Detector material and sensitivity analysis for space-based infrared sensors

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(Received 26 September 2009)

The ultimate detection performance of HgCdTe, quantum well (QW) and extrinsic Si detectors under low temperatures is analyzed. The theoretical limits of the internal photon response for the three detectors are compared. The materials of space-based detectors in space tracking and surveillance system (STSS) are discussed. The results show that among three detectors, the best performance can be obtained from HgCdTe detectors under 40 K in the mid-long wave infrared (MLWIR) and long wave infrared (LWIR) spectral regions. Its ultimate detectivity in the MLWIR spectral region, with a cutoff wavelength of 8 μm, is on the order of 1×10^{18} cm·Hz$^{1/2}$/W. And that in the LWIR spectral region, with cutoff wavelengths of 12 μm, 16 μm and 20 μm, is on the order of 1×10^{15} cm·Hz$^{1/2}$/W, 1×10^{14} cm·Hz$^{1/2}$/W and 1×10^{13} cm·Hz$^{1/2}$/W, respectively.

Document code: A **Article ID:** 1673-1905(2010)01-0027-4
DOI 10.1007/s11801-010-9008-8

In space-based infrared sensor systems especially military systems, the materials of the detectors are mostly unknown because of the secrecy. To predict the system performance, it is important to comparatively analyze the performance of different material detectors according to their spectral region and operation temperature.

Researches have been carried out on analyzing IR detector performance. Ye et al.[1] analyzed the dark current mechanisms of the n-on-p planar photodiode and n$^+$-on-p heterojunction mesa photodiode for HgCdTe detectors. Rogalski et al.[2,3] presented the intrinsic physical characteristics of HgCdTe, quantum well (QW) and extrinsic Si detectors. Levine[4] summarized the performance of the spectral response, dark current and detectivity for different structural QW detectors. Szmulowicz et al.[5] presented the effects of device dimensions, doping concentrations and applied reverse bias on the detectivity of impurity band conduction (IBC) detectors. However, according to the published references obtained by authors, the comparative analyses of materials and ultimate detectivity of HgCdTe, QW and extrinsic Si detectors for space-based infrared sensors are rarely provided. In this paper, based on the theoretical models for detector detectivity of different materials and the experimental data, the ultimate detection performance for the three kinds of detectors under low temperatures is analyzed. The theoretical limits for the internal spectral response are also compared. As an example, the materials and ultimate detectivity of space-based detectors in space tracking and surveillance system (STSS) are discussed.

According to the current state-of-art technologies for detector material manufacture, HgCdTe, QW and extrinsic Si are the main detection materials for space-based infrared sensors[2-7]. The common detectivity model for infrared detectors with different materials can be expressed as[2]

$$D^* = 0.31\frac{\lambda}{hc}C_k\left(\frac{\alpha}{G}\right)^{1/2} , \tag{1}$$

where C_k is dependent on the recombination and backside reflection, h is the Planck's constant, c is the velocity of light, λ is the response cutoff wavelength of detectors in this letter, α is the absorption coefficient, and G is the generation rates. α/G determines the detectivity for different types of detectors with the same material. The calculation models of α/G for HgCdTe, QW and extrinsic Si detectors are the same as those in Ref.[2].

With a higher temperature for HgCdTe detectors, the detection performance limited by the Auger mechanism can be considered as the ultimate performance. With a lower temperature, the detection performance is mainly determined by the tunneling mechanism which is slightly affected by the temperature of detectors[1-3]. Therefore, to calculate the ultimate performance of HgCdTe detectors with a low temperature, the effects of Auger, trap-assisted tunneling and band-to-band tunneling mechanisms should be all considered. The

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detectivity of HgCdTe detectors can also be given as[2]

$$D^* = \frac{\lambda \eta q}{hc}\sqrt{\frac{R_0 A}{4kT}} \ , \tag{2}$$

where η is the quantum efficiency of detectors, q is the electron charge, k is the Boltzmann constant, T is the temperature of detectors, and R_0A is the resistance-area product without bias .

The theoretical detectivities calculated by the above model and the measured values obtained from Refs.[2-5,8] for HgCdTe, QW and extrinsic Si detectors are summarized in Fig.1. In the calculation, the meanings of parameters for

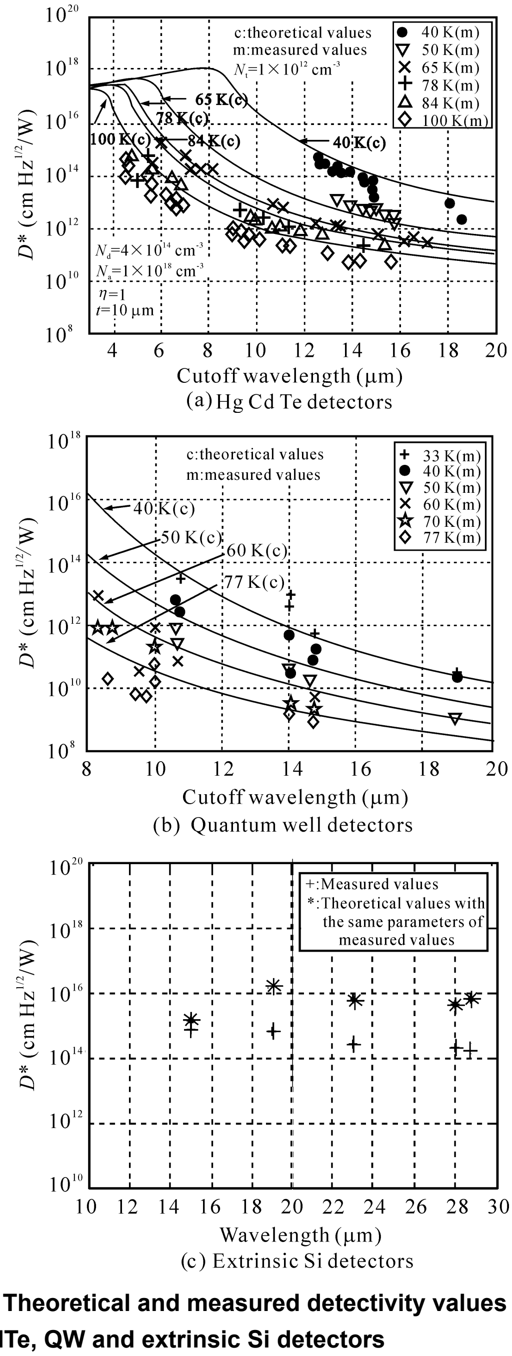


Fig.1 Theoretical and measured detectivity values for HgCdTe, QW and extrinsic Si detectors

HgCdTe detectors and the values of parameters for QW and extrinsic Si detectors are the same as those in Ref.[2].

It is seen from Fig.1 that the theoretical detectivity values for HgCdTe, QW and extrinsic Si detectors are higher than the measured values. However, the variation trend of the theoretical detectivities is consistent with that of the measured values. And the magnitude order of the theoretical results is in agreement with the experimental data for all three types of detectors. Therefore, the model results can be regarded as the ultimate performance under current technologies.

The STSS target tracking sensor includes a mid-long wave infrared (MLWIR) and a long wave infrared (LWIR) focal plane arrays with an operation temperature of 40 K[9]. To facilitate the discussion, the response wavelength ranges are focused on 3-8 μm and 8-16 μm for MLWIR and LWIR, respectively. This will not affect the rationality of the relevant conclusions.

Moreover, in the future, with the mature cryogenic technology, a lower operation temperature might be used. Thus, the performance of detectors with 40 K and 10 K is analyzed in the following research.

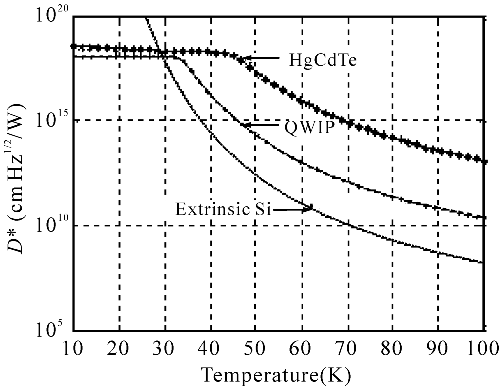
Fig.2 demonstrates the detectivity varying with the operation temperature for different cutoff wavelengths. In the calculation, the effects of Auger, trap-assisted tunneling and band-to-band tunneling mechanisms are considered for HgCdTe detectors. The thermal generation mechanisms of sequential resonant tunneling and optical phonons are included for QW detectors. The thermal noise of detectors and the photon noise of the optical system with a temperature of 25 K and emissivity of 0.1 are taken into account for extrinsic Si detectors.

It is seen from Fig.2 that, the detectivities of HgCdTe and QW detectors are higher than that of extrinsic Si detectors until the temperature further drops to around 10 K. On the other hand, in the MLWIR spectral region, there is no obvious difference between HgCdTe and QW detectors under the cryogenic temperature.

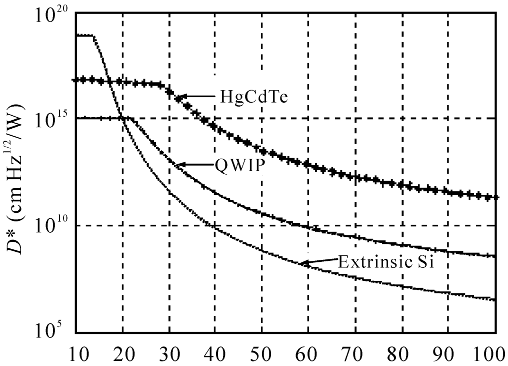
Theoretical limits of the internal photon response for today's advanced materials are summarized in Ref.[10]. Among HgCdTe, QW and extrinsic Si detectors, the internal photon response of HgCdTe detectors is the highest followed by extrinsic Si detectors. The detector response spectral bandwidth of extrinsic Si detectors is the widest followed by HgCdTe detectors, and that of the QW detectors is the narrowest.

Based on the above model and experimental results, it can be concluded that:

Firstly, the detectivity of HgCdTe detectors is better than that of extrinsic Si detectors in MLWIR and LWIR bands



(a) With a cutoff wavelength of 8 μm



(b) With a cutoff wavelength of 16 μm

Fig.2 D^* vs. detector temperature under different response cutoff wavelengths

with a cryogenic temperature of 40 K. As the temperature further drops to about 10 K, the detectivity of extrinsic Si detectors will be better than that of HgCdTe detectors. In the LWIR spectral region, the detectivity of HgCdTe detectors is better than that of QW detectors. But there is no obvious difference in the MLWIR spectral region under the cryogenic temperature. Therefore, it is not possible that extrinsic Si detectors are used with a cryogenic temperature of 40 K.

Secondly, in the internal photon response, the response spectral bandwidth of HgCdTe detectors is much wider than that of QW detectors, and the corresponding internal photon response is also higher than that of QW detectors. Therefore, the QW detectors are unlikely to be applied in space-based infrared sensors under a cryogenic temperature of 40 K.

Thirdly, compared with extrinsic Si detectors, the internal photon response of HgCdTe detectors is higher, but the response spectral bandwidth of extrinsic Si detectors is wider, and the cutoff wavelength can be easily extended to outside 20 μm. With a mature cryogenic temperature of about 10 K, the detectivity of extrinsic Si detectors is also higher than that of HgCdTe detectors. Therefore, in the future, with the cryogenic temperature around 10 K, extrinsic Si detectors are the first choice.

Therefore the HgCdTe detectors have the best performance at 40 K in both MLWIR and LWIR regions for space-based infrared sensors.

The theoretical ultimate detectivity and the experimental result for p-on-n photovoltage (PV) HgCdTe detectors at 40 K are illustrated in Fig.3. In the calculation, the effects of Auger, trap-assisted tunneling and band-to-band tunneling mechanisms are considered and the values of parameters are the same as those in Fig.1.

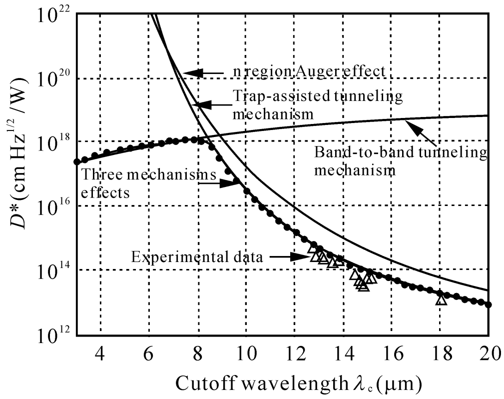


Fig.3 Theoretical ultimate detectivity and experimental result for HgCdTe detectors at 40 K

It can be seen from Fig.3 that the ultimate detectivity of PV HgCdTe detectors in the MLWIR spectral region with a cutoff wavelength of 8 μm is on the order of 1×10^{18} cm·Hz$^{1/2}$/W. In the LWIR spectral region, with cutoff wavelengths of 12 μm, 16 μm and 20 μm, the ultimate detectivity is on the order of 1×10^{15} cm·Hz$^{1/2}$/W, 1×10^{14} cm·Hz$^{1/2}$/W and 1×10^{13} cm·Hz$^{1/2}$/W, respectively. The detectivity of p-on-n PV HgCdTe detectors is mainly affected by the trap-assisted tunneling and band-to-band tunneling mechanisms with the detector temperature of 40 K.

In conclusion, based on the results of previous researchers, theoretical models for detector ultimate detectivity of different materials are introduced and compared with experimental data. The ultimate detection performance and the theoretical limits of the internal photon response under current technologies for HgCdTe, QW and extrinsic Si detectors at cryogenic temperatures are analyzed. As an example, the materials and ultimate detectivity of space-based detectors for STSS are investigated. The conclusions which are useful to analyze the materials and sensitivity for space-based infrared sensors are obtained.

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