Investigation of multistack InAs/InGaAs/GaAs self-assembled quantum dots-in-double-well structures for infrared detectors

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(Received 1 October 2009; accepted 19 January 2010; published 22 March 2010)

The authors report the InAs/InGaAs/GaAs quantum dots-in-double-well (D-DWELL) design, which has a lower strain per DWELL stack than the InAs/InGaAs/GaAs DWELLs thereby enabling the growth of many more stacks in the detector. The purpose of this study is to examine the effects of varying the number of stacks in the double DWELL detector on its device performance. The structures are grown by solid source molecular beam epitaxy on GaAs substrates. After fabrication of single pixel devices, a series of device measurements such as spectral response, dark current, total current, and responsivity were undertaken and the photoconductive gain and the activation energies were extracted. The goal of these experiments is not only to optimize the device performance by optimizing the number of stacks but also to investigate the transport properties as a function of the number of stacks. © 2010 American Vacuum Society. [DOI: 10.1116/1.3319324]

I. INTRODUCTION

Quantum-dot infrared photodetectors (QDIPs) have attracted a lot of attention for applications in the infrared (IR) (3–30 μm). Infrared (IR) detectors today have varied design requirements such as the required level of sensitivity, operating temperature, spectral sensitivity, peak wavelength, and cost, depending on their application.6–8 The dominant detector technologies are represented in Fig. 1(a). For applications in the long wave IR (LWIR) regime with low volume and high cost, such as in astronomy, the mercury-cadmium-telluride (MCT) technology is the dominant technology. Although MCT detectors have demonstrated high sensitivity and very low noise due to problems in the epitaxial growth of mercury-based compounds, there is limited manufacturing yield for MCT large area focal plane arrays (FPAs) and hence leading to very expensive final imaging systems operated at 80 K.9 InSb detectors are dominant in the midwave infrared (MWIR) applications and Si:As impurity band conduction detectors in the very long wave infrared (VLWIR) (>14 μm) regime operated at very low temperature at 10 K.9 Both of these technologies though simple in growth aspects have cutoff wavelengths that drift with change in operating temperature and require very low operating temperatures. In the long wave infrared (8–12 μm), quantum-well infrared photodetectors (QWIPs) have demonstrated large format FPAs. However, a limitation of QWIP is that due to transition selection rules, they are not sensitive to normal incidence radiation.12–18 Moreover, QWIPs have a low absorption quantum efficiency and high dark current restricting their operation to low temperatures at 77 K. QDIPs are expected to absorb normal incidence radiation due to the geometry, which enables carrier confinement in all three dimensions and provides long excited carrier lifetime as compared to QWIPs. The QDIPs are also expected to have lower dark current due to the three-dimensional confinement. However, the performance of QDIPs is inherently dependent on the shape and the size of the dots, which in turn is governed by the random self-assembly process.

In our research group, we have investigated the quantum dots-in-a-well (DWELL) design for IR detectors.19–21 These DWELL structures are hybrids between the conventional QWIPs and QDIPs. The standard DWELL heterostructures consist of InAs quantum dots embedded in an InGaAs quantum well with GaAs barriers as seen in Fig. 2(a). The transitions in these structures take place from the quantum dot ground state to either a bound level in the quantum well (bound to bound) or to the continuum (bound to continuum). These intersubband transitions can be controlled by varying the widths of the quantum wells and compositions, thereby providing better control over the emission wavelength. The presence of quantum wells in DWELLs also allows efficient capture of carriers. DWELL detectors not only demonstrate low dark currents, but also higher operational temperature, better control over operating wavelength, and potential bias tunability.22–27 Bias dependent spectral response which facilitates multispectral detection is possible due to the quantum confined Stark effect (QCSE) that is associated with asymmetrically designed DWELL detectors.25 They have also demonstrated multicolor operation in the MWIR, LWIR, and the VLWIR (>14 μm) regimes.28–30 Focal plane arrays (FPAs) of sizes up to 1024 × 1024 pixels have been successfully demonstrated on DWELLs.31–36 The lattice mismatch in these structures gives rise to strain in the system, which in turn leads to self-assembly of QDs during growth of DWELL structures. This cumulative compressive strain buildup per stack limits the number of stacks that can be grown before defects set in. This leads to low quantum efficiency (QE) in DWELL detectors.36 Various studies have been examined to improve the performance of DWELLs,
such as using distributed Bragg reflector mirrors to form a resonant cavity, implementing photonic crystal cavity, and combining an avalanche photodiode along with a DWELL to introduce gain into the system. The capping of quantum dots with GaAs, AlGaAs, InGaAs, and InGaAlAs has become a hot research topic in the DWELL technology because good capping material can reduce the intermixing of species between quantum dot and capping layer, hence preserving the shape and enhancing quantum confinement.

In this article we focus on another approach to improve the performance of dots-in-double-well (D-DWELL), wherein the volume of the active region is maximized. This is realized by reducing the overall indium content in the system, which lowers the strain per layer generated during growth. Quantum D-DWELL comprises of InAs quantum dots embedded in In$_{0.15}$Ga$_{0.85}$As and GaAs quantum wells with Al$_{0.10}$Ga$_{0.90}$As barriers. The band diagram of the conduction band of D-DWELL is illustrated in Fig. 2(b) and from this we can infer that in D-DWELL the GaAs layers acts as the primary well as opposed to In$_{0.15}$Ga$_{0.85}$As in earlier (standard) DWELL.

II. GROWTH AND FABRICATION

All the samples were grown using a VG Semicon V80H molecular beam epitaxy reactor with an As$_2$ cracker source. The development of the InAs/In$_{0.15}$Ga$_{0.85}$As/GaAs D-DWELL structure with Al$_{0.10}$Ga$_{0.90}$As barriers required several cycles of optimization. This process involved optimization of quantum well (QW) sizes above and below the dot; barrier thickness along with optimization growth rate, amount of material in the quantum dots, and doping in the dots. During initial attempts, the DWELL structure comprised of InAs quantum dots placed in GaAs wells surrounded by Al$_{0.10}$Ga$_{0.90}$As barriers. But this structure showed poor photoluminescence and low QD density and hence this layer of In$_{0.15}$Ga$_{0.85}$As was introduced. The InAs dots on In$_{0.15}$Ga$_{0.85}$As layer instead of GaAs increased the QD density by two orders of magnitude. One of the critical parameters in the growth of D-DWELL structure is the GaAs well width as the dots are essentially formed over the GaAs/In$_{0.15}$Ga$_{0.85}$As wells. As our objective is to minimize the strain in the structure, we have to keep the amount of In$_{0.15}$Ga$_{0.85}$As to a minimum and hence the depth of the well below the dot is determined by the GaAs layer. The optimization details of these parameters and results are described elsewhere.

The D-DWELL detector structure utilized in our experiment is illustrated in detail in Fig. 3(a). It comprises of the optimized active region consisting of $n$-doped InAs dots in an In$_{0.15}$Ga$_{0.85}$As/GaAs well with Al$_{0.10}$Ga$_{0.90}$As barriers. The dots consist of 2 ML (monolayer) of InAs, grown at 470 °C. The width of the In$_{0.15}$Ga$_{0.85}$As well is 1 nm above and below the dots, while the GaAs wells are asymmetrically designed, with a width of 4 nm below the dot and 6.85 nm above the dots. This is done to obtain bias dependent spectral response, by exploiting the QCSE. This active region is sandwiched between two highly doped $n$-GaAs contact regions and the whole structure is grown on GaAs semi-insulated substrate. Five samples with 15, 30, 40, 50, and 60 active region stacks were grown to study the performance of detectors. Several research groups have already demonstrated that the absorption efficiency of a QWIP is directly proportional to $N$ (number of QW layers) and the photocon-
Inductive gain is inversely proportional to $N$, thus making the responsivity independent of $N$. However, there is currently no detailed study of the effect of the number of QD stacks on the absorption QE, responsivity, and photoconductive gain. This study revolves on obtaining the figures of merit of the detector by systematically increasing the number of QD layers ($N=15, 30, 40, 50, \text{ and } 60$) in detector structures.

A. Fabrication of a single pixel device

An array of $400 \times 400 \, \mu m^2$ detector mesas with top pixel apertures, ranging from 25 to 300 $\mu m$ in diameter were fabricated using conventional photolithography. Inductively coupled plasma etching and metal contacts were made via e-beam metallization. The contacts were annealed at 380 °C using rapid thermal annealing and the devices were characterized. The final structure of a fully processed $n$-$i$-$n$ D-DWELL single pixel device is shown in Fig. 3(b). After processing was complete these single pixel detectors were mounted on 68 pin chip carrier and wire bonded.

III. CHARACTERIZATION AND RESULTS

A. Photoluminescence and absorption measurements

The optical response of D-DWELL structures were examined and the photoluminescence (PL) spectra were taken for the 15, 30, 40, 50, and 60 stacks at room temperature with a 2.5 mW He–Ne laser, a grating spectrometer, using standard lock-in techniques. Figure 4 shows the integrated PL intensity of these stacks as a function of wavelength. The PL intensity of the 15X–50X sample is comparable but there is a significant decrease in the PL intensity of the 60X sample. This could be attributed to the formation of dislocation. This premise is corroborated by the dark current measurement. Full widths at half maximum of the PL spectra are found to be nearly constant indicating disclose that QD size distribution does not change too much between the QD stack. One of the promises of QD is the dominant normal incidence ($P$-polarized) response, i.e., incident light normal to the wafer along the growth direction. Unfortunately most reports do not show polarization dependence of the photocurrent spectra and some show dominant $P$-polarized response in the $45^\circ$ facet geometry very similar to QWIP. In this article, we

![Fig. 3](Color online) Schematic of a (a) detector InAs/In$_{0.15}$Ga$_{0.85}$As/GaAs D-DWELL structure with Al$_{0.10}$Ga$_{0.90}$As barriers. (b) D-DWELL processed single pixel device.
are reporting absorption measurements spectra of two of our five samples under both P- and S-polarized radiations in the 45° facet geometry. Figure 5(a) (polarized) shows clearly the P-polarized response is stronger in the range of 8–10 μm but S-polarized response is much stronger in the range of 10–12 μm. We believe that the peak at ~9 μm is probably a transition from a bound state in the quantum dot to a bound state in the QW whereas the broad shoulder around 12 μm is possibly due to transition between two states in the quantum dot, whereas the peak between 3 and 5 μm is possibly a transition from a state in the dot to a quasibound state close to the top of the well and is independent with P- as well as S-polarized response. We observed the similar trends when we used the unpolarized light as shown in Fig. 5(b) (unpolarized). This is a clear evidence of absorption features due to in-plane confined quantum dot levels.

**B. Dark current and activation energies measurements**

Dark currents are one of the most prominent figures of merit of a detector and for a given signal to noise ratio, the dark currents determine the maximum operating temperature of a detector. The lower the dark current, the better the device performance. Dark current densities at 77 K for the different devices are plotted in Fig. 6(a). The 60 stack device showed abnormally large dark currents indicating the formation of dislocation or defects in the structure as a function of electric field. In an effort to better understand the dark current measurements, the activation energies were calculated. The dark current at various temperatures and bias were plotted. Arrhenius plots for each device were obtained. Slope of the logarithm of dark current versus 1/T yields the activation energy. The activation energies were then plotted against the applied electric field, as shown in Fig. 6(b). The activation energies of 15, 30, and 40 stack devices are seen to increase with increasing number of stacks and decrease with applied bias. This result agrees with the conclusion of Asano et al. and that this increase in activation energy could be caused by increase in the built-in potential barrier which reduces the free carrier density in the undoped region. The increase in the barrier height is possibly due to self-consistent band bending occurring during the increase in active region thickness. This analysis also explains the steady decrease in the activation energies with the increase in the applied electric field. The abnormally low activation energies of the 60 stack device is due the high dark currents and this may be an indication of dislocations present in the material.
C. Spectral measurements

The spectral response at several temperatures and applied biases were measured using a Fourier transform infrared spectrometer in the normal incidence configuration as a function of the number of QD layers (N=15, 30, 40, 50, and 60). Figure 7(a) shows the spectral response of the 15, 30, 40, 50, and 60 stack devices at applied electric field of 10 kV/cm measured at 30 K. We can infer from this graph that the 15 stack device has a peak at \(\lambda \approx 10\) \(\mu\)m along with a midwave peak at 6.55 \(\mu\)m. All the devices showed midwave response ranging from 3 to 8 \(\mu\)m with a double peaking curve which may be an indication of multiple transitions from a state in the dot to a state in the well. The intensity of the spectral response in the MWIR regime seems to steadily increase with the increase in the number of stacks in the positive bias. Figure 7(b) shows the spectral response of the 15, 30, 40, 50, and 60 stack devices at applied electric field of \(-10\) kV/cm measured at 30 K. Again we notice that the 15 stack device showed response in LWIR regime peaking at \(\sim 8.7\) \(\mu\)m. In the negative bias, all of them showed MWIR response ranging from 3 to 7.9 \(\mu\)m with their spectral response intensities increasing with the increase in the number of stacks.

D. Responsivity and photoconductive gain measurements

Responsivity of a detector is basically the detector output per unit of radiant input and it is generally desirable to have higher responsivity as it is directly related to the sensitivity of the device and is proportional to the QE of the detector. To measure the responsivity, the samples were cooled down to 77 K (liquid nitrogen temperature). They were then irradiated by using a calibrated blackbody at 800 K. The photocurrent was then amplified using a SRS 570 low noise am-
plifier and measured using a SRS760 fast Fourier transform spectrum analyzer at 77 K. The expression used to compute the peak responsivity is given as

\[ R_p = \frac{I_0}{\int_{\lambda_1}^{\lambda_2} |R(\lambda)/R(\lambda_0)| L_s(\lambda, T) A_s A_d (t F_p / r^2) d\lambda} \]

where \( I_0 \) is the photocurrent, \( L_s \) is the blackbody spectral existence, \( A_s \) is the area of the source, and \( A_d \) is the area of the detector. \( F_p \) is the geometrical form factor, \( t \) is the transmission of the window, and \( r \) is the distance between the source and the detector. Figure 8(a) shows responsivity as a function of applied field for the different number of QD layers. It has to be noted that the applied electric field is calculated by dividing the applied bias by the thickness of the active region ignoring the variation in the electric field in the active region. We expect that the responsivity does not depend on the number of stacks since the increase in the absorption quantum efficiency is accompanied by a decrease in the photoconductive gain. This is borne out in the experiments as the variation in the responsivity is not very pronounced. The 15 stack device shows the highest responsivity of all the devices. At an applied electric field of 50.37 kV/cm, the 15 stack device gave peak responsivity of 491.8 mA/W. As more number of stacks is grown, the cumulative strain in the system increases. This may be the reason for the lower responsivity and hence sensitivity of devices with large number of stacks.

Another crucial device parameter is photoconductive gain of the device, which is inversely proportional to its capture probability. Higher photoconductive gain implies longer carrier lifetimes. It increases the responsivity as many electrons flow in the external circuit for a single photon absorbed in QD. The photoconductive gain is given as

\[ g = \frac{i_n^2}{4qI_{dc} \Delta f} \]

where \( i_n \) is the noise current, \( I_{dc} \) is the total current, and \( \Delta f \) is the frequency bandwidth. The photoconductive gain of the device can be computed from the noise power spectral density \([i_n/\sqrt{\Delta f}]\) and the total current. Along with measuring the photocurrent, the noise current in the system was also measured.\(^4\)\(^7\) We can infer that noise was the lowest in the 40 and 50 stack devices and was higher in 30 stack devices. It increases the responsivity, as many electrons flow in the external circuit for a single photon absorbed in the active region. The photoconductive gain of the system is computed and plotted in Fig. 8(b). The 15 stack device showed the highest gain of 361.59 at 40.29 kV/cm. It is to be noted that the photoconductive gain does not show an increase with respect to bias for the devices with higher number of stacks due to low electric fields applied in the measurements.

**IV. CONCLUSION**

In conclusion, we have investigated the performance of the InAs/InGaAs/GaAs/AlGaAs D-DWELL detectors as a function of the number of stacks. The 15 stack device showed the highest photoconductive gain of 361.59 at 40.29 kV/cm. The spectral response of these devices which indicate that LWIR response in 30–60 stack devices can only be seen in higher bias (>5 V) and this may pose a problem during FPA implementation. Responsivity and dark current scaled with the electric field and number of stacks. We also observed an increase in activation energies with the increase in the number of stacks and a steady decrease in the activation energies with an increase in the applied bias. In the future, we intend to develop a model to investigate the capture probability and effect of nonuniform electric field in these structures.
ACKNOWLEDGMENTS

This work was supported by AFRL/AFOSR FA9453–07–C-0171 and KRiSS-GRL program.