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High operating temperature mid-wavelength infrared HgCdTe focal plane arrays

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Abstract: This paper presents the recent progress in the research of high operating temperature (HOT) mid-wavelength infrared (MWIR) HgCdTe focal plane arrays (FPAs) at Kunming Institute of Physics. By optimizing the structural parameters of mid-wavelength infrared HgCdTe detectors, a 640×512@15 μm mid-wavelength infrared focal plane array (FPA) was fabricated based on high-quality in situ indium-doped HgCdTe film grown by liquid phase epitaxy (LPE) using arsenic-ion-implanted p-on-n planar junction device technology. The spectral response, device dark current, noise equivalent temperature difference (NETD), operability, and the distribution of defective pixels of the prepared p-on-n chip arrays at various operating temperatures were tested using a variable temperature Dewar. The test results demonstrate that the detector has the ability to operate at temperatures above 180 K.

Key words: high operating temperature, MWIR, HgCdTe, NETD, operability

高工作温度中波红外碲镉汞焦平面研究

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摘要：该文报道了昆明物理研究所高工作温度中波红外碲镉汞焦平面探测器器件的研究情况。通过优化焦平面器件结构参数，采用As离子注入形成p-on-n平面结器件技术，在液相外延生长的高质量原位In掺杂的碲镉汞薄膜上制备了阵列规格为640×512@15μm的中波红外焦平面探测器。利用变温杜瓦测试了焦平面芯片在不同工作温度下的光谱响应、器件暗电流、噪声等效温差、有效像元率以及盲元分布等，测试结果表明器件具备180K以上工作温度的能力。

关 键 词：高工作温度；中波红外；碲镉汞；噪声等效温差；有效像元率

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Introduction

The $Hg_{1-x}Cd_xTe$ (MCT) material, invented by British scientists Lawson and co-workers in 1959, is a direct bandgap semiconductor material with perfect adjustable band-gap property[1-2]. Compared with InSb, InAs/GaSb superlattices and other materials, HgCdTe materials have significant advantages in the development of high operating temperature infrared detectors due to their longer minority carrier lifetime and larger absorption coefficient[3-7]. Due to its excellent photoelectric performance, HgCdTe infrared detector has been playing a leading role in the field of the high-end infrared detection field, and is considered a core and key device for battlefield information acquisition in the future information warfare. Currently, there is an urgent demand for high performance, miniaturized, low power consumption, and low cost ($SWaP^3$) HgCdTe mid-wavelength infrared (MWIR) de-

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tectors in various fields such as the new generation of multi-functional handheld thermal imagers, intelligent unmanned photoelectric systems, precision guidance and reconnaissance alarms. Among them, one of the main development directions of infrared detector technology is to improve the high operating temperature (HOT) of detector assemblies and realize the miniaturization and low power consumption of detector assemblies on the premise of maintaining the high performance of detectors[8-11].

The p-on-n structure of HgCdTe devices is achieved by extrinsic doping with arsenic and indium impurities, effectively eliminating the impact of Hg-vacancy defects on the device performance. Based on planar p-on-n junction device technology, high-performance HgCdTe focal plane arrays (FPAs) have been developed by RVS in American, AIM in Germany, and Sofradir in France. The dark current level of the proposed device is more than two orders of magnitude lower compared to that of Hg-vacancy-doped n-on-p structure devices, which have been the primary technical route for the development of HgCdTe HOT FPAs[12-15].

In this paper, the latest advancements in the development of MWIR HgCdTe HOT FPAs at Kunming Institute of Physics (KIP) are reported in detail.

1 Experiment

Based on the planar p-on-n junction structure, we have accomplished the optimal design of high operating temperature MWIR HgCdTe devices. Planar p-on-n HgCdTe mid-wavelength infrared (MWIR) FPAs with a 640×512 pixels format and a 15 μm pitch (640×512@15 μm) based on liquid phase epitaxy (LPE)-grown in situ indium-doped HgCdTe films are fabricated by arsenic ion implantation. The prepared MWIR HgCdTe FPA is packaged into a variable temperature Dewar. The dark current level, noise equivalent temperature difference (NETD), and operability of the MWIR HgCdTe HOT FPA are then tested and analyzed at various operating temperatures.

2 Results and Discussion

2.1 Device Structure design and Performance Calculation

For high operating temperature (HOT) HgCdTe detectors, the concentration of the intrinsic, thermally excited carriers increases exponentially with rising operating temperature[6-9]. Consequently, both diffusion current ($J_{diff} \propto n_i^2$) and generation-recombination current ($J_{GR} \propto n_i$), which are related to the intrinsic carrier concentration, increase exponentially as well. Ultimately, this exponential increase negatively impacts device performance[14-16]. The results of calculating the diffusion current and generation-recombination current (τ_{SRH}=5 ms) of a planar p-on-n MWIR HgCdTe detector with the composition x=0.295 (λ_C=4.8 μm@180 K) and the thickness of the absorbing layer of 5 μm as a function of operating temperature, are presented in Fig. 1. Fig. 1 (inset) illustrates the relationship between the concentration of intrinsic, thermally excited carriers and operating temperature of the detector.

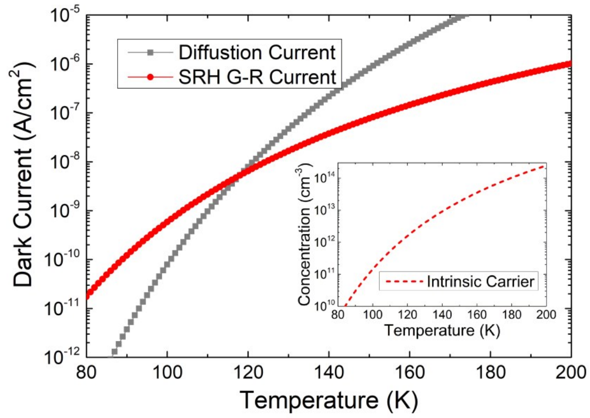

Fig. 1 The dependence of diffusion current density and generation-recombination current density on the operating temperature of a planar p-on-n MWIR HgCdTe detector. Inset: the relationship between the concentration of intrinsic, thermally excited carriers and operating temperature of the detector.
图1 平面p-on-n MWIR HgCdTe器件的扩散电流、产生-复合电流与工作温度的关系

Based on the calculation results, it can be concluded that the diffusion current associated with the absorbing layer becomes dominant when the operating temperature exceeds 120 K. Therefore, effective suppression of diffusion current at elevated temperatures is the fundamental to the development of HOT devices.

The Shockley-Read-Hall (SRH) lifetime in high crystal quality n-type MWIR HgCdTe materials can exceed 10 ms, with intrinsic recombination processes such as Auger-1 and radiative recombination limiting the minority carrier lifetime[17-19]. Due to photon recycling effects, radiative recombination can be disregarded, and the minority carrier lifetime in the materials is primarily limited by Auger-1 recombination[20]. The relationship between Auger-1 lifetime and operating temperature of HgCdTe materials with composition x=0.295 at various n-type indium doping concentrations is illustrated in Fig. 2. By reducing the doping concentration in the absorbing layer, it is possible to increase the minority carrier lifetime in the material and inhibit Auger recombination effectively, as indicated by these calculations.

For planar p-on-n MWIR HgCdTe infrared detectors, the absorbing layer acts as a common conductive layer. As the doping concentration in the absorbing layer decreases, so does its conductivity. However, this also leads to an increase in series resistance which is detrimental to consistent device operation.

Figure 3 shows the relationship between the thickness of the absorbing layer and the quantum efficiency of MWIR HgCdTe infrared detector. The calculation results indicate that the overall quantum efficiency of the MWIR HgCdTe device exceeds 73% when the thickness of the absorbing layer reaches approximately 5 μm.

Based on the results of the aforementioned calculations and analyses, combined with actual material and

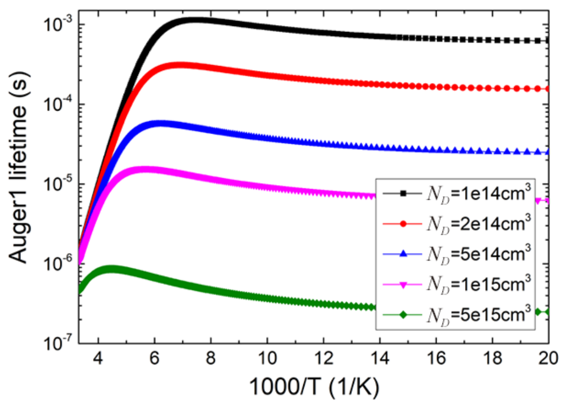

Fig. 2 The relationship between minority carrier lifetime and operating temperature of n-type HgCdTe materials
图2 n型中波碲镉汞材料的少子寿命与工作温度的关系

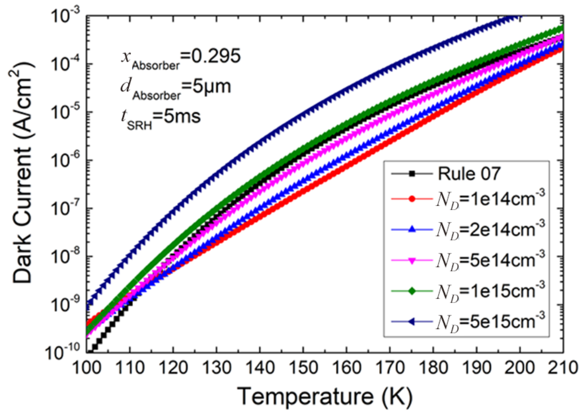

Fig. 4 The calculation results of the dark current of MWIR HgCdTe FPAs versus the predicted values by "Rule 07"
图4 中波碲镉汞器件暗电流计算结果与"Rule 07"暗电流预测值对比

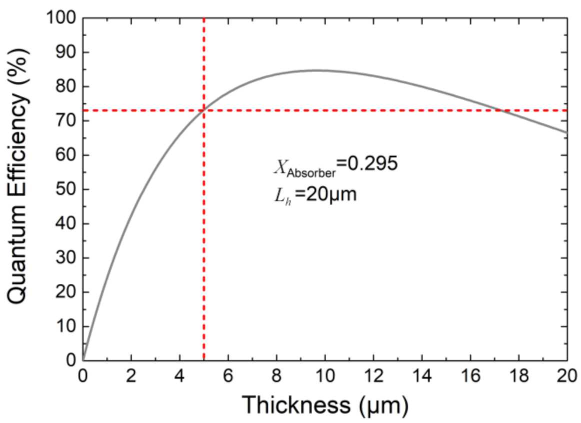

Fig. 3 The relationship between the quantum efficiency of MWIR HgCdTe detector and the thickness of its absorbing layer
图3 中波器件量子效率与吸收层厚度的关系

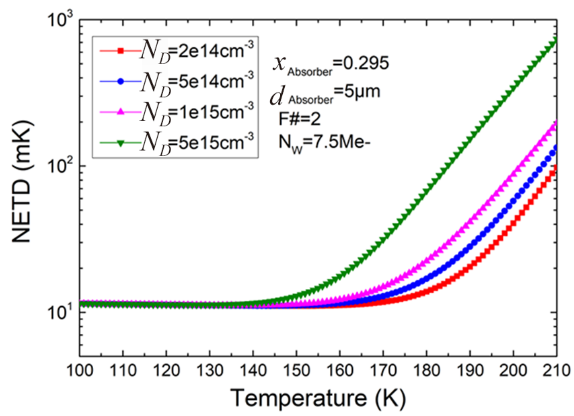

Fig. 5 Comparison of the NETD among HgCdTe devices with different doping concentrations
图5 吸收层不同掺杂浓度时碲镉汞器件NETD对比

device technology, the Indium doping concentration in the absorbing layer is set within a range of 2 to 5×10^{14} cm^{-3}, while the thickness of the absorbing layer is approximately 5-6 μm. As shown in Figure 4, the dark current of MWIR HgCdTe FPAs with varying doping concentrations in the absorbing layer at different operating temperatures are calculated and compared to the predicted values of dark current by "Rule 07" under the same composition[21-22].

Based on the calculation results of the dark current at various temperatures, the noise equivalent temperature difference (NETD) of MWIR HgCdTe FPAs operating at different temperatures has been calculated[23]. Figure 5 shows the dependence of NETD on FPA temperature, with varying doping concentrations in the absorbing layer.

According to the aforementioned calculation results, optimizing the doping concentration in the absorbing layer to suppress Auger recombination at elevated temperatures can effectively improve the operating temperature of MWIR HgCdTe FPAs while maintaining the high performance of detectors.

2.2 Fabrication of MWIR HgCdTe HOT FPAs

High-quality in situ In-doped MWIR HgCdTe thin films are grown by Te-rich LPE in a horizontal sliding-boat system on lattice-matched CZT(111)B substrates. Planar p-on-n MWIR HgCdTe HOT FPAs are fabricated using an arsenic implantation technique and a high temperature annealing process to activate the arsenic impurity, as shown in Figure 6.

For MWIR HgCdTe HOT FPAs, the low-frequency noise associated with surface states is a significant factor that limits device performance at high operating temperatures. Particularly when the operating temperature exceeds 160 K, the low-frequency noise related to surface states gradually becomes the primary limiting factor for device performance[24-26]. During the device preparation process, a CdTe/ZnS composite passivation layer is utilized for surface passivation, while the annealing process is optimized to generate a high component HgCdTe gradient layer with a specific width on the surface of HgCdTe. The introduction of a high component wide-bandgap layer on the surface of HgCdTe can effectively inhibit the surface states of the device. The SEM test results of the

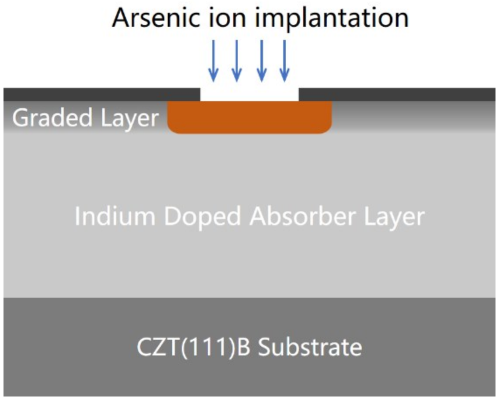

Fig. 6　Schematic diagram of a planar p-on-n HgCdTe FPA device fabricated by Arsenic-ion implantation
图6　As离子注入形成p-on-n平面结碲镉汞器件示意图

HgCdTe film with a CdTe passivation layer are presented in Figure 7.

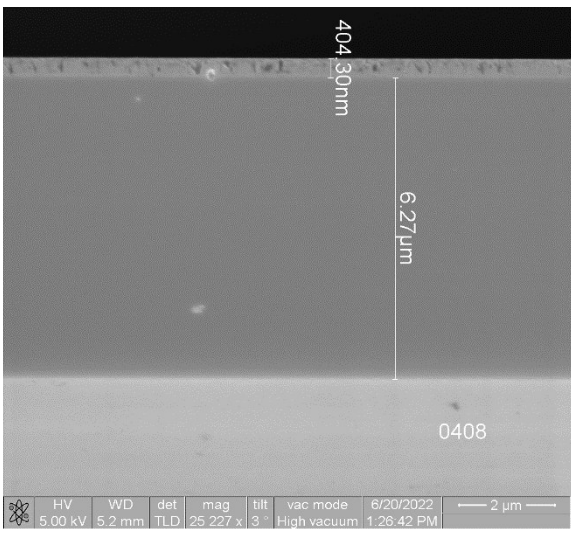

Fig. 7　SEM photomicrograph of the CdTe passivation layer
图7　CdTe钝化层SEM显微照片

2.3　Performance Characterization

The 640×512 MWIR HgCdTe FPAs with a pixel pitch of 15 μm are fabricated using planar p-on-n junctions achieved by arsenic implantation into an indium-doped HgCdTe base layer. The HgCdTe chip arrays and column-level analog-to-digital converter (ADC) digital Silicon readout integrated circuit (ROIC) (N_w=7.5 Me$^-$) are interconnected to hybrid FPAs by flip-chip bonding using indium bumps. The CZT substrate of 640×512 MWIR HgCdTe FPAs is completely removed, and the anti-reflective film is subsequently prepared. Then, the prepared hybrid FPAs chip is packaged into a variable temperature Dewar (F# =2) and tested for spectral response at different operating temperatures. The relative spectral response curves of MWIR HgCdTe FPA at operating temperatures of 77 K and 150 K are depicted in Figure 8.

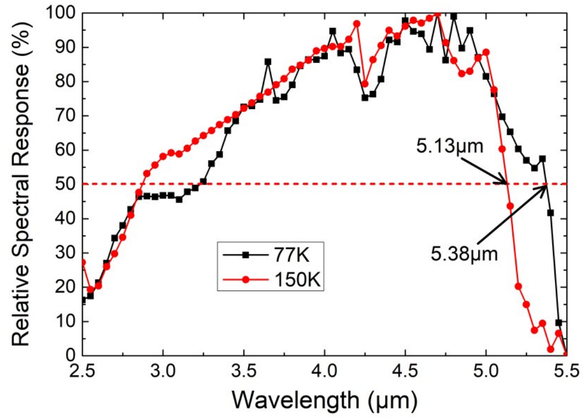

Fig. 8　Relative spectral response of MWIR HgCdTe FPAs at 77 K and 150 K.
图8　器件相对光谱响应测试结果

The dark current of the MWIR HgCdTe FPA device is tested at various temperatures to evaluate its performance. The dark current test results of the FPA device at different operating temperatures, along with the predicted value of dark current by "Rule 07" under the same composition, are depicted in Figure 9. According to the test results, it has been observed that when the operating temperature of the device exceeds 140 K, the dark current is significantly lower than what is predicted by "Rule07". These values are basically equal to those reported by AIM in Germany and Lynred (formerly Sofradir) in France[14-15].

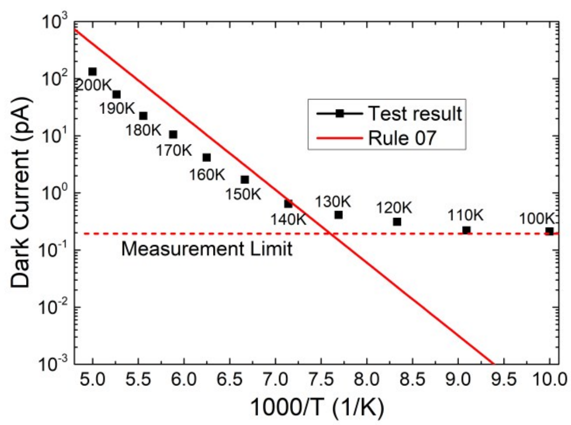

Fig. 9　Dark current test results of p-on-n MWIR FPAs versus the predicted values by "Rule 07"
图9　器件变温暗电流测试结果

The temperature-dependent NETD and operability of MWIR HgCdTe FPAs are tested, and the corresponding test results are presented in Figure 10. Here, the operability is defined as the number of pixels with a NEDT value or temporal noise within ±100% of the mean value of all pixels, or the number of pixels with responsivity value within ±30% of the mean. According to the temperature-dependent performance results of the FPAs, the operability of the FPAs exceeds 99.8% at operating temperature of 150 K. When the operating temperature reaches

180 K, NETD begins to increase significantly. However, the operability of the FPAs still exceeds 99%, indicating that MWIR HgCdTe FPA exhibits excellent high operating temperature (HOT) characteristics.

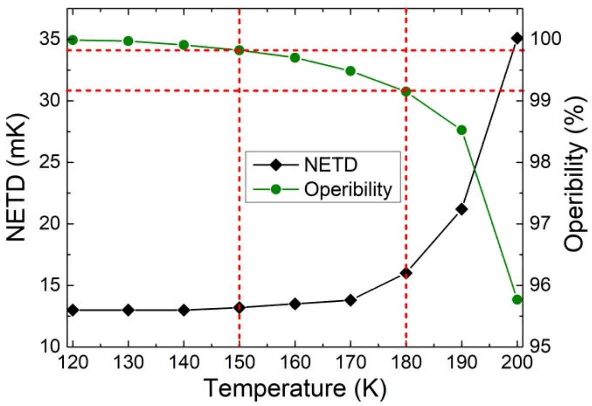

Fig. 10 Temperature-dependent NETD and operability of MWIR HgCdTe FPA
图10 不同工作温度下器件的NETD和有效像元率测试结果

Figure 11 shows the thermal response pixel mapping and defective pixel mapping for the MWIR HOT 640×512, 15 μm pitch FPAs at operating temperatures of 80 K, 150 K, and 180 K. Here, pixels are defined as defective, when individual NETD or temporal noise exceeds ±100% of the mean value of all pixels or if its response is less than 0.7 or larger than 1.3 times the mean response. The test results indicate that the developed MWIR HgCdTe FPA is capable of operating at 180 K initially.

3 Conclusion

The development of MWIR HgCdTe HOT FPAs are reported in this paper by Kunming Institute of Physics. By optimizing the device structure design and surface passivation process, high-performance MWIR HgCdTe detector arrays with 640×512 pixels and a 15 μm pixel pitch are fabricated based on LPE-grown in situ indium-doped HgCdTe films using arsenic-ion-implanted p-on-n planar junction device technology. The relevant parameters of the FPAs are tested at various temperatures, and the dark current level of the device is lower than that predicted by "Rule07". The temperature-dependent NETD and operability test results of MWIR HgCdTe HOT FPAs demonstrate that the FPAs have the ability to operate at temperatures above 180 K.

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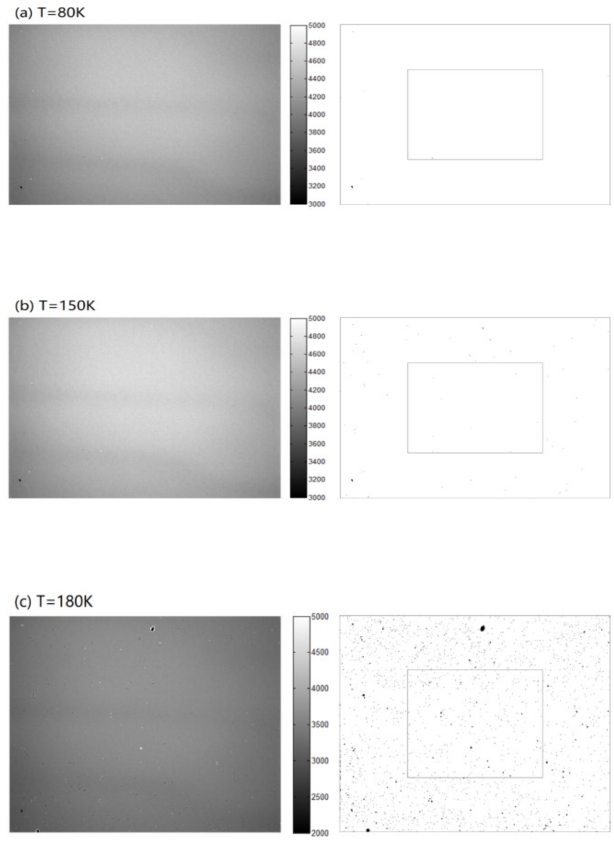

Fig. 11 Thermal response pixel mapping and defective pixel mapping for HOT 640×512, 15 μm pitch FPAs
图11 焦平面器件热响应及盲元分布

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