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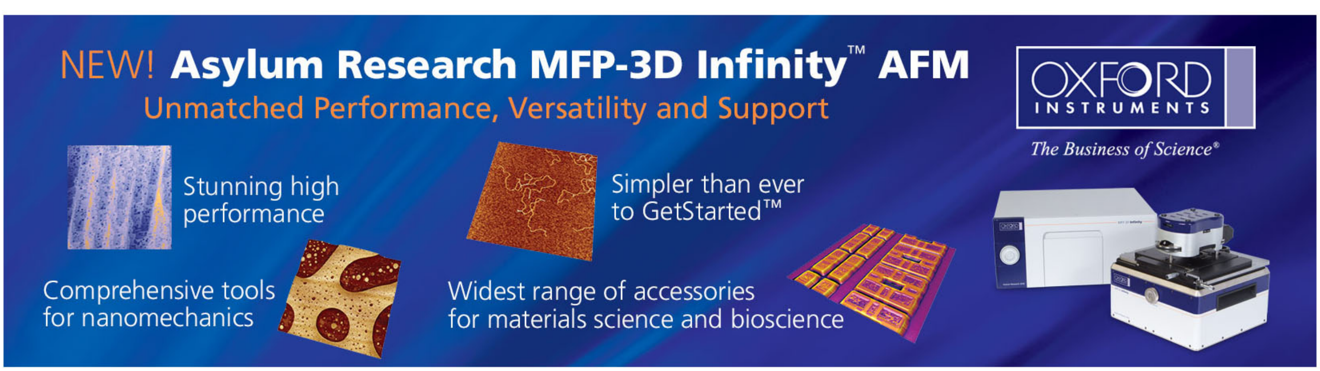

Low dark current quantum-dot infrared photodetectors with an AlGaAs current blocking layer

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Low dark current InAs/GaAs quantum-dot infrared photodetectors (QDIPs) are demonstrated. The dark current is reduced by over three orders of magnitude by using a thin AlGaAs current blocking layer. This thin AlGaAs layer reduces the dark current much more than the response signal. The responsivity at 0.5 V is 0.08 A/W with a peak detection wavelength at 6.5μm. The corresponding detectivity is 2.5×10^9 cm Hz$^{1/2}$/W$^{1/2}$, which is the highest detectivity reported for a QDIP at 77 K.
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Quantum-well infrared photodetectors (QWIPs) utilizing an intersubband transition have been extensively investigated over the last decade.[1] The mature GaAs processing technology makes it possible to produce large QWIP arrays with high yield.[2] Although great potential has been shown, QWIPs suffer from problems that are related to the nature of the quantum-well structures. The thermally induced dark current is large and the carrier lifetime is short. In addition, the normal incidence absorption is forbidden for *n*-type QWs. These drawbacks keep the HgCdTe detectors from having superior performance compared to QWIPs.[3] However, replacing the quantum wells (QWs) with ideal quantum dots (QDs) can diminish the drawbacks of QWIPs. Defect-free quantum dots can be easily produced by molecular-beam epiatxy (MBE) or metal–organic chemical-vapor-deposition techniques. The three-dimensional confinement of the quantum-dot structure provides the possibility to suppress the electron–phonon interaction and relax the selection rule of the intersubband transition in quantum-well structures. Thus, quantum-dot infrared detectors (QDIPs) have great potential as low dark current, high gain devices with a normal incident response.

Recently, several QDIP results have been reported using In(Ga)As/GaAs,[4–6] InAs/InAlAs/InP,[7] and InAs/InGaP/GaAs (Ref. 8) quantum-dot systems. However, most of the QDIP results reported so far are disappointing, in spite of the great potential predicated theoretically. The dark current of QDIPs is much higher than expected and is much higher than that of QWIPs with the same doping density and cutoff wavelength. For InAs/GaAs QDIPs, the dark current density reported at 77 K is about 0.05 A/cm^2 at 0.5 V for a ten-period QD structure with 500 Å barriers.[4–6] This value is over 100 times larger than that of the AlGaAs/GaAs QWIPs with even higher doping concentrations.[1] The origin of the large dark current has been attributed to the nonuniform dopant distribution and the background impurities in GaAs.[7] Additionally, the spacing between dots provides a leakage path for the carriers.

In order to reduce the dark current in this work, a thin AlGaAs barrier layer is introduced between the InAs QDs. This AlGaAs layer, which fills the area between the dots but leaves the top of the dots not covered, blocks the leakage current between the dots and thereby reduces the dark current.

The samples were grown by a Varian Gen II MBE system on (100) GaAs semi-insulating substrates. The active region consisted of ten periods of InAs/GaAs QDs with 500 Å GaAs barriers. The active region is sandwiched by 6000 Å *n*-type contact layers. The nominal thickness of the InAs QD is 2.6 ML. During the deposition of InAs, a 6 s interruption was added for every 0.2 ML of InAs deposition. The Al content in the AlGaAs layer was 20% and the layer was grown after the growth of the InAs QDs. The structure is shown in Fig. 1. Due to the strain distribution, most of the AlGaAs atoms accumulate in the area between the QDs. As a result, the AlGaAs layer covers the region without QDs but leaves the tips of the QDs uncovered. Two different samples were fabricated, one with (sample A) and one without (sample B) a 30 Å AlGaAs layer. The InAs QDs were measured by atomic force microscope. The typical lateral size of the QDs is about 30 nm and height is about 7 nm. The density is about 1×10^{10} cm^{-2}. The 8 K photoluminescence (PL) spectrum shows an emission peak width around 35

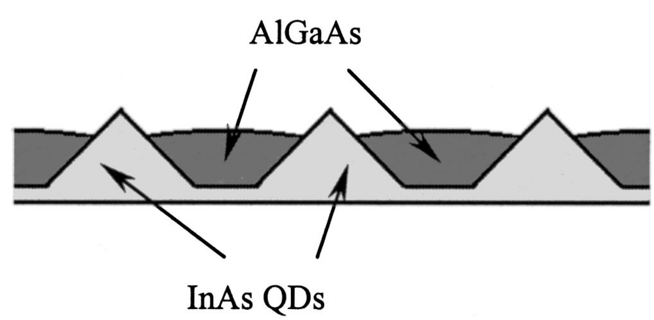

FIG. 1. Schematic diagram of a QDIP with an AlGaAs current blocking layer.

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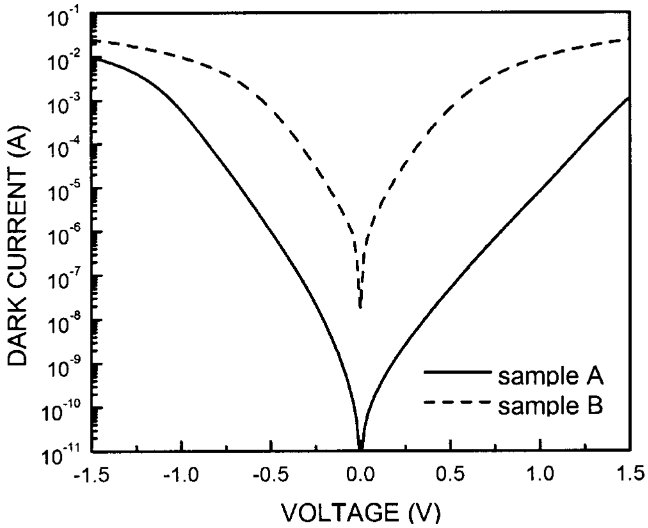

FIG. 2. 77 K dark current of the QDIPs with (sample A) and without (sample B) the AlGaAs current blocking layer.

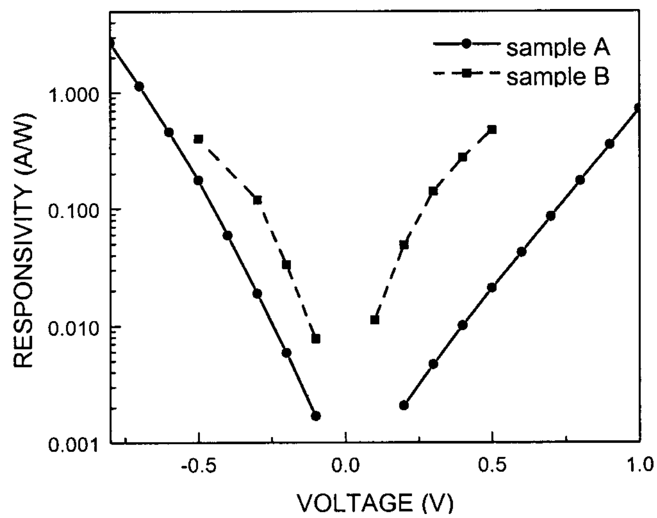

FIG. 3. Responsivity vs voltage curves for sample with (sample A) and without (sample B) the AlGaAs current blocking layer.

meV indicating good uniformity of the QDs. Similar PL spectra were obtained for both samples. This shows that the energy levels of the QDs are not altered by the thin AlGaAs layers. The sheet doping concentration used for the samples is $2\times10^{10}\,\mathrm{cm}^{-2}$, which gives approximately two electrons in each QD. Standard processing techniques were used to define the mesas and to make Ohmic contacts. A 45° facet was then polished for light entrance and the following optical measurements.

Figure 2 shows the 77 K dark current of the samples. In all the measurements, the bottom contact is referenced as the ground. As expected, the dark current of sample B is large, which is of the same order as has been reported. For sample A, the dark current is about 1000 times lower than sample B. This results clearly shows the carrier blocking effect of the AlGaAs layer between the quantum dots. We also notice that the dark current versus voltage curve is not symmetric for the sample with the AlGaAs layer. The dark current is lower at forward bias. The carriers in the dots have to overcome the AlGaAs barrier to get out when the device is forward biased but only see the GaAs barrier when the device is reversed biased.

The response spectrum of devices is then measured by a Fourier transform infrared spectrometer. A similar spectrum with a peak at 6.5 μm is obtained for both samples. This result shows that the thin AlGaAs layer does not affect the positions of the energy levels of the QDs. The full width at half maximum of the spectrum is less than 1 μm, indicating that the absorption is due to bound-to-bound (BB) transitions. The narrow spectrum also shows the high uniformity of the quantum dots. The BB transition is further confirmed by the responsivity curves. This result implies that the energy states of the QDs are mainly determined by the z-direction confinement. The increase of the barrier confinement in the lateral direction has little effect on the transition energy. This explains why the observed normal incidence response is still low compared with that of the light having an electric field polarized perpendicular to the quantum wells. We believe the normal incident absorption controversy between different research groups[3–5] comes from the different QD shapes and sizes. These differences can induce different wave-function distributions corresponding to the energy states. Different transition properties can thus be observed.

The added AlGaAs layer can also affect the transport property of the carriers; the photocurrent can also suffer. The photoresponse was measured in a close-cycle cryostate. The responsivity versus voltage curves of the samples are shown in Fig. 3. The insertion of the AlGaAs layer decreases the responsivity. The effect is especially strong when the device is forward biased. Although the QDs are not fully covered by the AlGaAs layer, the photoexcited carriers still feel a higher effective barrier under forward bias. The tunneling probability decreases as the barrier thickness. In order to see the effect of transport properties on the performance of QDIPs, we have calculated the gain from the measured noise current. Figure 4 shows the results. The gain for the sample without the AlGaAs barrier layer is large, as expected, indicating the excellent transport property. The large gain at high voltage also shows the possible impact ionization process. The gain

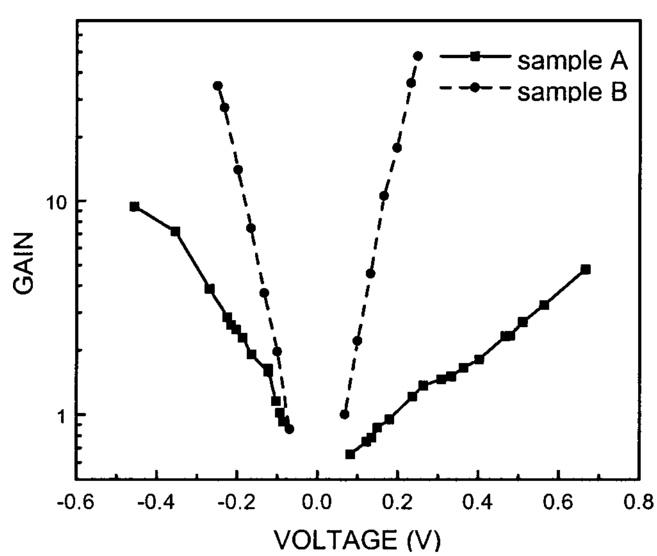

FIG. 4. Gain at different voltages for sample with (sample A) and without (sample B) the AlGaAs current blocking layer.

of the sample with the AlGaAs layer is lower (by about the same amount as the responsivity compared with the sample without AlGaAs), but is still high compared to the AlGaAs/GaAs QWIPs. The gain saturates at a value of 1.5 at 0.4 and -0.2 V. As the voltage increases, the gain increases again. This indicates that the avalanche multiplication can exist with the thin AlGaAs blocking layer. It should be noted that the gain difference between samples A and B becomes larger as the voltage increases. When the bias is high, the tunneling current dominates the dark current. The low-energy carriers tunneling through the barrier will be blocked by the AlGaAs layer. Thus, the gain decreases more at higher voltages.

Typically, the doping concentration for the QDIPs is 20 times lower than that of conventional QWIPs ($2-4 \times 10^{11}\,\mathrm{cm}^{-2}$). If the same order of responsivity is needed, the gain of the QDIPs has to be at least ten times higher. This is exactly the case for sample A. The detectivity at 77 K for sample A is about one order of magnitude higher than sample B. The detectivity at 0.5 V is 2.5×10^9 cm $\mathrm{Hz}^{1/2}/\mathrm{W}^{1/2}$. This is the highest detectivity reported for a QDIP at 77 K.

In conclusion, we have demonstrated a low dark current InAs/GaAs QDIP using an AlGaAs current blocking layer. The current blocking layer can decrease both the dark current and the photocurrent. It is shown that using a 30 Å $Al_{0.2}Ga_{0.8}As$ layer, the dark current can be lowered by more than 1000 times while the high responsivity and gain are still obtained. The detectivity is greatly enhanced. Further optimization of the AlGaAs layer is expected to improve the device performance even more.

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