n-v-π-B-p HgCdTe avalanche photodiodes for high gain and low dark current via band and field engineering

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Section S1 Energy-band evolution under different bias voltages

To provide a clearer understanding of the band alignment and its evolution under reverse bias, the energy-band diagrams of the proposed n-v-π-B-p APD were further simulated at 77 K under bias voltages of 0, 5, 10, 15, 20, and 25 V. The corresponding conduction-band and valence-band profiles are shown in Fig S1.

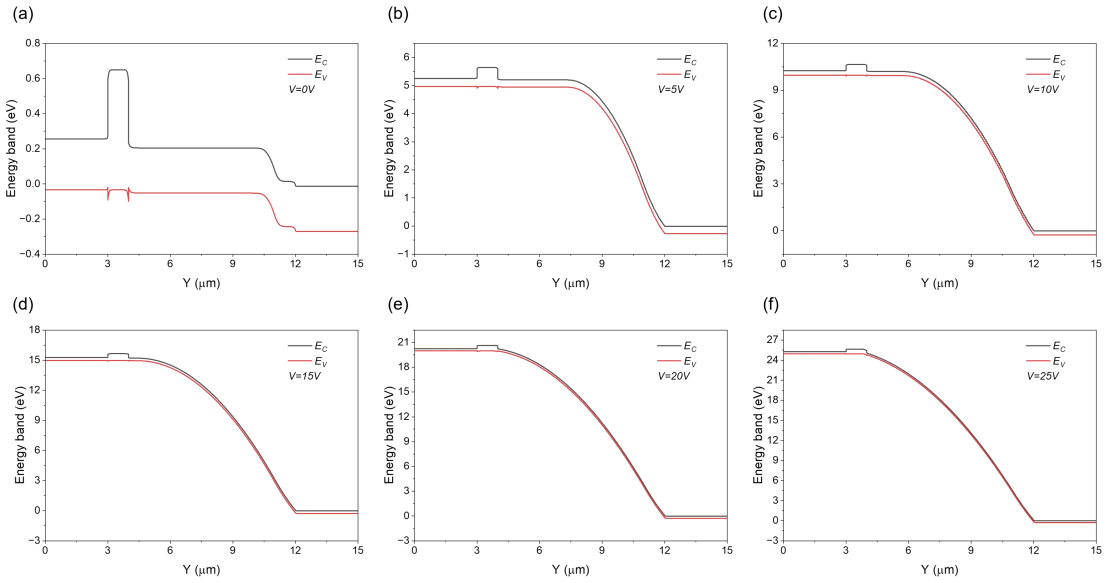


Fig S1. Energy band diagrams of the n-v-π-B-p APD under different bias voltages: (a) 0 V, (b) 5 V, (c) 10 V, (d) 15 V, (e) 20 V, and (f) 25 V.

Section S2 Estimation of the avalanche-onset critical electric field

The critical electric field of HgCdTe cannot generally be treated as a universal material constant because it depends strongly on the Cd composition, bandgap, temperature, doping profile, junction configuration, and device geometry. In addition, different field-assisted physical processes may correspond to different characteristic electric-field criteria. For example, the electric field associated with the onset of impact ionization is not necessarily identical to that required for pronounced band-to-band tunneling or to the apparent breakdown field of a complete device. Therefore, no predefined universal critical electric field was imposed in the present TCAD simulation.

In this work, the critical electric field was interpreted specifically as the electric field associated with the onset of linear avalanche multiplication. The avalanche gain extracted from the calibrated TCAD simulation was used as the practical criterion. At low reverse bias, the gain remains close to unity, indicating that impact ionization makes a negligible contribution to the photocurrent. As the reverse bias increases, the gain begins to deviate from unity and subsequently increases with bias, indicating the onset of the linear avalanche multiplication regime. The electric-field distribution at the corresponding bias point was therefore used to estimate the avalanche-onset critical electric field of the simulated device.

Fig S2 shows the electric-field distribution of the n-v-π-B-p APD at 77 K under the bias condition corresponding to the onset of linear avalanche multiplication. The peak electric field at this operating point is 2.0355×10^{4} V/cm. Accordingly, for the specific Cd composition, operating temperature, doping profile, and device structure considered in this work, the avalanche-onset critical electric field is estimated to be approximately 2.0×10^{4} V/cm. This value should be regarded as a device- and condition-specific estimate rather than a universal critical electric field for HgCdTe.

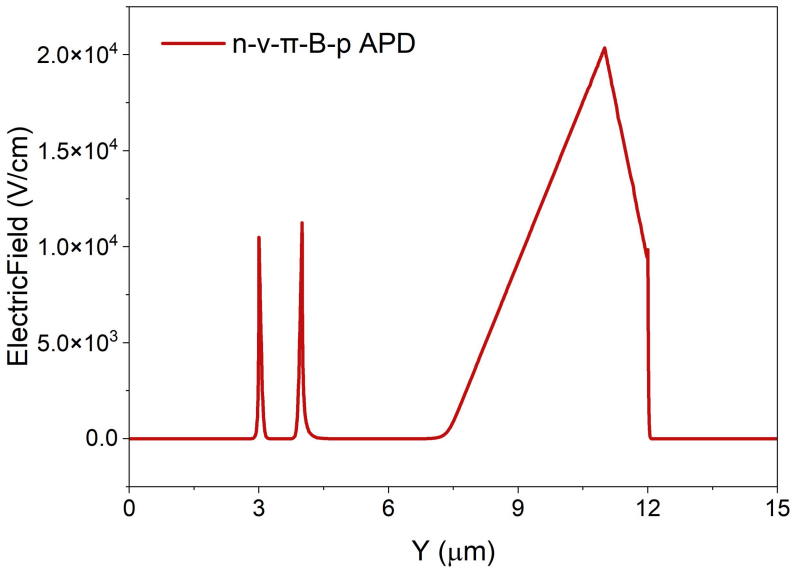


Fig S2. Electric-field distribution of the n-v-π-B-p APD at the onset of linear avalanche multiplication at 77 K.

Section S3 Effect of the B layer on the dark current at 150 K

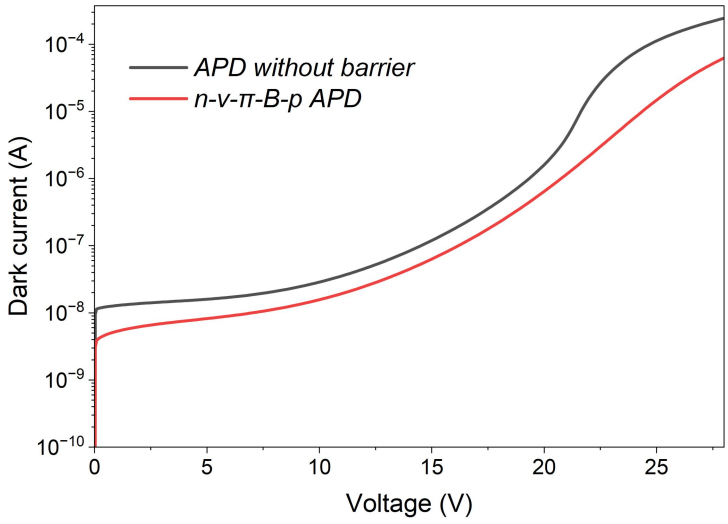


Fig S3. Comparison of dark currents between the n-v-π-B-p APD and the APD without the barrier layer at 150 K.

The comparison shows that, after removing the B layer, the dark current increases obviously, especially under high-temperature and high-bias conditions. This result indicates that the barrier layer plays an effective role in suppressing carrier replenishment from the contact side into the multiplication region. Therefore, the reduced dark current in the proposed n-v-π-B-p APD is not only related to the electric-field redistribution introduced by the v/π regions, but also benefits from the carrier-blocking effect of the B layer.