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RESEARCH ARTICLE

AlGaAs/GaAs quantum well infrared photodetector focal plane array based on MOCVD technology

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Abstract 128 × 128, 128 × 160 and 256 × 256 AlGaAs/GaAs quantum well infrared photodetector (QWIP) focal plane arrays (FPA) as well as a large area test device are designed and fabricated. The device with n-doped back-illuminated AlGaAs/GaAs quantum structure is achieved by metal organic chemical vapor deposition (MOCVD) epitaxial growth and GaAs integrated circuit processing technology. The test device is valued by its dark current performance and Fourier transform infrared spectroscopy (FTIR) spectra at 77 K. Cut off wavelengths of 9 and 10.9 μm are realized by using different epitaxial structures. The blackbody detectivity D_B* is as high as 2.6 × 10^9 cm·$Hz^{1/2}·W^{-1}$. The 128 × 128 FPA is flip-chip bonded on a CMOS readout integrated circuit with indium (In) bumps. The infrared thermal images of some targets under room temperature background have been successfully demonstrated at 80 K operating temperature. In addition, the methods to further improve the image quality are discussed.

Keywords metal organic chemical vapor deposition (MOCVD), AlGaAs/GaAs, quantum well infrared photodetector (QWIP), infrared thermal images

1 Introduction

AlGaAs/GaAs quantum well infrared photodetectors (QWIPs) focal plane array (FPA) is a novel infrared detecting method resulting from advanced epitaxial growth technology and the energy band engineering theory. QWIPs are becoming a focus in the field of infrared photodetectors because of their advantages in response speed, uniformity, anti-radiation, pixel format, multi-color integration and lower cost compared with those traditional detectors such as HgCdTe and InSb, etc. There are promising applications for QWIPs in industrial monitoring, surveillance, astronomy observing, and medical diagnosis. A series of QWIP thermal cameras with pixel format of 320 × 240, 512 × 486 and 512 × 640, etc. have been developed at the Jet Propulsion Laboratory (JPL), QWIP technology Co., AIM and Sofradir [1–5]. The trend of QWIP FPA is large format and multi-color FPA. A 640 × 512 format four-color QWIP FPA and a 1024 × 1024 format mid and long wavelength two-color QWIP FPA were reported by JPL in 2003 and 2005, respectively. There are a lot of reports about QWIPs in China. Most of them focused on the device physics and energy band structure. Furthermore, some linear array and two-dimensional array of 64 × 64, 128 × 128 and 128 × 160 format FPA have been reported, while the demonstration of thermal images with 128 × 1, 64 × 64 and 128 × 128 format AlGaAs/GaAs QWIP has been realized [6–9].

Most of the current epitaxy technologies used in the manufacture of AlGaAs/GaAs QWIP are molecular beam epitaxy (MBE). Based on the metal organic chemical vapor deposition (MOCVD) technology, the epitaxial structure and growth, the fabricating process and performance of AlGaAs/GaAs QWIP, the related readout integrated circuits (ROICs) as well as the related flip-chip bonding process were developed in our group in recent years. In this paper, the result of our long wavelength 128 × 128, 128 × 160 and 256 × 256 format AlGaAs/GaAs QWIPs is reported.

2 Basic principle of QWIPs

Different from the traditional intrinsic infrared detectors such as HgCdTe based on the interband transition between valence band and conduction band, AlGaAs/GaAs QWIPs use the mechanism of intersuband absorption between the energy levels of a quantum well related with the conduction band or the valence band. Carriers in

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ground state near the well bottom are excited to the first excited state near the well top, and then form a photocurrent with an externally-applied voltage. The absorption infrared wavelength can be adjusted easily by changing the parameters of the quantum well. Considering that the infrared absorption is most dependent on the transport perpendicular to the wells, the device is usually coupled with a 45° facet or optical grating on the surface of the active mesa.

3 Epitaxial structure and growth

The epitaxy structure based on n-doped AlGaAs/GaAs QWIP consists of the n-type heavily doped top and bottom ohmic contact layers and the AlGaAs/GaAs multi-quantum wells (MQWs) absorption layers. The MQW is typically stacked by AlGaAs/GaAs quantum wells with 30–50 periods to increase the infrared photon absorption. The responsible spectrum and efficiency are related to the parameter of MQW and the type of the transport. The thickness of the barrier $Al_xGa_{1-x}As$ ($x = 0.23$–0.27) layer and the well GaAs layer is in the range of 30–50 nm and 4–6 nm, respectively. The Si-dopant density, typically 5×10^{17} cm^{-3}, in the well involves with the quantum efficiency, the dark current performance, as well as the resistance of the device. The absorption layer is sandwiched between the top 1000 nm and bottom 1500 nm GaAs contact layer (1.5×10^{18} cm^{-3} Si-doped). The epitaxial wafers were fabricated on 2-inch commercially available (100) semi-insulator GaAs substrates using the AIX2000 MOCVD system. The uniformity and the crystal lattice quality of the epitaxial wafers were characterized by photoluminescence (PL) and X-ray diffraction (XRD).

4 Device structure and process

A large area element infrared photodetector with a mesa size of 300 μm × 300 μm was designed and processed to optimize the epitaxy structure and growth parameter. The performance of the responsible spectrum, dark current and detectivity is evaluated by testing the device according to which epitaxial structure, growth parameter and fabrication process were corrected. A two-dimensional periodic grating was etched on the surface of the mesa to coupling the input infrared signals. Considering that the QWIPs do not absorb radiation incident normal to the surface, two-dimensional 2 μm × 2 μm periodic grating cavity arrays with a pitch of 4 μm and depth of 0.75 μm were fabricated for a peak wavelength of 8.5 μm. 128 × 128, 128 × 160 and 256 × 256 format QWIP FPAs were designed and fabricated with flip-chip bonding (FCB) process. The related structure parameters of the QWIP FPAs are listed in Table 1.

Tab. 1 Structure parameters of different QWIP FPAs

format	parameter		
	pixel size/μm	pitch/μm	die size/μm
128 × 128	45 × 45	50	6.9 × 6.9
128 × 160	25 × 25	30	5.7 × 4.7
256 × 256	30 × 30	35	10 × 10

The QWIPs were manufactured using the 2–3 inch GaAs integrated circuits (ICs) process in our laboratory. The process includes conventional photolithography, optical grating etching, mesa etching, top and bottom contact metallization and chip dicing. The optical grating cavity and active mesa are etched by inductance chemical plasma (ICP) etch instead of the wet chemical etch to avoid the serious lateral etch. Using Cl_2 based reactive gas, nearly vertical and smooth pattern for the grating and the mesa were realized. The ohmic contact on n-type GaAs was formed with AuGeNi/Au by lift-off and rapid annealing process.

Indium bumps were formed by evaporating and lift-off process on the surface of pixels since the QWIP chips needed to be integrated with the CMOS readout integrated circuits (ROICs). Figure 1 is the photograph of the optical grating etched by ICP. Figure 2 is the fabricated 2-inch QWIP FPA wafers of different pixel formats.

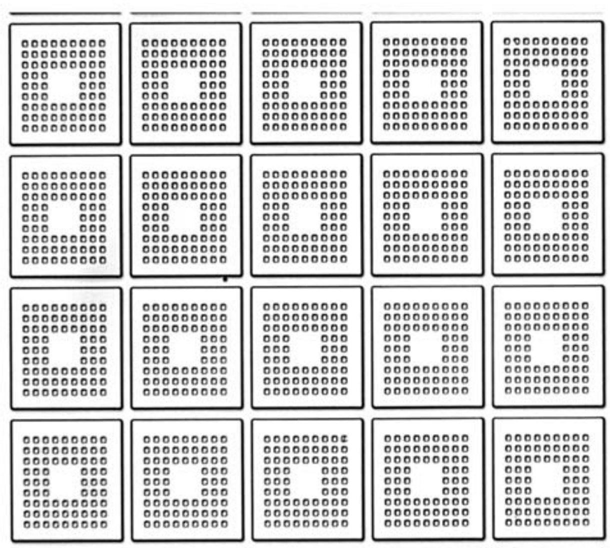


Fig. 1 Pixels of QWIP with two-dimensional grating array on the surface

5 Performance of element QWIP

An on-wafer testing system for the dark current of the large area element QWIP was set up using a simple liquid nitrogen probe bench and a Keithely 4200 semiconductor parameter analyzer. Figure 3 shows the curve of the dark current density versus the bias voltage for an element test-

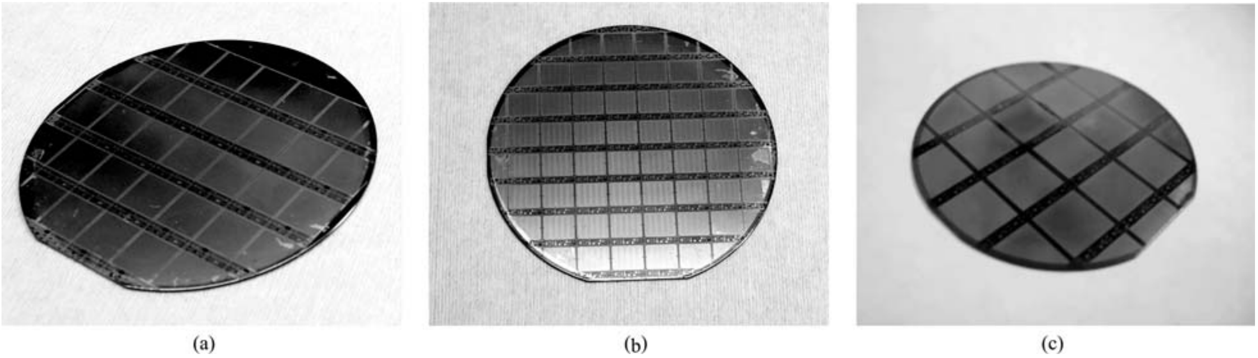


Fig. 2 Fabricated 2-inch wafers of QWIP FPA with different formats. (a) 128 × 128; (b) 128 × 160; (c) 256 × 256

ing QWIP with a mesa size of 300 μm × 300 μm at 77 K with room temperature background. The forward bias on the *X* axis means that the top contact of the device is forward biased. Figure 3 shows the asymmetry of the *I*-*V* curves with forward bias and reverse bias, which is due to the asymmetry of the quantum well structure resulting from the distribution of the Si dopant changing along the growth direction in the epitaxial process [10,11].

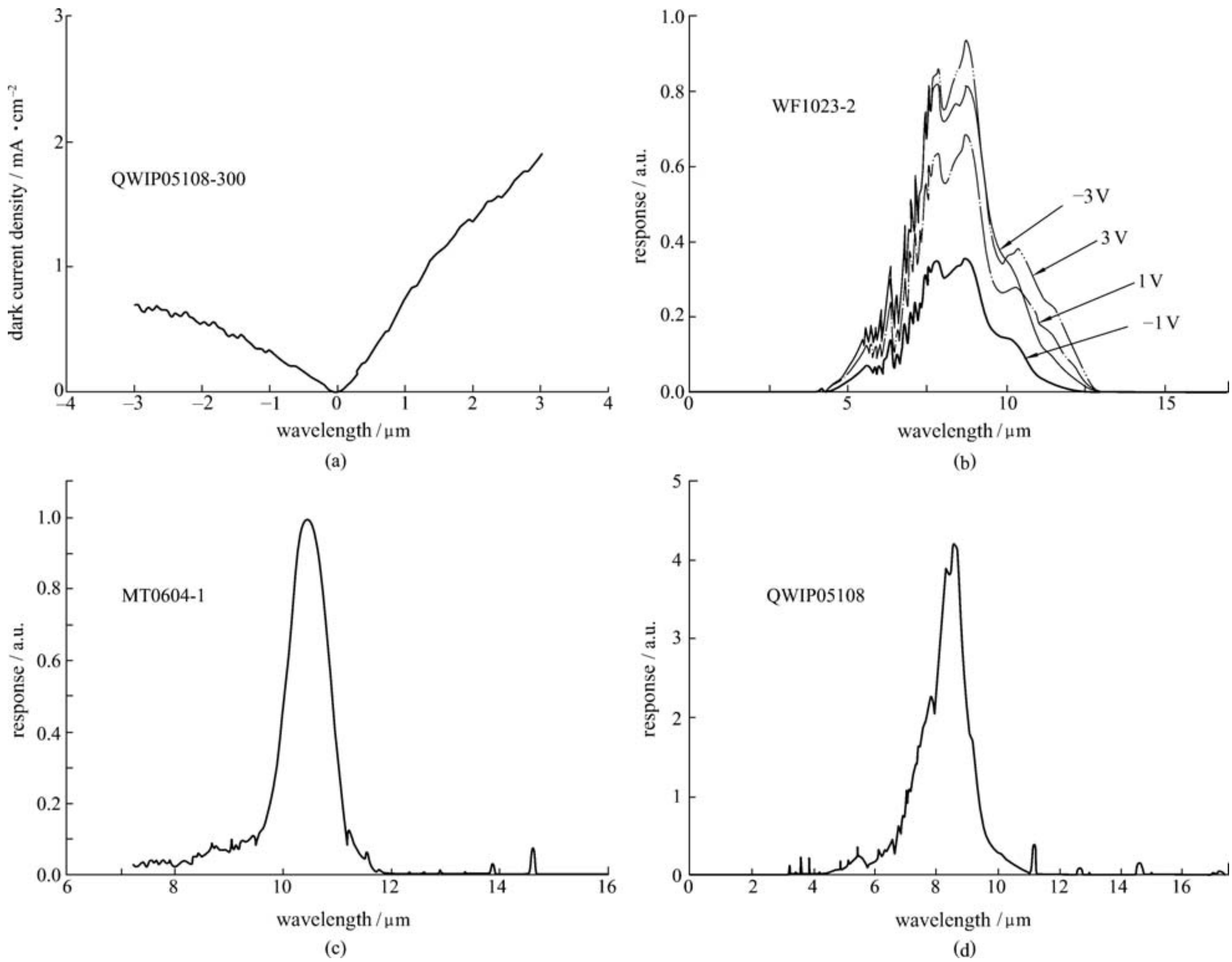


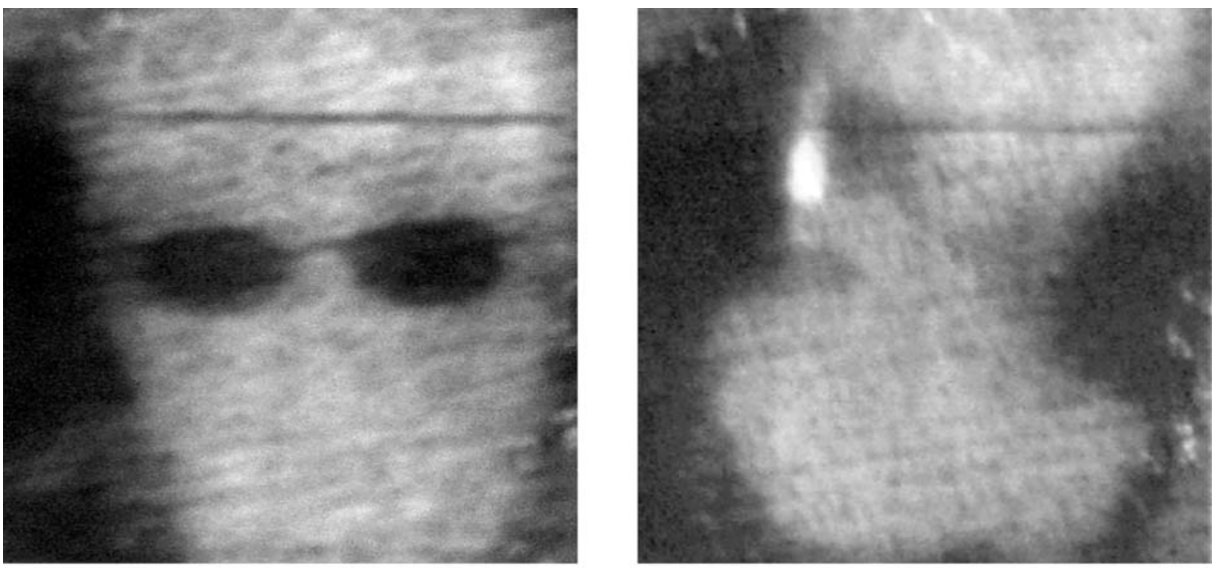
Fig. 3 Characteristics of dark current and Fourier transform infrared spectroscopy (FTIR) spectra for QWIPs. (a) Dark current density of QWIP dependence of bias voltage at 77 K; (b) FTIR spectra of epitaxial structure at 80 K, $V_{\text{bias}} = 3$ V, $\lambda_p = 8.7$ μm, $\lambda_c = 9.1$ μm, $\Delta\lambda = 2.5$ μm, $\Delta\lambda/\lambda = 28\%$; (c) FTIR spectra of epitaxial structure at 80 K, $V_{\text{bias}} = 5$ V, $\lambda_p = 10.4$ μm, $\lambda_c = 10.9$ μm, $\Delta\lambda = 0.9$ μm, $\Delta\lambda/\lambda = 8.6\%$; (d) FTIR spectra of epitaxial structures at 80 K, $V_{\text{bias}} = 1.5$ V, $\lambda_p = 8.5$ μm, $\lambda_c = 9$ μm, $\Delta\lambda = 1.7$ μm, $\Delta\lambda/\lambda = 20\%$

The element device was bonded on a testing AlN carrier and then mounted into a testing dewar cooled by liquid nitrogen to evaluate the performance of the responsivity spectrum and detectivity. The practical temperature of the QWIP chip should be about 80 K considering the temperature grads between the chip and the carrier. The responsivity spectrum of the test QWIP was evaluated with a Nicolet 5700 Fourier transform infrared spectrometer. Figures 3(b), 3(c), 3(d) are the responsivity spectrums with different epitaxial structure, among which, Fig. 3(b) reveals the curves of responsivity versus the bias voltage. From the responsivity spectrum, the peak wavelength λ_p, the cutoff wavelength λ_c and the spectral width $\Delta\lambda/\lambda$ could be obtained [1]. The transition type of photoexcited electrons between the intersubbands could be roughly revealed with the spectral width [2,8]. The thickness of GaAs well and the index of Al in AlGaAs barrier was 5 nm and 0.27, respectively, for the wafer WF1023-2 and 05108, and was 6 nm and 0.23, respectively, for the wafer MT0604-1. The doping density in the wells was also somewhat different. All these resulted in that the cutoff long wavelength was extended to 10.9 μm and the spectral width is as small as 8.6% for the wafer MT0604-1. In addition, infrared responses were observed during the FTIR spectrum measurement for the devices without optical grating on the surface of the mesas by front illumination. Compared with the responses of those with optical grating, these responses were a little weaker. This may be related to the quantum structure aberrant with the theoretically rectangular structures for the imprecisely controlling in the interface growth of MOCVD.

The blackbody detectivity of the testing devices was evaluated coupling with a 45° facet and optical grating on the surface, respectively. The related testing system consisted of a calibrating 500 K blackbody source, an optical chopper and a lock-in amplifier. The measured blackbody detectivity D_B* for different devices was in the range of 3.95×10^8 cm·Hz$^{1/2}$·W^{-1} to 2.6×10^9 cm·Hz$^{1/2}$·W^{-1}.

6 Thermal image demonstration of 128 × 128 QWIP FPA

The 128 × 128 QWIP FPA was flip-chip bonded on the related ROIC designed in our laboratory through indium bumps to form a 128 × 128 QWIP FPA module. The GaAs substrate of the QWIP FPA was then thinned and polished to 200 μm to lower crosstalk between pixel elements. The final QWIP FPA module was mounted on a testing carrier into a dewar cooled by liquid nitrogen with the germanium lens cooled by liquid nitride to demonstrate a thermal imaging camera with an image processing system, which is assembled to process the clock signals from the readout multiplexer and correct the obtained image. The infrared thermal video images for static and moving targets at room temperature background were taken and demonstrated. Figures 4(a) and 4(b) are the thermal image at 80 K operating temperature after one-point correction for a man's face and lighting flame with a hand in the room temperature background, respectively. The quality of the images is not ideal enough yet at present. The image quality should be further improved by the following means. First, the epitaxial structure and process should be optimized again to further



(a) (b)

Fig. 4 Thermal images of objects by 128 × 128 QWIP at 80 K operating temperature. (a) A man's face; (b) a hand with a lighting flame lower the dark current and increase detectivity. Second, thinning and polishing the GaAs substrate of QWIP to under 20 μm to eliminate crosstalk between pixel elements. In addition, lowering the operating temperature of QWIP to below 65 K by using a Sterling cooler will also result in much better image quality.

The 128 × 160 and 256 × 256 format QWIP FPAs module were still in the assembly and testing stage, and the results will be reported in the coming papers.

7 Conclusion

We have designed and fabricated n-doped large area testing AlGaAs/GaAs QWIPs and 128 × 128, 128 × 160 and 256 × 256 AlGaAs/GaAs QWIP FPAs basing on the MOCVD technology and the GaAs integrated circuits fabricating process. The element testing devices were evaluated with the dark current density and FTIR responsible spectrum measured under liquid nitrogen temperature. The devices with cutoff wavelength of 9 and 10.9 μm were realized using the different epitaxial structures. The highest blackbody detectivity D_B* was 2.6×10^9 cm·Hz$^{1/2}$·W^{-1}. The infrared thermal images of targets under room temperature background were demonstrated with the 128 × 128 AlGaAs/GaAs QWIP FPA flip-chip bonded on the related CMOS readout integrated circuit. To realize the commercialization of the QWIP FPA, the quality of the thermal image is expected to be improved by optimizing the epitaxial structure, thinning the GaAs substrate and lowering the operating temperature further.

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