increase in QE.[117]

One specific contribution that the JPL group added to the design of DWELL FPAs has to do with their sensitivity to non-normally incident light (not S-polarized). While one of QDIP and DWELL advantages over QWIPs lies in its sensitivity to S-polarized light, it is also known that DWELLs should have increased sensitivity to non-normally incident light as well. This is believed to be related to the QD's lateral size being dramatically larger than its height.[118] This was confirmed by the JPL group. While the S-polarized light is approximately an order of magnitude more responsive than comparable QWIPs the P-polarized light is five times more responsive than that. These dramatic improvements naturally lead to the inclusion of a grating on the surface of the detector.[117]3

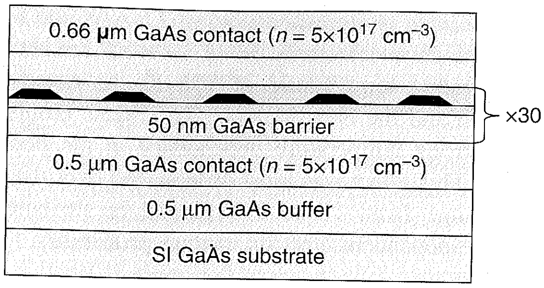


Fig. 6. A schematic for the JPL crystal structure, consisting of a GaAs buffer layer followed by an n-doped contact layer grown on top of a GaAs substrate. The active region is repeated 30 times and contains a 7.5 nm 12% InGaAs quantum well with InAs quantum dots imbedded in the middle of the well. This QW then has 50 nm of GaAs on both sides. The entire structure is then capped with 660 nm n-doped GaAs contact layer. Reprinted with permission from [117], S. D. Gunapala et al., *IEEE J. Q. Elec.* 43, 3 (**2007**). © 2007, Institute of Electrical and Electronics Engineers.

Following a process similar to the standard process outlined in the Introduction section of this paper a 640×512 DWELL FPA was processed at JPL using this newly enhanced design. Under test the FPA had an NEDT of 40 mK, which is only twice that of the best NEDTs reported for QWIPs and a QE of 5% for a LWIR response at 60 K.[117] This was by far the best LWIR response reported for a DWELL FPA. This camera additionally was used to image scenes, where the quality of the image is visually dramatic.

11. UNIVERSITY OF MASSACHUSETTS AT LOWELL

The UMass-Lowell group, while being new to the field has made some significant contributions and they are a group to watch in the future. The focus of the group is creating long wavelength photodetectors with a high operation temperature.[126, 127]

While this group has new results with a detector functioning at 11.7 microns accepted for publication in Infrared physics and technology, at the time of this review their best result is published in Ref. [126]. This paper is quite well put together and includes a good summary derivation of the relevant figures of merit. The detector detailed here is a variant on the standard DWELL with the inclusion of 20% AlGaAs current blocking layers. These layers included above and below the active region decrease the dark current. This is a similar technique to the one employed by the New Mexico group for their multi-wavelength high operation temperature detectors. Here, the DWELL-IP was able to achieve a large photoresponsivity of 2.5 A/W and a high peak specific photodetectivity D^* of 1.1×10^8 cm $Hz^{1/2}$/W at the operating temperature of 190 K. As noted with the Swedish and the New Mexico, the UMass group also observed strong temperature dependence in the photoresponsivity. This effect was most pronounced over the temperature range from 78 to 190 K and is attributed to temperature-dependent electron capture probability.

12. CONCLUSION

As is evident from the detailed discussions in the previous sections, there is active research in the quantum dots in a well (DWELL) design. However, the performance of the best DWELL based FPAs from the JPL group has shown a noise equivalent temperature difference of a factor of two higher than QWIPs for a comparable operating wavelength and operating temperature. The QD detector technology is at a cross roads. Even thought it has made significant improvements in the past few years, the performance has not exceeded that of QWIPs. Hence it has still been a design in university laboratories. One of the fundamental limitations arises from the shape of the dot that is "pancake" in nature with a small aspect ratio. In order to obtain improved normal incidence response, longer carrier lifetime with improved SNR of devices and lower dark currents with higher operating temperatures, the shape of the dots have to be altered to form high aspect ratio quantum dots. Dots with a base dimension of 5–10 nm and a height of 5–10 nm would lead to a better confined "quasi-zero" dimensional systems. That seems to be the general focus of all the university research groups working on the QD detectors. If shape engineering of the dots can produced high aspect ratio quantum dots, one can expect dramatic improvements in the QD detector technology in the next decade.

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REVIEW

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