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ABSTRACT
By utilizing the low-noise benefits of staircase avalanche photodiodes (APDs) and the high-field tolerance of conventional APDs, a “cascaded multiplier” device has been grown and characterized showing significantly reduced excess noise compared to staircase devices of similar gain. Slight adjustments to the device design could increase the gain to even higher values—further improving the signal-to-noise ratio in the detector.

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Near- to mid-infrared applications, such as LIDAR, telecommunications, and imaging, often rely on avalanche photodiodes (APDs) for high sensitivity optical detection. APD sensitivity generally trends with the signal-to-noise ratio (SNR), which, owing to internal gain from impact ionization signal multiplication, has been shown to be larger than traditional photodiode detectors. Unfortunately, impact ionization is a stochastic process leading to gain variation that manifests as a contribution to detector shot noise and limits APD speed and sensitivity. This gain variation is usually parameterized using the excess noise factor, \( F(M) \), of the amplification material and is related to the impact ionization ratio between electrons and holes, \( k \), by

\[
F(M) = kM + (1 - k)(2 - 1/M),
\]

where \( M \) is the internal multiplication gain of the detector. The excess noise factor increases with increasing \( M \) but increases more slowly for lower values of \( k \), leading to both improved speed and sensitivity if an APD is to operate with a substantial gain. Bulk materials, such as \( \text{Hg}_{1-x}\text{Cd}_x\text{Te} \), \( \text{Si} \), and \( \text{InAs} \), work well as extremely low-noise amplifiers due primarily to their \( k \sim 0 \) characteristic. Aside from bulk materials, some APDs use impact ionization engineering to achieve low noise multiplication, where band-engineered heterojunctions incentivize single-carrier impact ionization.

\( \text{Al}_{1-x}\text{In}_{x}\text{As}_{y}\text{Sb}_{1-y} \) (henceforth referred to as AlInAsSb) grown as a digital alloy lattice-matched to GaSb substrates has recently shown great promise for APDs in the near- to mid-IR owing to its flexible bandgap engineering, small valence band offsets, and very low impact ionization ratio, \( k \lesssim 1 \). For example, AlInAsSb was used to demonstrate wavelength-flexible separate absorption, charge, and multiplication (SACM) APDs with \( k \sim 0.01 \) performance and gain \( >50 \) and \( >100 \) at room temperature under 1.55- and 2-\( \mu \)m illumination, respectively. In addition, AlInAsSb was used to demonstrate Capasso’s staircase APD, which utilizes complex alloy “step” gradings to promote deterministic, localized electron-initiated impact ionization with \( \sim 2^N \) gain scaling, where \( N \) is the number of staircase steps. The three-step staircase APD features a modest gain of \( \sim 8 \) and shows extremely low-noise amplification well below that of an ideal McIntyre-limited \( k = 0 \) material.

Unlike a conventional APD that exhibits exponential gain with increased electric field, staircase APD gain is limited by the number of steps. Further biasing of staircase devices leads to increased dark current density due to band-to-band tunneling in the narrow bandgap staircase layers. This effect is detrimental to staircase APD operation and limits the external bias that can be applied. By leveraging the exponential nature of high-field impact ionization found in conventional
APDs, this study attempts to improve detector sensitivity by increasing the maximum gain of a staircase device. Furthermore, a high-field staircase device should decrease carrier transit times which would increase bandwidth compared to a pure (low-field) staircase APD of equal gain. The SNR of a high-field staircase device would benefit significantly by using a low-noise staircase step before a conventional, high-field, avalanche bulk multiplier. Friis cascaded amplifier noise theory highlights the importance of the early noise contributions in a multi-stage amplifier represented by

$$F_{\text{total}} = \frac{F_1 - 1}{M_1} + \cdots + \frac{F_N - 1}{M_1M_2\ldots M_{N-1}},$$

(2)

where $F_N$ and $M_N$ are the excess noise factor and gain for the $N$th stage of a cascaded amplifier with a net excess noise factor $F_{\text{total}}$. The noise contribution from the last stage, for example, is divided by the gain products in the earlier stages, in effect reducing the relative contribution of the latter stages to the overall amplifier noise. It stands to reason that the low-noise multiplication afforded by a staircase multiplier as the first stage of a cascaded amplifier would improve the total noise output for a device as compared to a non-cascaded conventional avalanche multiplier.

The design for such a cascaded amplifier device needs to achieve two distinct electric field regions in order to operate. SACM APDs accomplish this by utilizing a charge layer—a doped region used to contain the noise contribution from the last stage, for example, is divided by the gain products in the earlier stages, in effect reducing the relative contribution of the latter stages to the overall amplifier noise. It stands to reason that the low-noise multiplication afforded by a staircase multiplier as the first stage of a cascaded amplifier would improve the total noise output for a device as compared to a non-cascaded conventional avalanche multiplier.

Here, we report the cascaded multiplier APD, which employs a low-field staircase step followed by a conventional, high-field, avalanche bulk multiplier, separated by a charge layer. A multiplication gain of ~6 is reached at room temperature, determined in comparison with a step-free control device. The excess noise factor as a function of gain for the cascaded multiplier lies between that of a conventional bulk AlInAsSb (k = 0.01) APD and a pure AlInAsSb staircase device, suggesting that the noise benefits of a low-field staircase APD are realized in combination with a high-field avalanche multiplier, as described in Eq. (2).

AlInAsSb cascaded multiplier APDs were grown on n-type Te doped GaSb (001) substrates via molecular beam epitaxy (MBE) using the approach described in detail by Maddox et al. The AlInAsSb digital alloys were grown as repeating periods of stable binary materials adding up to 10 monolayers (AlSb, InAs, etc.) at a growth rate of 0.75 monolayers per second. The substrate was held at a growth temperature of ~460–480 °C measured in situ by blackbody thermometry (k-Space BandIT). The substrate was also rotated at relatively high speeds of 22.5 rotations per minute to ensure layer uniformity. V/III beam equivalent pressure ratios of 7 for antimony and 6.2 for dimeric arsenic (over indium) were used, which corresponded to flux ratios of 4.2 and 1.9, respectively. Growth rates and lattice matching calibrations were grown and characterized in advance to ensure intended thicknesses and compositions. Structural quality of the crystal was confirmed with ω–20 rocking curve scans using x-ray diffraction, and surface quality was confirmed using dark field microscopy (see the supplementary material). A cross-sectional schematic of the device layer structure can be seen in Fig. 1(a). The staircase region followed by the charge layer and avalanche multiplier region is shown in the energy-band vs position diagram shown in Fig. 1(b). Figure 1(c) shows the effect of the moderately doped p-type charge layer, which suppresses the electric field before and after the staircase step gradings. Devices were fabricated using standard photolithography techniques, citric acid wet etching circular mesas to 150-µm diameters, Ti/Au contact deposition, and SU-8 surface passivation.

The device structure consists of a $10^{18}$ cm$^{-3}$ p-type GaSb/AlInAsSb top contact, a 500 nm undoped (UID) AlInAsSb absorber (thick enough to absorb 99% of 543 nm light), a 128 nm UID staircase step grading, a 200 nm AlInAsSb ~1017 cm$^{-3}$ p-type charge layer, a 500 nm UID AlInAsSb bulk multiplier region, and a 200 nm $10^{16}$ cm$^{-3}$ n-type AlInAsSb bottom contact layer. All AlInAsSb layers contain 70% Al and ~33% As except for the staircase step region (featuring compositional grading between 70% Al and 7% Al). The approximate bandgap energy of Al$_{0.7}$InAsSb is 1.2 eV, and Al$_{0.07}$InAsSb is 0.3 eV. A step-free control sample was grown that

![FIG. 1.](image-url)
suppresses staircase amplification by removing the compositional gradings present in the cascaded multiplier device, maintaining 70% Al composition for all layers. They contain identical layer thicknesses and doping values, so that the only variable is the compositional grading present in the cascaded multiplier device. The band and field diagrams of the control are shown as the dashed lines in Figs. 1(b) and 1(c). The charge layer doping was chosen to maintain a sufficiently low electric field to mitigate band-to-band tunneling in the staircase region while promoting high-field impact ionization in the bulk multiplier over a relatively wide bias range.

Device performance was characterized using room temperature current–voltage measurements performed under dark and 543-nm illumination conditions for both the cascaded multiplier and its step-free control, shown in Fig. 2(a). The punch-through depletion bias of the control device occurs at approximately $-25 \text{ V}$, corroborated by capacitance–voltage measurements (shown in Fig. 3). The cascaded multiplier shows limited photocurrent for low reverse biases under $-25 \text{ V}$ due to charge trapping in the staircase step region. At slightly higher reverse bias these trapped charges release, and multiplication gain is observed. The cascaded multiplier dark current trend is consistent with previously demonstrated staircase devices and is attributed to the increase in band-to-band tunneling that occurs in the narrow bandgap staircase region. However, a dark current density of $\sim 70 \text{ mA/cm}^2$ at the operation bias of $-31.8 \text{ V}$ is significantly reduced from two- and three-step staircase devices, which feature room temperature dark current densities of $\sim 170$ and $\sim 400 \text{ mA/cm}^2$, respectively. This is attributed to the reduction in a narrow bandgap material present in step regions. The one-step staircase device with a gain of 2 exhibits a dark current density of $\sim 21 \text{ mA/cm}^2$. Given the similarities in the dark current trend to the pure staircase devices, this breakdown behavior suggests that the operation of the cascade device is limited by tunneling in the staircase region around $-32 \text{ V}$.

Figure 2(b) shows the multiplication gain of the two devices. The cascaded multiplier reached a gain of $\sim 6$ prior to breakdown beyond $-32 \text{ V}$, where the dark current contribution dominates the measured photocurrent. This is compared to a gain of $\sim 3$ by the control. The inset is a plot of the photocurrent ratio between the cascaded multiplier and the control, indicating the staircase gain contribution is the expected $\sim 2^N$ ($N = 1$), consistent with previously demonstrated staircase devices. It is worth noting the non-trivial nature of determining gain and noise in these devices; impact ionization occurs in the conventional multiplier at low bias prior to reaching punch-through. Thus, the unity photocurrent cannot be measured directly. To determine the unity photocurrent, the gain at punch-through was calculated in the control based on the well-known impact ionization coefficients of the material and the electric field at that bias. The electric field at punch-through was determined with electro-static
simulations supported by capacitance–voltage (CV) measurements, where the simulated (Lumerical CHARGE) CV profile is nearly identical to the device measurement. Using the impact ionization coefficients and the electric field calculations, the gain in the control device at punch-through was determined to be ~1.4 at −25 V. The unity photocurrent is then the punch-through photocurrent divided by the punch-through gain, ~1.1 μA. Calculating the gain in the cascaded multiplier device was the trivial next step of dividing the cascaded multiplier photocurrent by this unity photocurrent.

To obtain the excess noise factor, \( F(M) \), the shot noise power had to be scaled from the control. The shot noise power, \( S \), of the cascade and control (in the absence of dark current) are as follows:

\[
S_{\text{cascade}} = 2qI_{\text{photo}}R\Delta fM_{\text{cascade}}^2 F(M)_{\text{cascade}},
\]

\[
S_{\text{control}} = 2qI_{\text{photo}}R\Delta fM_{\text{control}}^2 F(M)_{\text{control}},
\]

where \( q \) is the electron charge, \( R \) is the resistance, and \( \Delta f \) is the measurement bandwidth. The gain values, \( M \), are known. The term \( 2qI_{\text{photo}}R\Delta f \) can be found by using the control structure, which has a known k-factor within a small range [and therefore \( F(M)_{\text{control}} \)]. Rearranging Eq. (3) gives us the following equation:

\[
F(M)_{\text{cascade}} = \frac{S_{\text{cascade}}}{2qI_{\text{photo}}R\Delta fM_{\text{cascade}}^2}.
\]

Using Eq. (5), the excess noise factor \( F(M) \) as a function of gain is shown in Fig. 5(a). The cascaded multiplier device shows noise values below the conventional AlInAsSb APD, which follows the expected \( k \sim 0.01 \) trend with multiplication gain. It does, however, lay above the pure staircase APD.\(^{16,17}\) Figure 4 also indicates that the intermediate cascaded multiplier noise is further supported by Monte Carlo simulations, which predict a slightly lower multiplication gain but a very similar excess noise factor. For this, 10,000 simulation iterations were run for the cascaded multiplier at a bias value of ~32 V. The simulation iterations represented individual electron–hole pairs generated according to the absorption properties of the material. Secondary carriers from impact ionization were also generated and tracked until...
recombination or reaching the n-contact. Carrier transport and scattering rates were based on first-principal calculations using Fermi’s Golden rule (accounting for intervalley, intravalley phonon, alloy, and impurity scattering), and impact ionization threshold energies were taken from previously reported work on AlInAsSb digital alloy P–I–N devices. These values are consistent with Friis noise theory described in Eq. (2), where placing a low-noise multiplier at the early stage of a cascaded amplifier reduces the total amplification noise.

Further work should be done to increase the gain in the bulk multiplier region to higher values. This could be attempted by increasing the charge layer doping, allowing for higher bias measurements (i.e., higher field in the bulk multiplier) without suffering from staircase region breakdown. Achieving higher gain values could improve the signal-to-noise ratio in the device by leveraging the $F(M) < 2$ noise scaling afforded by the cascaded multiplier architecture. In addition, the flexible bandgap energies of AlInAsSb offer an easy path to extending the absorption wavelength of these devices to 2 $\mu$m and beyond by reducing the aluminum composition in the absorber.

The presented cascaded multiplier APD with a gain of $\sim 6$ offers an effective way to reach improved gain above the $2^{\text{nd}}$ limitation exhibited by pure staircase APDs at reduced dark current densities. Additionally, the presence of an early-stage staircase multiplier region prior to a conventional high-field bulk multiplier reduces the overall amplifier noise while supporting an increased applied electric field. As the first solid-state device of its class, the staircase cascaded multiplier APD has the potential to dramatically improve APD sensitivity moving forward.

See the supplementary material for details of post-growth character-ization of the epitaxial material (including high resolution x-ray diffraction and dark field microscope images), capacitance–voltage measurements of the cascaded multiplier device, and spectral response of the cascaded multiplier device.

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**AUTHOR DECLARATIONS**

**Conflict of Interest**

The authors have no conflicts to disclose.

**Author Contributions**

J. Andrew McArthur: Conceptualization (equal); Data curation (equal); Formal analysis (lead); Investigation (lead); Methodology (equal); Validation (lead); Visualization (lead); Writing – original draft (lead); Writing – review & editing (equal). Adam A. Dadey: Data curation (equal); Formal analysis (equal); Investigation (supporting); Methodology (equal); Validation (supporting); Writing – review & editing (equal). Stephen D. March: Conceptualization (supporting); Formal analysis (supporting); Investigation (supporting); Methodology (supporting); Writing – review & editing (equal). Andrew H. Jones: Data curation (supporting); Formal analysis (supporting); Methodology (supporting). Xingjun Xue: Investigation (supporting); Methodology (supporting). Rodolfo Salas: Conceptualization (supporting); Formal analysis (supporting); Funding acquisition (lead); Project administration (lead); Supervision (supporting); Writing – review & editing (equal). Joe C. Campbell: Conceptualization (supporting); Data curation (supporting); Funding acquisition (lead); Project administration (supporting). Seth R. Bank: Conceptualization (equal); Funding acquisition (lead); Resources (supporting); Supervision (supporting); Visualization (supporting); Writing – original draft (supporting); Writing – review & editing (equal).

**DATA AVAILABILITY**

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

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