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High performance InAs/GaAs quantum dot infrared photodetectors with AlGaAs current blocking layer

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Abstract

Low dark current InAs/GaAs quantum dot infrared photodetector (QDIP) is demonstrated. The dark current reduced for over three orders of magnitude by introducing a thin AlGaAs current blocking layer. This thin AlGaAs can reduce the dark current much more than the response signal. The responsivity at 0.5 V is 0.08 A/W with peak at 6.5 μm and the corresponding detectivity about 2.5×10^9 cm $\mathrm{Hz}^{1/2}/\mathrm{W}^{1/2}$. It is the highest detectivity reported for QDIP at 77 K. © 2001 Published by Elsevier Science B.V.

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1. Introduction

Quantum well infrared photodetectors (QWIPs) utilizing intersubband transition have been extensively investigated over last decade [1]. The mature GaAs processing technology accelerates the demonstration of large format QWIPs arrays [2]. Although great potential of replacing the current II–VI compound devices is shown, due to the intrinsic quantum well properties, the thermally induced dark current is large and carrier life time is small. In addition, the normal incidence absorption is forbidden for n-type QWs. These drawbacks are expected to be diminished by replacing the quantum wells with quantum dots structure. By Stranski–Kranstanov growth mode, defect free quantum dots can be easily produced by MBE or MOCVD techniques. The 3-D confinement of the quantum dot structure provides the possibility to suppress the electron phonon interaction and relax the selection rule of intersubband transition in quantum well structures. Thus, the quantum dot infrared detectors are of great potential to be a low dark current and high gain devices with normal incident response.

Recently, several quantum dot infrared photodectors (QDIPs) results have been reported by In(Ga)As/GaAs [3–5], InAs/InAlAs/InP [6], InAs/InGaP/GaAs [7] quantum dot systems. However, most of the QDIPs results show inferior performance compared to the QWIPs. Although the QDIPs are of great potential theoretically, the results so far were disappointing. The dark current of QDIP 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

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is about 0.05 A/cm^2 at 0.5 V for 10 periods QDs structure with 500 Å barrier [3–5]. This value is over 100 times larger than AlGaAs/GaAs QWIPs with even higher doping concentration [1]. The origin of the large dark current was proposed due to the non-uniform dopant distribution and it was also reported that the background doping can cause large dark current especially when the dot density is low [6]. It is known that the excellent transport property of GaAs can induce large dark current such as the dark current of the InGaAs/GaAs QWIPs [8]. Besides, the spacing between dots can provide a unperturbed path to the carriers. Through this path, the carriers can transport along the region with only GaAs and causes high dark current.

In order to reduce the dark current, in this work, a thin AlGaAs layer is introduced between the InAs QDs. This AlGaAs spacer is designed to put at the region without InAs QDs to block the free path of the carriers. The excellent transport property is degraded deliberately.

2. Experiments

The samples were grown by Varian Gen II MBE on (1 0 0) GaAs semi-insulating substrate. The active region consisted of 10 periods of InAs/GaAs QDs with 500 Å GaAs barrier. The active region is sandwiched by 6000 Å n-type contact layers. The nominal thickness of InAs QD is 2.6 ML. During the deposition of InAs, a 30 s interruption was added every 0.6 ML InAs deposition. Samples with and without AlGaAs layer were fabricated. For samples with AlGaAs layer, the additional AlGaAs layer was grown after the InAs QDs' deposition and the corresponding concentration is 25%. The structure is shown in Fig. 1. Due to the strain distribution, most of the AlGaAs atoms accumulate on the area between the QDs and the structure can be formed automatically. The AlGaAs layer thickness was controlled to cover the region without QDs but not cover the whole QDs i.e., the tip of the QDs is not covered by AlGaAs. Two different samples were fabricated with 30 (sample A) and 60 Å (sample B) AlGaAs layer, respectively. The InAs QDs were investigated by photoluminescence and AFM. The typical 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 PL spectrum shows peak at 1.08 eV with FWHM around 35 meV indicating the uniformity of the QDs. Similar PL spectrum was obtained for all the samples. This shows that the energy states are not altered by such thin AlGaAs layers. It was further proved by the similar responsivity spectrum. Two samples without AlGaAs layer were also fabricated with (sample C) and without (sample D) doping in the active layer. The doping concentration is 2×10^{10} cm^{-2} for samples A, B and C to give two electrons in each QD. Standard processing techniques were used to define the mesas and make ohmic contacts. 45° facet was polished for the following optical measurements.

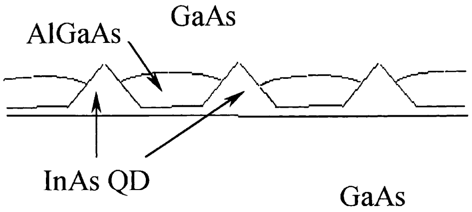

Fig. 1. The schematic diagram of the AlGaAs current blocking layer.

3. Results and discussion

The dark current was measured at different temperatures. Fig. 2 shows the 77 K dark current of the samples. In all the measurements, the bottom contact is referenced as ground. As expected, the dark current of sample C is the largest. The dark current of sample D is smaller than that of sample C but is still large than that of QWIPs. The larger dark current was also reported and was contributed to the unintentional doping [6]. The high dark current of the undoped sample also indicates the excellent transport property of the whole sample. Several interesting features are found in the figure. First, both samples A and B have lower dark current than sample D. This result clearly shows the contribution to the dark current of the free path between dots. Second, the dark

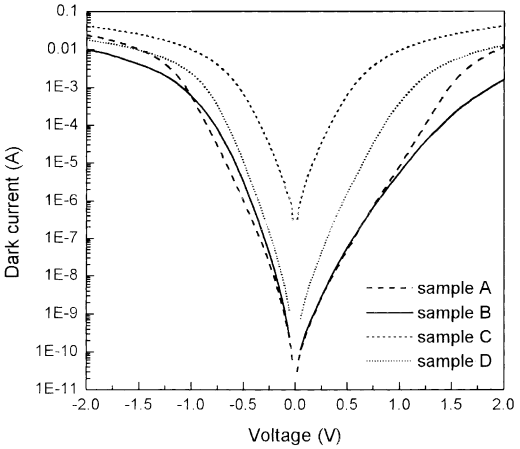

Fig. 2. The 77 K dark currents of the different samples.

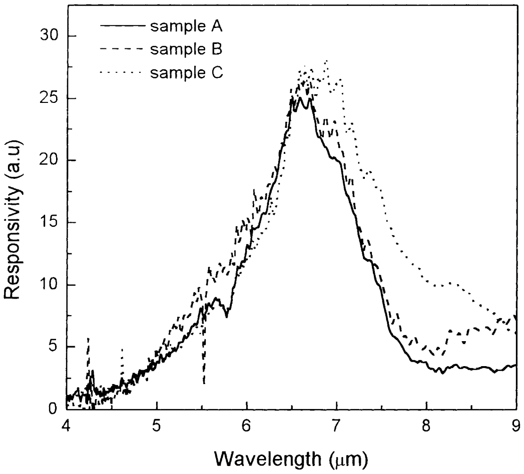

Fig. 3. The responsivity spectrum of samples A–C.

current is asymmetric for samples with AlGaAs layer. The dark current is lower under forward bias. Under forward bias, the carriers have to escape through the AlGaAs barrier while under reverse bias, the carrier from the QDs only sees the GaAs barirer. Comparing the dark current of samples A and C, the differences of dark current under reverse bias shows the difference of transport after the carrier escape the QDs and the differences of dark current under forward bias shows also the effect of the extra AlGaAs barrier. Besides, samples A and B showed almost the same dark *I–V* characteristics. This means that the 30 Å blocking layer is enough to block the free path and the carrier is transport through the quantum dots.

Similar spectrum with peak at 6.5 μm is obtained as shown in Fig. 3 for samples A–C. This result confirmed that the AlGaAs is too thin to change the energy states of QDs. The FWHM of the spectrum is less than 1 μm which indicates the high uniformity of the quantum dots and also the feature of bound to bound transitions. The B–B transition is further confirmed by the responsivity curve. The increase of the *x–y* direction barrier confinement do little of the transition energy. This implies that the energy states of the QDs come from the *z*-direction confinement. This is the reason to the polarization selection rule of the responsivity. Although some reported results show normal incidence response, we still cannot get the same results. We believe the normal incident absorption controversy between different groups [3,5] comes from the different QDs' sharp and size that change the wave functions of the different energy states. Different epitaxial process is under investigation to solve the problem.

The insertion of AlGaAs is supposed to degrade the transport property of carriers. Not only dark current but also the photocurrent are decreased. The photoresponse was measured at different temperature in a close cycle cryostate. The responsivity versus voltage curve of samples A–C are shown in Fig. 4. The bias dependence responsivity shows the transition is bound to bound. The insertion of AlGaAs layer decreases the responsivity especially for the forward bias. Under reverse bias, the responsivity of sample C is about 10 times to the sample A and 100 times to sample B. Although the QDs are not fully covered by the AlGaAs layer, the photo excited carrier still feel a effective higher barrier under forward bias. The tunneling probability decrease as the barrier becomes thick. Under such effect, the responsivity difference between the samples becomes larger and the onset voltage increases with the AlGaAs thickness. For sample B the AlGaAs layer is too thick to produce a reasonable responsivity. The responsivity of sample A was degraded but not as severe as sample B. That means the AlGaAs layer can be optimized to decrease the dark current but maintain the responsivity at a reasonable value. In order to see the

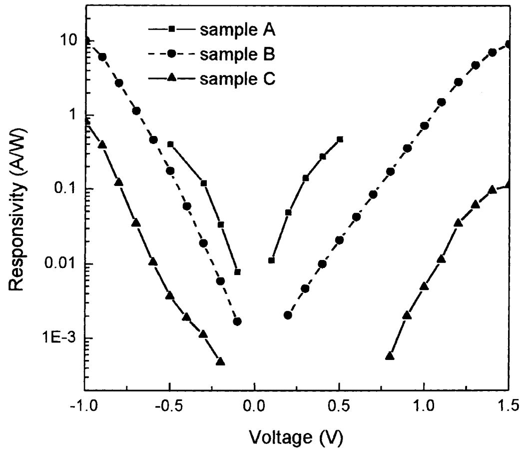

Fig. 4. The responsivity vs. voltage plot for samples A–C.

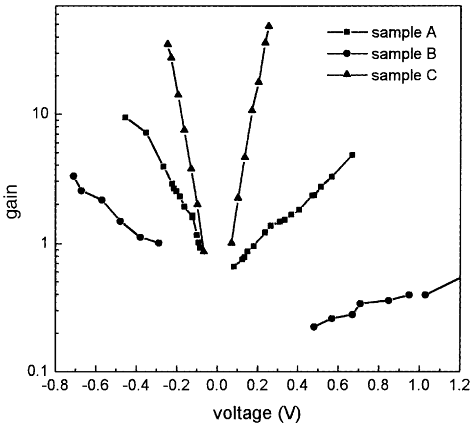

Fig. 5. The gain plot at different voltages for samples A–C.

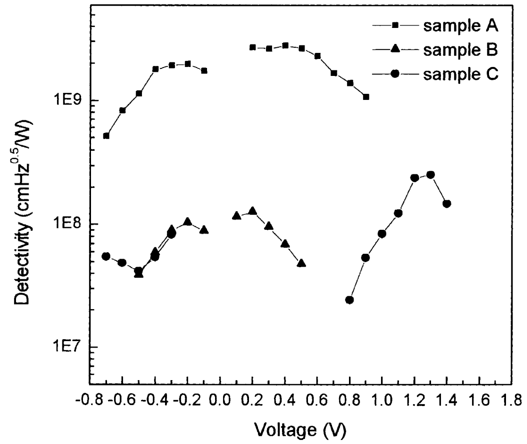

Fig. 6. The voltage dependence of detectivity for samples A–C.

transport properties of different samples, the gain is calculated from the measured noise current. Fig. 5 shows the results. Due to the limitation of experimental setup, only limited voltage range is measured. The gain for sample C is large as we expected, indicating the excellent transport property. The large gain at high voltage also shows the possible impact ionization process. The increase of AlGaAs thickness decreases the gain at the same order as that found in responsivity. For sample B, the thick barrier limits the gain less than 1 even at 1.5 V and the gain is about 10 times smaller than sample A. That is why the responsivity is low for sample B. For sample A, the AlGaAs layer decreases the gain but the gain is still high compared to the AlGaAs/GaAs QWIPs. The gain saturated about 1.5 at 0.4 V and −0.2 V. As the voltage increases, the gain increases again. This indicates the avalanche multiplication can exist with the thin AlGaAs blocking layer. It should be notice that the gain difference between samples A and C increases as the voltage increases. This implies that AlGaAs barrier can block the low energy carriers that become more when the tunneling current dominates. Typically, the doping concentration for the QDIPs is 20 times lower to the QWIPs ($2-4\times10^{11}$ cm^{-2}). If the same order of responsivity is needed, the gain of the QDIPs have to be at least 10 times larger. This is just the case for sample A. The detectivity of the samples is plotted in Fig. 6. The detectivity at 77 K for sample A is about one order of magnitude higher than the samples B and C. The detectivity at 0.5 V is 2.5×10^{9} cm Hz$^{1/2}$/W$^{1/2}$. This is the highest detectivity reported for QDIP at 77 K.

4. Conclusion

We have demonstrated a low dark current InAs/GaAs QDIP using the AlGaAs current blocking layer. The current blocking layer can decrease both the dark current and photocurrent. It is shown that using 30 Å $Al_{0.25}GaAs$ layer, the dark current can be lowered for over 1000 times while the high responsivity and gain are still obtained. The detectivity is greatly enhanced. The quantum efficiency is still low for current sample. More QD layers are needed for the compensation for the low density. Combining the high quantum efficiency and high gain, the higher performance QDIPs is expected. However, the quality of large stacks of QDs and modification of dot shape for normal incidence absorption need more work in epitaxial techniques.

Acknowledgements

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