Area-dependent gain and noise characteristics of mid-wavelength infrared HgCdTe planar electron avalanche photodiodes

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Abstract

This paper mainly investigates the area-dependent gain and noise characteristics of mid-wavelength infrared (MWIR) Hg\textsubscript{0.7}Cd\textsubscript{0.3}Te planar electron avalanche photodiodes (e-APDs) operated at 80 K. The 10-\textmu m-radius diode exhibits low dark current in the magnitude of $10^{-13}$ A below $\text{-}5.5$ V, high gain up to 1270 at $\text{-}10$ V, and low excess noise factor between 1 and 1.2. The optimal performances are compromised by tunneling current, which should be further suppressed. Studies on variable-area diodes show that larger diodes have a reduced gain due to a smaller contribution from edge gain, as well as an increased 1/f noise and corner frequency due to higher defect density. From the gain and noise perspectives, HgCdTe e-APDs with smaller junction areas are more suitable for focal plane array (FPA) applications.

1. Introduction

Avalanche photodiodes (APDs) are increasingly in demand, especially for low flux detection, due to their higher sensitivity than traditional photodiodes. This is made possible by the impact ionization process of carriers, which allows APDs to obtain internal gain [1]. The gain boosts the signal level yet introduces a higher shot noise named excess noise due to the stochastic nature of avalanche process. For high-performance APDs, it is preferable to have carriers with highly unequal ionization coefficients, which depend on the band structure of material [2, 3]. Hg\textsubscript{1-x}Cd\textsubscript{x}Te is one of the attractive materials that can satisfy this feature by adjusting the Cd composition $x$. The rapidly decreasing effective mass of electrons for $x < 0.56$ enables HgCdTe APD pure electron avalanche (i.e., e-APD) [4]. Benefiting from that, HgCdTe e-APDs have achieved the advantages of high gain, low excess noise factor, and fast response time [5]. Combined with a broad spectral range of tunability, HgCdTe e-APD focal plane arrays (FPAs) are promising in applications such as active and passive imaging, atmospheric lidar, and free space optical communication.

In HgCdTe e-APDs, gain and noise are the fundamental performance indicators. A stable exponential gain is usually associated with the behavior of dark current since it will increase with the electric field required for gain. There are many studies on the dark current transport and avalanche mechanisms, and the dominant current components in different voltage ranges have been clarified [6–9]. Moreover, at lower voltages, a critical concern is that the APD devices usually suffer from low-frequency noise in addition to excess noise. It will result in performance degradation if the devices switch from shot noise limit to low-frequency noise limit [10].

In this paper, we focus on the area-dependent gain and noise characteristics of mid-wavelength infrared (MWIR) HgCdTe e-APDs. The diodes were fabricated with ion-implanted planar homojunctions, and tested at the temperature of 80 K. A 10-\textmu m-radius diode was firstly characterized for basic properties. Larger diodes with radii ranging from 40 \textmu m to 240 \textmu m were introduced to investigate the effect of junction area on performances.
2. Device fabrication and experimental details

HgCdTe e-APDs studied here are based on a backside-illuminated planar $n^+$/p structure. Figure 1 shows a cross-sectional schematic of the APD array. A $p$-type Hg-vacancy doped ($\sim 1 \times 10^{16} \text{ cm}^{-3}$) $\text{Hg}_{0.7}\text{Cd}_{0.3}\text{Te}$ epi-layer was grown on the CdZnTe substrate by liquid phase epitaxy (LPE). The formation of $n^+$/p homojunction was first to generate a highly-doped $n^+$ region ($\sim 7 \times 10^{16} \text{ cm}^{-3}$) near the surface by boron ion ($\text{B}^+$) implantation, which provides a diffusion source of Hg interstitials. As the annealing process was carried out, these Hg interstitials would neutralize the Hg vacancies of epi-layer, forming a low-doped $n^-$ region ($< 5 \times 10^{14} \text{ cm}^{-3}$) with a finite width. The surface was coated with thermally evaporated CdTe and ZnS to achieve double-layer passivation. A metal layer was deposited to form the $p$-contacts and $n$-contacts. The indium bumps can interconnect the APD array with the readout integrated circuit (ROIC) for FPA. $D$ is the implant diameter and $\Delta D$ is the lateral collection length. The primary carriers are generated after photon absorption in the $p$ region. With the reverse bias voltage applied, the minority carriers (electrons) enter the high electric field region ($n^-$ region) and trigger the avalanche process. The excited secondary carriers are the main contributors to the APD gain.

In the experiments, the APD devices were mounted inside liquid nitrogen Dewars and hold at an operating temperature of 80 K. A cold shield with $F/2$ aperture was used to receive the background photon flux and that of 0 field of view (FOV) was used under dark conditions. The experimental setup for noise measurement is presented in figure 2. The APD devices, and the batteries used to provide the bias voltage were shielded in a grounded copper box to prevent noise from external disturbance. A low-noise current amplifier (AMP) with an adjustable gain converted the diode current into a proportional voltage. The output voltage signal was processed by a Fast Fourier Transform (FFT) spectrum analyzer to obtain the noise information. The measurement linewidth was 31.25 Hz over the frequency range. To improve the accuracy, 1000 repetitions of root mean square (RMS) averaging were performed for each spectrum. The system noise floor was determined by shorting out the APD devices, and was found to be almost independent of the applied voltages.
3. Results and discussion

3.1. Performance analysis of 10-\(\mu\)m-radius diode

Circular HgCdTe e-APD with a radius \(R\) of 10 \(\mu\)m was studied in this section. Figure 3(a) shows the current-voltage (I-V) and resistance-voltage (R-V) curves measured with a source meter. The current floor of the Dewar system is at the magnitude of \(\sim 10^{-13}\) A. The APD device has a maximum operating bias voltage of about \(-10\) V. Over the voltage range, the background illuminated total current \(I_{\text{total}}\) is at least two orders of magnitude larger.

![Figure 3](image-url)

**Figure 3.** (a) The measured I-V and R-V curves of 10-\(\mu\)m-radius HgCdTe e-APD operated at 80 K. (b) Gain and GNDC as a function of reverse bias voltage. (c) The excess noise factor \(F\) varies with gain between 1 and 1.2. The inset is the corresponding noise power spectra at different applied voltages.
than the dark current $I_D$. Therefore, the photocurrent $I_{ph} = I_{total} - I_D$ is approximately equal to the total current. It exhibits a voltage-independent photoresponse below around $-0.5$ V and thereafter increases exponentially with voltage. The photocurrent multiplication resulting from impact ionization will limit the infinite growth of differential resistance [11]. The unity gain point was chosen from the flat photocurrent region to be $-0.05$ V, at which the differential resistance reaches its peak, as shown by the $R$- $V$ curve in figure 3(a). Figure 3(b) displays the avalanche gain $M$ as a function of voltage $V$, which is calculated by $M(V) = I_{ph}(V)/I_{ph0}$, where $I_{ph0}$ is the photocurrent at $-0.05$ V. As shown in this figure, the gain up to 1270 at $-10$ V is achieved. To further understand the dependence of gain and dark current on the applied voltages, the gain-normalized dark current (GNDC), defined as $I_d/M$, is also depicted in figure 3(b). The GNDC starts from the dark current at unity gain, climbs up to an extreme value at $-0.6$ V, and then rapidly drops until $-5$ V. The reason for the sharp drop is that the carriers constituting the dark current in this voltage range underwent partial multiplication rather than full multiplication. After that, the dark current grows more rapidly than the gain due to band-to-band tunneling, resulting in a dramatic increase in GNDC. Moreover, the generation of tunneling current is also responsible for the slight non-exponential increase in gain when approaching the maximum tolerable voltage [12]. As a result, the maximum useful gain is limited to around 658 at $-9.5$ V under this background photon flux.

The noise power spectra of HgCdTe e-APDs were measured under background illuminated conditions to investigate the excess noise generated from the avalanche process. As shown in the inset of figure 3(c), the resulting noise power spectral density (PSD) in A$^2$/Hz measured at varied voltages are all above the system noise floor. The frequency-independent noise in this frequency range is considered as the shot noise due to the negligible thermal noise. The total shot noise $S_{shot}$ includes both the noise generated from photocurrent $S_{ph}$ and dark current $S_d$, which can be expressed by [13]

$$S_{shot} = S_{ph} + S_d = 2q(I_{ph} + I_{db}) \cdot M^2 \cdot F + 2qI_{db},$$

where $q$ is the electron charge, $I_{db}$ is the gain-multiplied bulk dark current, $I_d$ is the unmultiplied surface dark current. The dark noise was also measured and subtracted from the total noise to deduce the photocurrent noise $S_{ph} = S_{shot} - S_d$. Thus, the excess noise factors $F$ were calculated by

$$F = \frac{S_{ph}}{2qI_{ph} \cdot M^2} = \frac{S_{ph}}{S_d \cdot M^2},$$

where $S_d$ is the measured PSD at $-0.05$ V. As plotted in figure 3(c), the obtained $F$ values retain close to unity between 1 and 1.2. It indicates that the impact ionization process is deterministic and the HgCdTe e-APD device can offer avalanche gain with no significant degradation of signal-to-noise ratio.

### 3.2. Area-dependent performance analysis

HgCdTe e-APDs with different radii $R$ varied from 40 μm to 240 μm were characterized at 80 K in this section. As the radius (area) increases, the photocurrent also increases due to a rise in the number of photogenerated carriers. However, the avalanche gain extracted from the photocurrent shows an opposite trend. Figure 4(a) shows the gain curves for diodes with variable area. The unity gain points were still determined by their resistance characteristics. The diode with the largest area provides the lowest gain at the same bias voltage. For example, the gains at $-3.9$ V range from 5.7 for $R = 40$ μm diode to 3.1 for $R = 240$ μm diode; and the difference will be enlarged as the voltage increases. In fact, the gain of each diode originates from two dimensions: vertical collection within the area (interior gain), and lateral collection outside the area (edge gain) [4, 14]. The presence of lateral collection gives rise to a nonlinear relationship between photocurrent and area, as shown in the inset of figure 4(a). Moreover, due to edge effects caused by the curvature of junction, a higher electric field commonly exists at the edge for ion-implanted planar junction diodes [15]. Larger diodes with narrower π regions (smaller radius of curvature) may have fewer edge-related carriers to trigger the avalanche process. This will result in a smaller contribution from the edge gain, thus a reduction in total gain. In this regard, for a readout circuit with a limited maximum bias voltage, a smaller APD device may be an advantage owing to higher detection sensitivity.

Figure 4(b) presents the noise power spectra measured at a battery voltage of $-3.9$ V and under background illumination. The noise profiles were fitted with $S = Af^{-\gamma}$ to investigate the frequency dependence, where $A$ is a constant and $\gamma$ is the frequency exponent ($0 < \gamma < 2$) [16]. The $R = 40$ μm, 90 μm, 140 μm, and 240 μm diodes exhibit $1/f$ noise before the corner frequency $f_c$, with exponents of 0.3, 0.5, 0.9, and 1.1, respectively, and behave as shot noise afterwards. As the area expands, the intensity of $1/f$ noise goes up and the corner frequencies shift to a higher frequency. Even though there is a deviation in $f_c$ for $R = 40$ μm diode because the interference spikes from background noise obscure its exact location. It is known that the $1/f$ noise is linearly related to dark current stemming from bulk or surface [17]. The nearly constant dark current densities in figure 4(c) indicate that the dark current of the device is dominated by the bulk components. Based on previous study, the effect of diffusion current can be excluded at 80 K since it requires a higher activation energy close to...
Figure 4. (a) The gain-voltage curves for diodes with variable area operated at 80 K. The inset shows the photocurrent at $-3.9$ V versus the area. (b) The noise power spectra measured at $-3.9$ V. (c) The dark current density versus the inverse of radius at different bias voltages. The data for $R = 190 \mu$m diode is used to avoid the impact of the current floor.
the bandgap to become dominant [8]. The band-to-band tunneling current is more prominent at higher voltages where the device is in deep depletion with large band bending. Therefore, the major contributor may be one or both of generation-recombination current and trap-assisted tunneling current [13]. These two current mechanisms are strongly associated with defects in the depletion region, which are either created during the material growth or the junction formation processes [18]. These defects will act as Shockley-Read (S-R) centers and trap centers, respectively, which are easily activated at relatively low temperatures. The larger diodes, however, have higher defect density and are more likely to contain the killer defects, such as dislocations, voids, and inclusions [19]. In this way, there is an increased level of 1/f noise, and the higher corner frequency means a greater role of the 1/f noise compared to the unavoidable shot noise. This suggests that, on the one hand, the quality of HgCdTe epi-layer is non-uniform since the corner frequency would be area independent if the diodes were produced on the equivalent quality [20]. On the other hand, larger diodes are more susceptible to the 1/f noise at a given bias voltage, weakening the device performance.

4. Conclusion

In conclusion, we have mainly investigated the area-dependent gain and noise behaviors of MWIR HgCdTe planar e-APDs operated at 80 K. The 10-μm-radius diode exhibits low dark current in the magnitude of 10−13 A below −5.5 V, high gain up to 1270 at −10 V, as well as low excess noise factor varying from 1 to 1.2. However, tunneling current at larger bias voltages should be further suppressed, as it causes a sharp increase in GNDC, which would limit the maximum useful gain, particularly at low background radiation. Studies on variable-area diodes with radii varied from 40 μm to 240 μm show a reduction in gain, an increased level of 1/f noise, and a higher corner frequency for larger diodes. The decrease in gain may be due to a smaller contribution from edge gain as the number of laterally collected carriers decreases. The behavior of noise is because more of the defects would be included as the area expands, which also illustrates the non-uniformity of epitaxial quality. Thus, HgCdTe e-APDs with smaller areas are more suitable in terms of gain and noise, especially for FPAs with a maximum voltage-limited readout circuit.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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References

[1] Stillman G E and Wolfe C M 1977 Avalanche photodiodes Semiconductor and Semimetals 12 291–393
[2] Jones A H, March S D, Bank S R and Campbell J C 2020 Low-noise high-temperature AlInAsSb/GaSb avalanche photodiodes for 2-μm applications Nat. Photonics 14 559–63
[3] Velicu S, Ashokan R and Sivananthan S 2000 A model for dark current and multiplication in HgCdTe avalanche photodiodes J. Electron. Mater. 29 823–7
[4] Reine M B et al 2007 HgCdTe MWIR back-illuminated electron-initiated avalanche photodiode arrays J. Electron. Mater. 36 1059–67
[5] Singh A, Srivastav V and Pal R 2011 HgCdTe avalanche photodiodes: a review Opt. Laser Technol. 43 1358–70
[6] Qiu W C, Hu W D, Chen L, Lin C, Cheng X A, Chen X S and Lu W 2015 Dark current transport and avalanche mechanism in HgCdTe electron-avalanche photodiodes IEEE Trans. Electron Devices 62 1926–31
[7] Li Q, He J L, Hu W D, Chen L, Chen X S and Lu W 2018 Influencing sources for dark current transport and avalanche mechanisms in planar and mesa HgCdTe p-i-n electron-avalanche photodiodes IEEE Trans. Electron Devices 65 572–6
[8] Zhu L Q et al 2021 Temperature-dependent Characteristics—Temperature-dependent characteristics of HgCdTe mid-wave infrared e-avalanche photodiode IEEE J. Sel. Top. Quantum Electron. 28 1–9
[9] Chen J et al 2021 High-performance HgCdTe avalanche photodetector enabled with suppression of band-to-band tunneling effect in mid-wavelength infrared npn Quantum Mater. 6 1–7
[10] Tournié E and Cerutti L 2019 Mid-infrared Optoelectronics: Materials, Devices, and Applications (London,UK: Woodhead publishing)
[11] Elliott C T, Gordon N T and Hall R S 1990 Reverse breakdown in long wavelength lateral collection Cd$_x$Hg$_{1-x}$Te diodes J. Vac. Sci. Technol. A 8 1251–3
[12] Rothman J et al 2012 Short-wave infrared HgCdTe avalanche photodiodes J. Electron. Mater. 41 2928–36
[13] Kopytko M, Sobieski I, Gawron W and Martyniuk P 2022 Study of HgCdTe (100) and HgCdTe (111) B heterostructures grown by MOCVD and their potential application to APIDs operating in the IR range up to 8 μm Sensors 22 924
[14] Reine M B et al 2008 Characterization of HgCdTe MWIR back-illuminated electron-initiated avalanche photodiodes J. Electron. Mater. 37 1376–86
[15] Tosi A, Acerbi F, Dalla Mora A, Itzler M A and Jiang X 2010 Active area uniformity of InGaAs/InP single-photon avalanche diodes IEEE Photon. J. 3 31–41
[16] Keshner M S 1982 1/f noise Proc. IEEE 70 212–8
[17] Nemirovsky Y and Unikovsky A 1992 Tunneling and 1/f noise currents in HgCdTe photodiodes J. Vac. Sci. Technol. B 10 1602–10
[18] Gopal V, Singh S K and Mehra R M 2002 Analysis of dark current contributions in mercury cadmium telluride junction diodes Infrared Phys. Technol. 43 317–26
[19] Wijewarnasuriya P S et al 2002 Advances in large-area Hg$_{1-x}$Cd$_x$Te photovoltaic detectors for remote-sensing applications J. Electron. Mater. 31 726–31
[20] Williams G M, De Warnes R E, Bajaj J and Blazejewski E R 1993 Photo-induced excess low frequency noise in HgCdTe photodiodes J. Electron. Mater. 22 931–41