Enhanced Carrier Multiplication in InAs Quantum Dots for Bulk Avalanche Photodetector Applications

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Exploring the potentiality of enhancing the performance of avalanche photodiodes (APDs) using novel nanoscale structures is highly attractive for overcoming the bottleneck of avalanche probability. This work demonstrates, for the first time, multiplication enhancement of electron-initiated photocurrent due to impact ionization in InAs quantum dots (QDs) within a GaAs APD structure. A five-layer stacked 2.25 MLs InAs QD/50 nm GaAs spacer multiplication structure integrated into a separated absorption, charge, and multiplication GaAs homo APD results in up to six times higher multiplication factors in comparison to a reference device without QD over a temperature range of 77–300 K. In addition, extremely low excess noise factor in close proximity to that of silicon is also observed with an effective $k_{\text{eff}}$ factor below 0.1. This demonstration is of fundamental interest and relevant for future ultra efficient avalanche detector applications.

1. Introduction

Avalanche photodiodes (APDs) are one type of robust solid-state photodetection device utilizing carrier impact ionization effect in semiconductors, offering high internal photocurrent gain, compact size, low cost, and easy integration into electrical circuits in comparison to other sensitive detectors, for example, photoconductive detectors,[1] photomultiplier tubes,[2] and superconducting nanowire detectors.[3] Commercially available Si, InP/InGaAs, InP/InGaAsP, and InAlAs/InGaAs APDs operated in the 200–1700 nm wavelength range provide good gain, bandwidth, excess noise, and reliability, and have been used for a wide range of commercial, military, and research applications based on optical data communications and imaging. By applying a reverse bias over the avalanche breakdown voltage, APDs can enable ultrahigh photocurrent gain (>10⁵) and sensitivity down to the single photon level[4] that are essential for facilitating development of a number of cutting-edge short-wavelength infrared light detection applications, including 3D laser detection and ranging (3D LIDAR),[5] single photon counting,[4] and diverse quantum communication protocols.[6]

However, the performance of these advanced applications are currently limited by the APD’s photon detection efficiency which is essentially due to the bottleneck of the carrier avalanche probability in these bulk multiplication materials.[4,7,8] Breaking through this bottleneck especially relies on the exploration of novel multiplication structures that offer enhanced avalanche probability.

Nanoscale semiconductor structures have exhibited promising carrier multiplication capability for avalanche detector applications. Efficient photocurrent gain ranging from $10^2$ to $10^4$ due to carrier impact ionization in nanoscale p-n diodes consisting of silicon,[9,10] silicon-cadmium sulfide,[11] and InP/InAsP[12] 1D nanowires and InGaAs nanopillars[13] has been successfully demonstrated. Meanwhile, high-efficiency carrier multiplication in carbon nanotube,[14] PbSe[15–18] InP,[19] and InAs[20,21] nanocrystal quantum dots (QDs) due to multiple electron–hole pair generation has also been observed, in which a photon with energy greater than two times the band gap generates an average of more than one exciton, implying a drastic enhancement of conversion efficiency in nano solar cells. Nonetheless, to date the carrier transport and impact ionization behavior in QDs under strong electric field (E-field) have been unknown. Taking advantage of the discrete energy levels and the associated phonon bottleneck effect[22] of QDs, the kinetic energy relaxation of hot carriers via electron–phonon scattering is expected to be suppressed in QD multiplication structures and consequently enhanced multiplication performances are

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predicted. Moreover, carriers will gain extra kinetic energy when drifting from a wider band gap matrix barrier into a narrower band gap QD layer due to band discontinuities, which is similar to that in staircase APDs \cite{21,24} further enhancing the impact ionization rate. In particular, localization of carrier impact ionization events in QDs may lead to a more deterministic multiplication factor and consequently reduced excess noise. We demonstrate that a five-layer InAs QD multiplication structure integrated into a GaAs separated absorption, charge, and multiplication (SACM) APD can result in up to six times enhancement of multiplication factor in comparison to a reference device without QD, and extremely low excess noise comparable to Si APDs with an effective $k_{eff}$ factor below 0.1. This demonstration suggests QD avalanche structure is promising for enhancing the multiplication performance of APDs.

2. Results and Discussion

2.1. Growth and Device Fabrication

The InAs/GaAs QD APD structure was grown by a gas-source molecular beam epitaxy system. Figure 1a schematically illustrates the InAs/GaAs SACM QD APD structure with a five-layer stacked InAs QD multiplication region. In brief, after oxide desorption at 585 °C for 20 min of the heavily n-doped GaAs substrate, a 200 nm GaAs buffer (bottom contact) layer heavily doped to n-$4 \times 10^{18}$ cm$^{-3}$, a 300 nm five-layer stacked InAs QD multiplication structure, a 70 nm GaAs charge sheet layer doped to p-$6 \times 10^{17}$ cm$^{-3}$, a 1500 nm GaAs light absorption layer doped to p-$8 \times 10^{18}$ cm$^{-3}$, and a 100 nm GaAs top contact layer doped to p-$6 \times 10^{18}$ cm$^{-3}$ were grown sequentially, with silicon and beryllium as the n- and p-type dopants, respectively. Growth of the QD multiplication region was achieved by depositing 2.25 MLs unintentional-doped InAs at 500 °C spaced by 50 nm p-doped GaAs ($8 \times 10^{15}$ cm$^{-3}$). To suppress the island morphology degradation via InAs/GaAs intermixing during the initial GaAs capping, these spacer layers were deposited in a two-stage temperature growth pattern, that is, initial 10 nm at 500 °C and then 40 nm at 580 °C. All other GaAs epitaxial layers were grown at the same temperature of 580 °C. In order to gain information on the effects of the QDs on APD’s performance, a reference GaAs SACM APD with exactly the same structural parameters but without QDs was also grown for comparison. After wafer growth, variable diameter circular mesas ranging from 20 to 200 μm were chemically etched in a phosphoric acid-based solution. SiN$_x$ passivation and Ti/Pt/Au liftoff metallization techniques were applied to finish the device fabrication.

Figure 1b shows the simulated 300 K conduction ($E_c$) and valance ($E_v$) band edge line-up and the corresponding E-field profile along this QD APD at $-10$ V using nominal structural parameters. Stacking of five InAs QD layers generates five wells in series along the growth direction in the avalanche region. Electrons injected from the GaAs absorber into the QD avalanche region acquire extra kinetic energy of 0.6 eV whenever entering into an InAs QD layer from the GaAs spacer. The impact ionization threshold energy in the InAs QDs is expected to be much lower than that in bulk GaAs because of the collectively superiorities of much lower Γ-valley electronic effective mass (0.022m$_0$) and much larger intervalley separation.\cite{23,24} In addition, the threshold E-field intensity for electron impact ionization in bulk InAs has been predicted to be around 150 kV cm$^{-1}$\cite{27}. Note that the E-field intensity in the QD layers is merely 48 kV cm$^{-1}$ lower than that in the GaAs spacers (322–365 kV cm$^{-1}$), which ensures a high enough E-field for initiating impact ionization of electrons in InAs QDs. These band structures as well as E-field modifications suggest enhanced carrier multiplication may occur.

2.2. Structural and Optical Quality Assessments

Transmission electron microscopy (TEM) and high-resolution energy dispersive spectroscopy (EDS) studies of the InAs QD multiplication structure (i.e., Figure 2a,b) show that the InAs QDs’ morphology was well conserved during GaAs capping and is uniform over the five layers with an average QD height of 15 nm and an aspect ratio between 2 and 3. No observable structural defects were found in the GaAs spacer layers. High-resolution X-ray diffraction (XRD) rocking curve around (004) of the wafer was measured (Figure 2c), showing clear satellite peaks and a layer periodicity of 50 nm which is exact to the nominal thickness of the GaAs spacers. 300 K photoluminescence (PL) spectrum of the QD APD wafer (Figure 2d) demonstrates a strong emission at 1170 nm with an unsymmetrical line shape, which comes from individual contributions from the bound-to-bound (T$_{B-B}$) and excited-state transitions (T$_{ES}$)\cite{28} respectively. The decomposed PL energies of the T$_{B-B}$ and T$_{ES}$ peaks are 1.06 and 1.09 eV, respectively. These results suggest the achieved undoped InAs QDs are
well crystallized and strained with strong quantum confinement effect of carriers. This is especially important for studies of the multiplication behavior of QDs in APD, because crystalline defects in the QD multiplication region would cause high defect-assisted tunneling dark current on one hand, and on the other hand would result in carrier relaxation via defect-assisted recombination. More importantly, the phonon bottleneck effect would only be significant when quantized energy levels are formed in QDs.[22]

2.3. Avalanche Multiplication Characteristics

The avalanche multiplication properties of the QD and the reference APDs were probed by temperature-dependent light and dark current ($I$) versus bias voltage ($V$) measurements in a Lake Shore TTPX cryogenic probe station connected to an Agilent 4156C semiconductor parameters analyzer. A 633 nm He-Ne fiber-coupled laser with an attenuated output power of 1.05 µW was used as the illumination light source for photocurrent ($I_{ph}$) measurements. Representative data recorded from 100 µm diameter devices at 250 K (Figure 3a) show the same $I_{ph}$ of 200 nA at zero bias for both APDs, corresponding to a responsivity ($R_{\lambda^*}$) and an external quantum efficiency (EQE, $\eta$) of 0.19 A W$^{-1}$ and 37.22%, respectively (calculated by $R_{\lambda^*} = \eta \lambda / 1.24$). Reliability of the whole measurement system has been verified by measuring the $\eta$ of a commercial Si PIN photodiode with a known EQE. This $I_{ph}$ remained unchanged until −6.5 V, where the onset of multiplication of photocurrent took place. Therefore, the avalanche gain, $M$, was quantified by calculating $M = I_{ph}/I_{ph0}$, where $I_{ph0}$ is the primary unmultiplied photocurrent at the unity gain point of −6.5 V for both APDs. The dark current ($I_{dark}$) of the reference GaAs APD remained lower than 10 pA before a sharp breakdown at −12.5 V, while the $I_{dark}$ of the QD APD saw a sharp increase up to three orders of magnitude at reverse biases over −3 V and then a sharp breakdown at 13.2 V. It is also important to note that $I_{ph}$ of the QD APD sustains high currents, up to 100 µA, before merging with the $I_{dark}$. This delayed breakdown combined with the sustained higher photocurrent characteristics result in a considerable increase of the maximum $M$ before breakdown. These photo and dark $I$–$V$ features of both the QD and the reference APD had been examined on more than ten devices, showing good repeatability.

In addition, the maximum $M$ averaged from measurements on ten devices were obtained for both APDs as a function of temperature, as shown in Figure 3b. As expected, larger maximum $M$ of the QD APD was observed over the whole measured temperature range of 77–300 K. It is interesting to note that the

Figure 2. Structural and optical quality assessments of the QD multiplication region. a) TEM image of the five-layer stacked InAs QD multiplication structure. b) High-resolution EDS mapping of the indium element in the InAs QDs. c) XRD rocking curve around (004) of the wafer. d) 300 K PL spectrum of the QD APD wafer. The decomposed individual contributions of the bound-to-bound (TB-B) and excited-state (TES) transitions are indicated, respectively.

Figure 3. Avalanche multiplication properties of the QD and the reference APDs. a) Representative photocurrent (solid lines), dark current (dashed lines) $I$–$V$ data, and corresponding multiplication factors (hollow boxes) of the QD and the reference APDs with 100 µm diameter mesas at 250 K. b) Maximum $M$ and c) $M$ at 0.95$V_B$ averaged from measurements on ten devices as a function of temperature.
maximum $M$ of the QD APD at temperatures above 150 K is in the range of 350–430 K, 4–6 times higher than that of the reference APD (in the range of 50–100), while it drops to 100–150 at temperatures below 150 K, around two times higher than that of the reference APD in this temperature range. Such multiplication increment is suggestive of the occurrence of enhanced electron impact ionization in the InAs QD layers, which possibly benefits from the combined effects of a significant phonon scattering bottleneck effect[24] and a lower impact ionization threshold energy[25] in QDs, and also the obtained of extra kinetic energy of electrons at the InAs/GaAs interfaces.

The temperature-dependent $M$ at 0.95$V_B$ averaged from measurements on ten devices for both APDs are also extracted, as shown in Figure 3c. An overall similar trend of enhancement of $M$ at $T > 150$ K is also observed, while the enhancement factor decreases to 2–3. We had previously identified the temperature-dependent carrier scattering mechanisms in an indium-rich alloy of In$_{0.43}$Ga$_{0.57}$As, in which the dominating scattering mechanism evolves from phonon scattering at $120 < T < 300$ K to alloy and impurity scattering at $T < 120$ K.[28] The reduced gain enhancement at temperatures below 150 K, however, is likely to be related to such altered dominating carrier scattering mechanisms at lower temperatures and therefore the advantage of the phonon scattering bottleneck effect in QDs is weakened.

Further quantitative theoretical analyses are still in demand to thoroughly understand such temperature-dependent multiplication enhancement behaviors.

### 2.4. Dark Current and Avalanche Breakdown

To characterize the behavior of the InAs QDs on the generation of $I_{\text{dark}}$, we have calculated the activation energies ($E_a$) of $I_{\text{dark}}$ using temperature-dependent dark $I$–$V$ data. In contrast to the slow increase of the $I_{\text{dark}}$ from $6 \times 10^{-11}$ A at 150 K to $8.2 \times 10^{-10}$ A at 300 K at $-10$ V for the reference APD (Figure 4a), integration of InAs QDs in the GaAs multiplication region leads to a drastic climb of $I_{\text{dark}}$ from $4.5 \times 10^{-11}$ to $1.7 \times 10^{-8}$ A with the temperature increasing from 150 to 300 K at the same reverse bias (Figure 4b). This observation is consistent with the measured strong enhancement of the maximum $M$ of the QD APD that also starts from $T = 150$ K (Figure 3b), indicating a possible contribution for the $I_{\text{dark}}$ from multiplication of bulk dark carriers. In addition, the QD device exhibits an interesting two-step $I_{\text{dark}}$ increase behavior at $T > 150$ K which is distinctly different from the reference APD. The biases at the onset of both steps monotonically increase with decreasing temperature, indicating again the $I_{\text{dark}}$ is sensitive to not only thermal but also kinetic energies of dark carriers. Arrhenius plots of $I_{\text{dark}}$ of the APDs at a reverse bias of $-10$ V are given in Figure 4c, showing linear dependences with different slopes at $T > 250$ K and $175 < T < 250$ K, respectively, for the QD APD and a single slope at $T > 175$ K for the reference APD. Considering the fact that the $E_a$ of 0.55 eV coincides well with half of the $T_B$ transition energy of 1.06 eV for the InAs QDs (Figure 2d), we then identify the dominant source of $I_{\text{dark}}$ at $175 < T < 250$ K for the QD APD is the midgap trap states related Shockley–Reed–Hall (SRH) generation-recombination current in QDs.[30] And consequently, the bias increase for the two-step climb of $I_{\text{dark}}$ with decreasing temperature for the QD device is related to the trapping and detrapping of dark carriers by the midgap levels. With decreasing temperature, higher kinetic energy is required to detract the trapped dark carriers, resulting in an increased bias for the first-step climb of $I_{\text{dark}}$. The second step is correlated with the altered dominating source of $I_{\text{dark}}$ at higher electric fields, which is a combined contribution from both the SRH current and the avalanche multiplication of dark carriers, even though their relative proportion remain unclear. $E_a$ of 0.16 eV at $T > 250$ K and of 0.21 eV at $T > 175$ K for the QD and the reference APDs, respectively, however, indicate a similar $I_{\text{dark}}$ generation process of trap-assisted tunneling via some inherent deep-level traps in GaAs with $E_a$ around 0.2 eV.[31] Below 175 K, both devices are operated in a background limited regime[32] in which the dark currents are limited by background radiation and show a saturation trend.

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**Figure 4.** $I_{\text{dark}}$ generation behaviors of the devices. a,b) The temperature-dependent $I_{\text{dark}}$ versus reverse bias curves of the reference and the QD APDs, respectively. The $I_{\text{ph}}$ curves at 77 K are also shown, respectively, (Ip77k). c) Arrhenius plot of $I_{\text{dark}}$ of the APDs at a reverse bias of $-10$ V. Fitted $E_a$ at $T > 250$ K, $175 < T < 250$ K, and $T > 175$ K are indicated, respectively. d) Measured $V_B$ as a function of temperature. Solid lines are linear fittings.
Temperature coefficients of \( V_B \) for both the QD and the reference APDs were also studied as shown in Figure 4d. \( V_B \) was defined to be the voltage at which the dark current density reaches to 1 A cm\(^{-2} \). Both APDs exhibit positive temperature coefficients, a typical avalanche breakdown behavior.\(^{[33]} \) A constant increment of \( V_B \) of 0.4 V over the whole measured temperature range was observed for the QD APD, again demonstrating the delayed breakdown effect in QD multiplier. Temperature coefficients of 9.3 and 9.5 mV K\(^{-1} \) were extracted for the QD and the reference APDs, respectively, by fitting the data using \( V_B = (\Delta V_B/\Delta T) \times T + V_{0B} \), as shown in Figure 4d. These values are comparable to that of In\(_{0.53}\)Ga\(_{0.47}\)As/In\(_{0.52}\)Al\(_{0.48}\)As SACM APDs with the same multiplication layer thickness of 300 nm,\(^{[14]} \) indicating good temperature stability of these SACM GaAs APDs. The negligible difference of \( \Delta V_B/\Delta T \) between the two APDs, meanwhile, suggests integration of QDs in multiplication regions does not degrade the temperature stability of bulk APDs.

2.5. Spectral Responsivity Gain

Spectral responsivity gains of the APDs were also measured using a FTIR method. Figure 5a,b presents the bias-dependent spectral responsivities of the QD and reference APDs at room temperature, respectively, which have been corrected using a calibrated \( \eta \) spectrum of a GaAs PIN diode. Spectral noise becomes apparent at low wavelengths due to the fact that intensity of the visible light source in FTIR is weak at wavelengths below 800 nm. Moreover, this noise is also multiplied with the increase of the responsivity gain for both devices. Mono-tonic increases of spectral responsivity for both APDs with increasing reverse bias are clearly observed after the unity gain (\(-6.5 \text{ V}\)). Measurements were stopped at reverse biases 0.2 V (\(-300 \text{ K}\)) data of a GaAs PIN photodiode with an i region width of 280 nm (adopted from ref. \[35\]) and a Si SACM APD (adopted from ref. \[36\]) is also shown for comparison. The bias-dependent spectral responsivities of the QD and reference APDs at room temperature, respectively, which have been corrected using a FTIR method. Figure 5a,b presents the bias-dependent spectral responsivities of the QD and reference APDs at room temperature, respectively. Figure 5a,b presents the bias-dependent spectral responsivities of the QD and reference APDs at room temperature, respectively. Figure 5a,b presents the bias-dependent spectral responsivities of the QD and reference APDs at room temperature, respectively.

2.6. Excess Noise Performances

We have also investigated the excess noise factors (\( F(M) \)) for these two electron-injected APDs by using a SRS-SR780 network signal analyzer and the 633 nm He-Ne fiber laser as shown in Figure 6. Also shown are the excess noise characteristics for an electron-injected GaAs PIN photodiode with an i region width of 280 nm,\(^{[16]} \) together with the \( F(M) \) results from a commercial electron-injected Si SACM APD.\(^{[16]} \) From this figure, it appears that in comparison to the GaAs PIN introducing a SACM device architecture (i.e., the reference GaAs APD) allows us to reduce the detector’s \( F(M) \) to almost half. Besides, a reduction of the effective impact ionization ratio, \( k_{\text{eff}} \) (defined by the ratio between the hole (\( \beta \)) and the electron (\( \alpha \)) ionization coefficients (\( k_{\text{eff}} = \beta / \alpha \)), from 0.4 for the PIN to \( \approx 0.2 \) for the reference SACM APD was also achieved. Integration of InAs QDs in the GaAs SACM APD leads to a significant improvement of the \( F(M) \) from \( \approx 3.5 \) to \( \approx 2.0 \) at \( M = 10 \) for the reference and the QD APDs, respectively. The effective \( k_{\text{eff}} \) was further reduced to be less than 0.1 accordingly, which is quite close to that of silicon, a superior multiplication material with extremely low excess noises.\(^{[16]} \) Reduced impact ionization ratios in Al\(_{0.4}\)Ga\(_{0.55}\)As/ GaAs\(^{[17]} \) and InGaAsP/In\(_{0.52}\)Al\(_{0.48}\)As\(^{[18]} \) superlattices (SLs) with respect to their bulk counterparts have also been reported in PIN or SACM APDs, and have been attributed to the large difference in the band edge discontinuities for electrons and holes at the heterojunction interfaces. In our work, pure electron injection was implemented via front-side illumination. Furthermore, kinetic electrons suffered stronger confinement in 3D in QDs as compared with the 1D confinement in SL APDs. Therefore, we attribute the achieved superior excess noise performance of our QD...
APDs to the more deterministic multiplication factors resulting from localized electron impact ionization events in QDs. These results further suggest that integration of QDs in multiplication structures are a highly promising route toward realization of extremely low excess noise APDs.

2.7. Comparison with the State of the Art

In Table 1, we have summarized the APD architectures as well as the measured primary performance parameters between this work and other state-of-the-art APDs incorporated with QDs or enhanced multiplier structures (staircase, SLs, and IIE). NC: not given, \( M_{\text{max}} \): maximum \( M \), \( R_{\text{max}} \): \( R \) at maximum \( M \).

<table>
<thead>
<tr>
<th>APD type</th>
<th>Architecture</th>
<th>Absorber</th>
<th>Multiplier</th>
<th>( 300 \text{ K} M_{\text{max}} )</th>
<th>( k_{\text{eff}} )</th>
<th>( 300 \text{ K} R_{\text{max}} )</th>
<th>Operating ( \lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td>This work</td>
<td>SAM</td>
<td>GaAs bulk</td>
<td>InAs/GaAs QD</td>
<td>430</td>
<td>&lt;0.1</td>
<td>85 (5)</td>
<td>400–950</td>
</tr>
<tr>
<td>QD[39]</td>
<td>PIN</td>
<td>InAs/InP QD</td>
<td></td>
<td>3.5</td>
<td>NG</td>
<td>4 (6)</td>
<td>1350–1600</td>
</tr>
<tr>
<td>QD[40]</td>
<td>SAM</td>
<td>InAs/GaAs QD</td>
<td>GaAs/AlGaAs SL</td>
<td>9</td>
<td>NG</td>
<td>0.05 (5)</td>
<td>1050–1350</td>
</tr>
<tr>
<td>Staircase[24]</td>
<td>PIN</td>
<td>Al(<em>{0.7})In(</em>{0.3})As(<em>{0.31})Sb(</em>{0.69})</td>
<td></td>
<td>4</td>
<td>NG</td>
<td>1 (6)</td>
<td>400–1100</td>
</tr>
<tr>
<td>SLs[38]</td>
<td>SAM</td>
<td>InGaAs</td>
<td>InGaAsP/InAlAs SL</td>
<td>50</td>
<td>NG</td>
<td>NG</td>
<td>900–1700</td>
</tr>
<tr>
<td>IIE[41]</td>
<td>PIN</td>
<td>Step-graded</td>
<td>( \text{In}<em>{0.51}\text{Al}</em>{0.49}\text{As} )</td>
<td>80</td>
<td>0.15</td>
<td>NG</td>
<td>200–800</td>
</tr>
</tbody>
</table>

\(^{a}\)Measured at a \( \lambda \) of 633 nm; \(^{b}\)Measured at a \( \lambda \) of 1550 nm; \(^{c}\)Measured at a \( \lambda \) of 1280 nm; \(^{d}\)Measured at a \( \lambda \) of 700 nm.

In Table 1, we have summarized the APD architectures as well as the measured primary performance parameters between this work and other state-of-the-art APDs incorporated with QDs or enhanced multiplier structures (staircase, SLs, and IIE) and impact ionization engineering (IIE). The multilayer stacked InAs QDs in the PIN or SAM APDs in refs. [39] and [40] acted virtually as light absorbers rather than carrier multipliers, and consequently no multiplication enhancement was identified. The reported maximum \( M \) were less than 10 and responsibilities were no higher than 5 A W\(^{-1}\), while information on the \( k_{\text{eff}} \) were not included. The one-stage Al\(_{0.7}\)In\(_{0.3}\)As\(_{0.31}\)Sb\(_{0.69}\) PIN staircase[24] APD revealed an \( M \) of 4 at 300 K and a corresponding responsivity of 1 A W\(^{-1}\), which is promising as an early stage demonstration. The InGaAsP/InAlAs SL multiplication structure in an InGaAs SAM APD[38] had shown a slightly enhanced maximum \( M \) of 50 compared to the InAlAs bulk multiplier, which has been presumed related to the conduction band discontinuity at the SL interfaces. Excess noise performances were not provided for either the staircase or the SL APDs. The IIE APDs[41] demonstrated by utilizing a PIN homojunction with a step-graded \( \text{In}_{0.52}\text{Al}_{0.48}\text{As} \) i region exhibited a maximum \( M \) up to 80 at 300 K and a very low excess noise (\( k_{\text{eff}} \approx 0.15 \)). By comparison, our QD multiplied SAM APD attains the highest maximum \( M \) and the most superior excess noise performances among these devices, which highlights the advantages of the 0D quantum structure multiplier in the development of ultraefficient APDs.

3. Conclusions

In summary, we have designed and fabricated a GaAs SACM APD with an enhanced electron multiplication structure consisting of five-layer stacked 2.25 MLs InAs QD/50 nm GaAs spacer. High-resolution TEM, EDS, XRD, and PL measurements were used to characterize the structural and optical properties of the QD multiplication region in the APD. Temperature-dependent transport measurements were used to characterize the avalanche behaviors and demonstrated up to six times higher multiplication factors in comparison to a reference device without QD over a temperature range of 77–300 K. A dominant source of \( I_{\text{dark}} \) associated with the SRH process in QDs at 175 < \( T < 250 \) K is also identified. Excess noise measurements show extremely low excess noise factor of this electron-injected QD APD with an effective \( k_{\text{eff}} \) value lower than 0.1, which is comparable to the performance of commercial Si APDs. This demonstration opens opportunities for exploring the performance enhancement of SACM APDs in other material systems using QDs. In addition, the QD APD structure will also enable further access to new and interesting physics associated with quantitative impact ionization rates in confined 0D semiconducting systems, as carrier–phonon interactions change due to confinement.

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