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Major Goals: The major goal of this effort was to significantly increase the multiplication levels and extended spectral response from InAs-based avalanche photodiodes (APD), as well as a superior understanding of the fundamental material properties that give rise to low-noise multiplication. The major goal of the Add-On to the program was to unambiguously demonstrate the staircase APD operation using the AlInAsSb alloy system. Please see the attached PDF for more details.

Accomplishments: Our progress is summarized as follows (please see attached PDF file for more details):

1. We significantly improved the performance of InAs APDs, which offer nearly ideal noise characteristics, leading to devices that exhibit record performance in both multiplication gain and dark current density. We believe that we have also identified the key contributor to our current performance limitations: silicon diffusion into the i-region from the underlying n-type layer. This work suggests that with increased i-region thickness, gains >1000 could be achieved at room temperature.
2. To extend the cutoff wavelength of InAs APDs, we have developed the growth of InAsBi. Specifically, we have found that growing at reduced substrate temperature can significantly enhance the optical properties at elevated bismuth concentrations.
3. We developed the digital alloy growth and used optical methods to determine the compositional dependence of AlInAsSb properties (bandgap, band offsets, direct-to-indirect bandgap crossover, etc.) that were required to design and grow the staircase APD.
4. We designed, grew, fabricated and tested several generations of staircase APDs. We identified the source of the bias-dependent responsivity in our first generation of devices was an unexpected electron-barrier between the p-GaSb absorber and the AlInAsSb staircase.
5. Eliminating the electron barrier, we unambiguously observed single-step staircase APD operation, having identified and eliminated the source of the bias-dependent responsivity. The observed noise and multiplication behavior are consistent with theory.
6. A fortuitous discovery was a novel multiplication device that uses two staircase steps, which we have termed the photoconductive detector. By biasing this device just below the staircase condition, electrons are collected at the top step, which induces a higher electric field in the bottom step and triggers band-to-band tunneling that

amplifies the signal. Initial noise measurements indicate that the noise is quite low in these devices.
7. A second exciting discovery was that AlInAsSb p-i-n APDs also exhibit low noise. This is the first III-V alloy family that exhibits low excess noise! We also employed different compositions of AlInAsSb to demonstrate p-I-N separate absorption, charge, and multiplication (SACM) APDs to demonstrate low-noise APDs operating at telecom wavelengths. In short, these devices offer noise comparable to silicon, but with operation at telecom wavelength; additionally, because the absorber is direct bandgap, the modulation bandwidth should greatly outstrip that of silicon APDs (by ~10-20x) as the absorber layer can be made significantly thinner.

Training Opportunities: This program supported the research of four Ph.D. students and two post-docs.

Results Dissemination: Research results were disseminated though several peer-reviewed publications and conference presentations.

Honors and Awards: One Ph.D. student, Scott Maddox, received the Electronic Materials Conference (EMC) Student Paper Award in 2014.

Protocol Activity Status:

Technology Transfer: This program has not yet directly led to tech transfer, but has enabled much of our research progress that has led to significant tech transfer opportunities. For example, our avalanche photodiode work has generated significant interest at Night Vision Labs (which we have visited), AFRL, and Lockheed Martin. We have filed multiple patents in this area and are in discussion to license the patents.

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Participant Type: PD/PI
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Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
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Abstract: We reduced the room temperature dark current in an InAs avalanche photodiode by increasing the p-type contact doping, resulting in an increased energetic barrier to minority electron injection into the p-region, which is a significant source of dark current at room temperature. In addition, by improving the molecular beam epitaxy growth conditions, we reduced the background doping concentration and realized depletion widths as wide as 5 um at reverse biases as low as 1.5 V. These improvements culminated in low-noise InAs avalanche photodiodes exhibiting a room temperature multiplication gain of ┐80, at a record low reverse bias of 12 V.
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1. Abstract

Low-noise, high gain-bandwidth, avalanche photodiodes (APDs) are essential, especially in the mid-infrared (~3-5 μm), for a variety of Army-critical applications in target imaging/identification (e.g. 3-D LIDAR), free-space communications, and chemical sensing. III-V materials offer many advantages over the dominant HgCdTe alloys; however, III-Vs could not historically produce low-noise APDs because the electron and hole impact ionization coefficients are typically comparable.

Our progress this FY is summarized as follows:

1. We have continued to develop the AlInAsSb material growth and have begun to explore the growth parameter space more thoroughly.[1]
2. Building on our results from the previous FY, we have unambiguously observed single-step staircase APD operation,[2] having identified and eliminated the source of the bias-dependent responsivity.[i] Observed noise and multiplication behavior are consistent with theory.
3. A fortuitous discovery this year was a novel multiplication device that uses two staircase steps, which we have termed the photoconductive detector.[3] By biasing this device just below the staircase condition, electrons are collected at the top step, which induces a higher electric field in the bottom step and triggers band-to-band tunneling that amplifies the signal. Initial noise measurements indicate that the noise is quite low in these devices.
4. A second exciting discovery was that AlInAsSb p-i-n APDs also exhibit low noise.[4] This is the first III-V alloy family that exhibits low excess noise! We also employed different compositions of AlInAsSb to demonstrate p-I-N separate absorption, charge, and multiplication (SACM) APDs to demonstrate low-noise APDs operating at telecom wavelengths.[5] In short, these devices offer noise comparable to silicon, but with operation at telecom wavelength; additionally, because the absorber is direct bandgap, the modulation bandwidth should greatly outstrip that of silicon APDs (by ~10-20x) as the absorber layer can be made significantly thinner.

Here, we focus our report on points #2 and #3, since they are most closely related to the core of the program. Consistent with this focus, our immediate near-term plan is to investigate cascading multiple staircase steps together to achieve greater multiplication values, as well as to vary the conduction band offset across the step to investigate the kinetic energy dependence of impact ionization.

2. Experimental Advances

2.1 Staircase APDs

A key approach to achieving low noise III-V APDs has been incorporating new materials and impact ionization engineering with appropriately designed heterostructure.[6] One particularly compelling structure, the staircase APD, was proposed by Capasso and co-workers[7] to achieve very low noise.[8] Conceptual band diagrams of a staircase APD at flatband and under reverse bias are illustrated in Figure 1. Unlike conventional APDs, in which impact ionization occurs relatively uniformly throughout the entire multiplication region, in the staircase structure avalanche events occur proximate to sharp bandgap discontinuities, which function similarly to dynodes in a photomultiplier tube. Unfortunately, initial studies of staircase APDs focused on the $Al_xGa_{1-x}As$ material system, which has inadequate band offsets to achieve the projected avalanche gain characteristics.[9,10]

[i] The source of the bias-dependent responsivity was an unexpected electron-barrier between the p-GaSb absorber and the AlInAsSb staircase, which we eliminated by using an AlInAsSb absorber for the second generation proof-of-concept device.

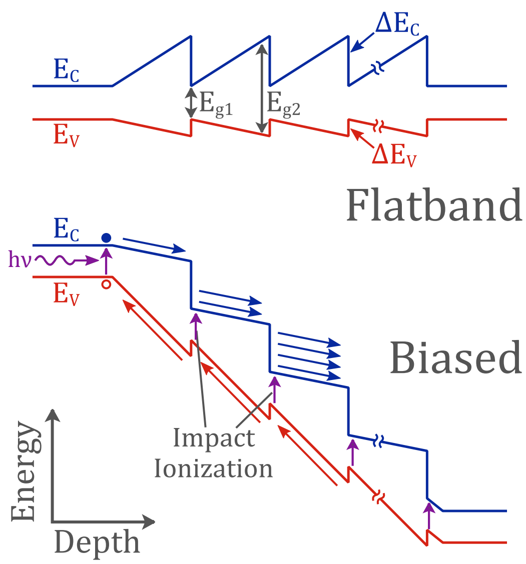


Figure 1. Conceptual band diagrams of a staircase APD unbiased (top) and under reverse bias (bottom). The arrows below the valance band indicate that holes do not impact ionize.

We have demonstrated – for the first time – a staircase APD based on the emerging $Al_xIn_{1-x}As_ySb_{1-y}$ material system (subsequently referred to as AlInAsSb), which was grown by molecular beam epitaxy (MBE) using a digital alloying technique.[1,11] The wide bandgap injector is $Al_{0.7}In_{0.3}As_{0.31}Sb_{0.69}$ and the narrow bandgap multiplication region is $InAs_{0.91}Sb_{0.09}$ (InAsSb in the following). For that program those regions had bandgaps of ~1.16 eV and ~0.25 eV, respectively, as determined by photoluminescence measurements.[1] Since the conduction band discontinuity (~0.6 eV) provides over twice the energy of the narrow bandgap InAsSb layer (~0.25 eV),[1] and the threshold for impact ionization in small-bandgap III-V's is approximately 1.5x the bandgap,[12] this is sufficient to provide a high probability of impact ionization at the bandgap discontinuity. The AlInAsSb material system provides the additional benefit of a low ratio of hole to electron ionization coefficients, or *k*-value, further suppressing excess noise.[4,13,14] To demonstrate the AlInAsSb staircase gain mechanism, 1-step staircase APD and control structures were grown on n^+ GaSb substrates; the structure cross-sections are shown in Figure 2.

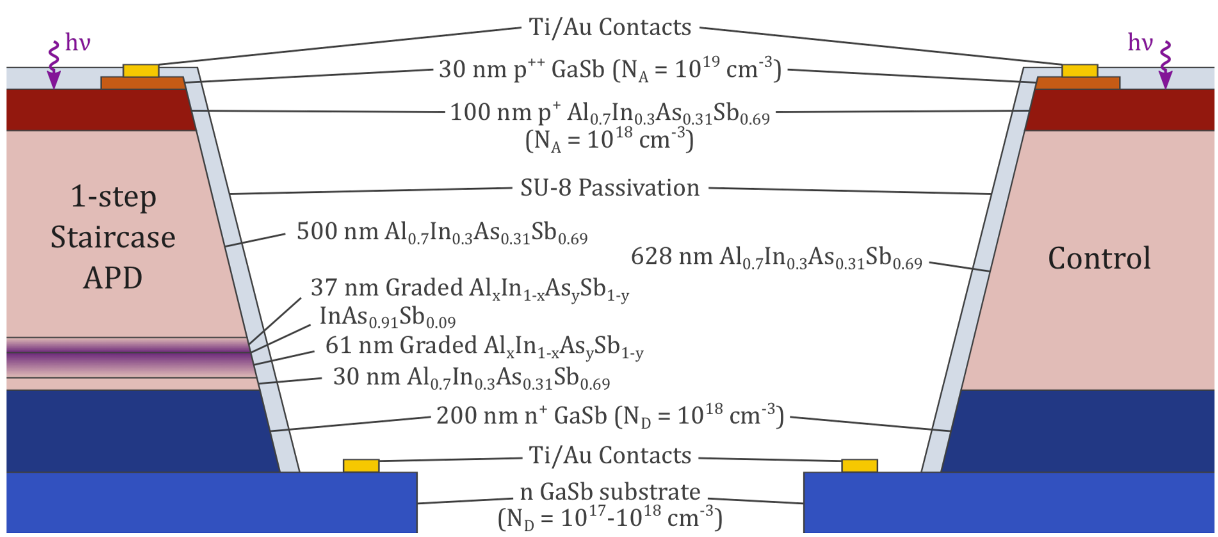


Figure 2. Schematic cross-sections of the 1-step AlInAsSb staircase APD (left) and control (right) structures that were investigated.

Figure 3 shows the band diagrams of the 1-step AlInAsSb staircase APD, as well as the step-free control that was used to determine the unity gain point. The staircase "step" was formed by digitally grading from $Al_{0.7}In_{0.3}As_{0.31}Sb_{0.69}$ to $InAs_{0.91}Sb_{0.09}$, then back to $Al_{0.7}In_{0.3}As_{0.31}Sb_{0.69}$. The grading rates on either side of the InAsSb were chosen such that, at sufficiently high bias, the band edges in the graded layers "flatten" to form the staircase-condition band structure shown in Figure 3. Note that the graded layers serve to reduce charge trapping and accumulation within the small-bandgap region.

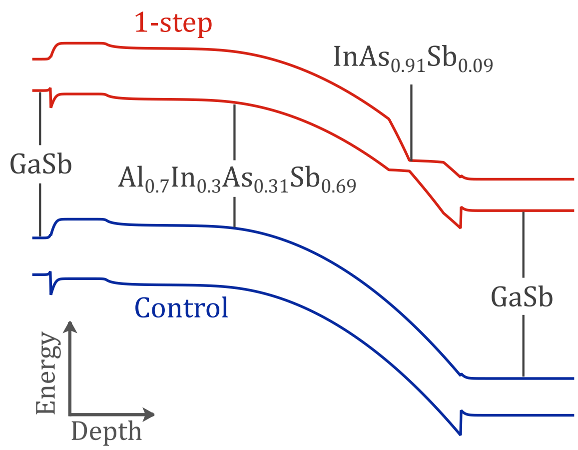


Figure 3. Band diagrams of the 1-step (top) and control (bottom) structures at the staircase condition.

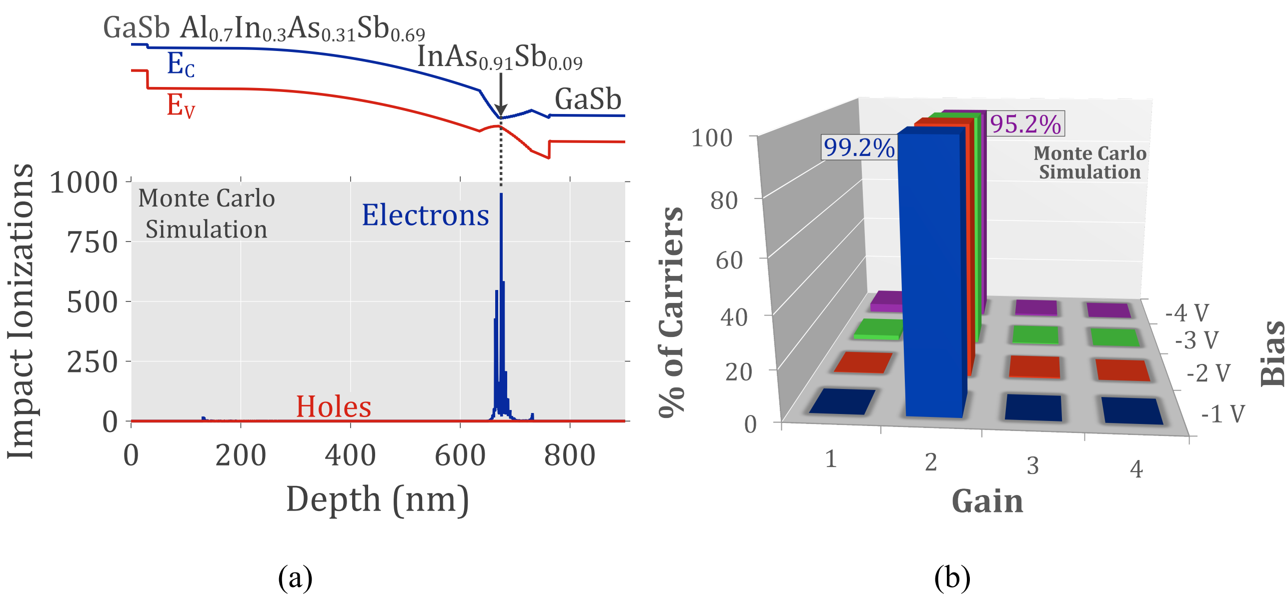
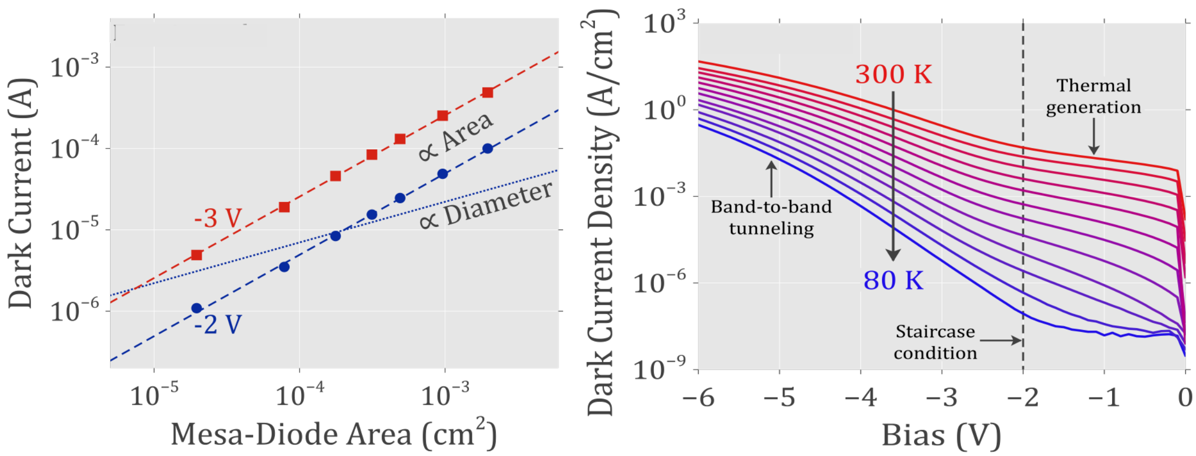


Figure 4. Monte Carlo simulations of a 1-step AlInAsSb staircase APD at -2 V bias (a) predict electron-only impact ionization, resulting in nearly ideal noise characteristics. Furthermore, the simulations predict an extremely sharp gain distribution independent of bias (b) with almost all electrons impact ionizing exactly once, resulting in a nearly excess-noise-free gain of ~2×.

In order to develop a deeper understanding of the electron and hole transport and impact ionization dynamics in these structures, we performed detailed Monte Carlo simulations using the tool reported in Ref. 15. The results are summarized in Figure 4. Notably, these simulations predicted electron-only impact ionization, as shown in Figure 4a, with a spatial distribution highly localized at the small-bandgap staircase step. The electron ionization probability is predicted to be ~ 95% at the step. This level of determinism results in an excess noise factor very close to unity.[7,8] The predicted variance, $\langle M^2 \rangle - \langle M \rangle^2$, of the multiplication gain, M, was less than 0.05 for reverse biases less than 4 V. Essentially, the Monte Carlo simulations predict that the AlInAsSb staircase gain would be almost completely free of excess noise, making it possible to achieve much greater performance and bandwidth than traditional APDs.

Initial experiments focused on devices with $Al_{0.7}In_{0.3}As_{0.31}Sb_{0.69}$ absorption regions, which exhibit a cutoff wavelength of ~1.1 μm, in order to simplify analysis by bypassing charge-injection issues. The temperature dependence of the dark current was measured in a liquid-nitrogen-cooled, low-temperature chamber. The dark current versus mesa-diode area at 2 V and 3 V reverse bias is plotted in Figure 5(a). The decrease in dark current with diameter is quadratic, indicating that bulk generation-recombination dominated surface leakage. As shown in Figure 5(b), for a 50 μm-diameter device the dark current is in the low picoamp range at low temperature and bias. For bias less than 2 V, the primary source of dark current is generation-recombination. At higher bias, tunneling becomes the dominant mechanism.



(a) (b)

Figure 5. The 1-step staircase APD exhibited bulk-dominated dark currents for all mesa-diode diameters ranging from 50 μm to 500 μm (a), and the dark current densities at the staircase condition ranged from moderate at room temperature to very low at liquid-nitrogen temperatures (b). The temperature dependence was consistent with thermal generation at low reverse biases and band-to-band tunneling at high reverse biases.

For gain measurements, a 543 nm He-Ne CW laser was used as the optical source, in order to ensure pure electron injection into the multiplication region. The multiplication gain of the staircase APDs was determined by comparing their photocurrent to that of the control devices. To eliminate device-to-device variations, 40 devices of each type (i.e. staircase and control) were measured, and results were replicated over multiple growth and fabrication runs. Figure 6 shows representative photocurrent curves as a function of the bias voltage for the 1-step staircase and control photodiodes under the same optical input power. The multiplication gain was found to be 1.8±0.2 independent of reverse bias in the range 1 V to 4 V. This is consistent both with the theory for staircase gain[8,16,17] and with the Monte Carlo simulations. Beyond 4 V of reverse bias, the 1-step photocurrent increased further, possibly due to carriers gaining additional kinetic energy from the wide bandgap field and impact ionizing as they would in a conventional APD. Wafers without composition grading between the AlInAsSb injection region and the InAsSb layer exhibited gain values of 1.6±0.2 for bias in the range 1 V to 4V.

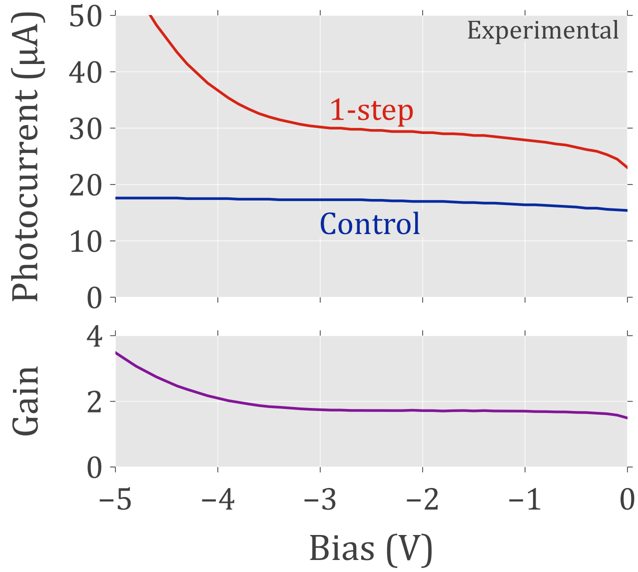


Figure 6. The 1-step staircase APD exhibited enhanced photocurrent compared to the control at all reverse biases and a gain of 1.8 ± 0.2 from -1 V to -4 V. The measurement was performed at room temperature using 543 nm light incident on 50 μm diameter mesa-diodes.

In order to verify that the increased photocurrent in the 1-step staircase was not due to enhanced absorption in the small-bandgap step, we performed spectral responsivity measurements. The resulting spectra for the 1-step staircase and control devices are shown in Figure 7. As expected, for wavelengths longer than ~950 nm, the 1-step staircase exhibited greater responsivity than the control, due to absorption in the small-bandgap step. More importantly, however, we observed an approximately constant 1-step gain of 1.8±0.2 over a broad range of wavelengths shorter than ~950 nm, ruling out enhanced absorption and confirming impact ionization as the source of the observed gain.

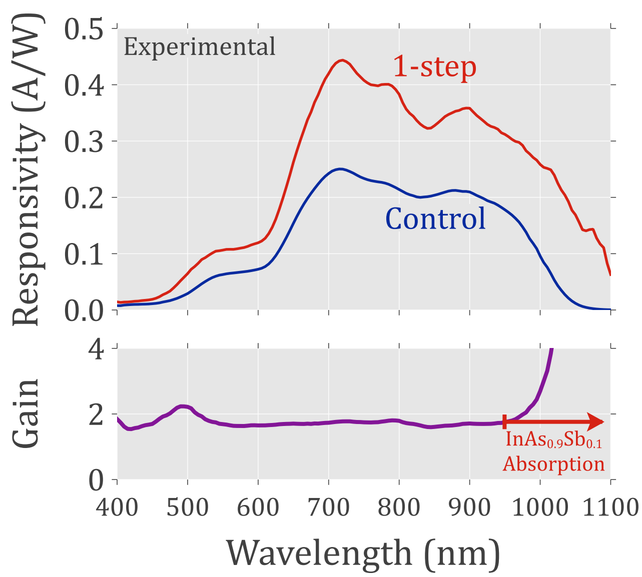


Figure 7. The 1-step staircase APD exhibited a gain of 1.8±0.2 over a broad range of wavelengths shorter than ~950 nm, ruling out enhanced absorption and confirming impact ionization as the source of the observed gain.

In order to confirm the low-noise characteristics of the multiplication gain, the noise power spectra density was measured as a function of bias. The noise power spectral density, φ, is related to the excess noise factor, $F(\langle M\rangle)$, by the equation $\varphi = 2qI\langle M\rangle^2 F(\langle M\rangle)R(\omega)$, where q is the charge of the electron, I is the primary photo current, $\langle M\rangle$ is the mean value of multiplication gain, and $R(\omega)$ is the device impedance.[18] Since the noise power scales as the square of the gain, the noise of the staircase device is expected to be 3.2x and 2.6x that of the control photodiode for the structures with and without compositional grading between the AlInAsSb and InAsSb layers. The measured noise was only 2 to 2.2 times that of the control device. While fortuitous, this unexpectedly low noise will be the subject of future study. It should be noted that F. Ma, et al., have previously observed similar noise suppression in impact-ionization engineered (I2E) heterojunction APDs.[19]

2.2 Photoconductive staircase APDs

While 1-step staircases exhibit excellent gain and noise characteristics, progress toward multi-step staircases has been stymied by non-uniform depletion of the staircase region. In the simple case of a 2-step staircase, free electrons or holes may become trapped in the small-bandgap regions, resulting in either enhancement or screening of the electric field, causing either parasitic photoconductive gain or suppression of impact ionization.

In the case of electrons being trapped in the top step, the electric field is enhanced in the bottom step resulting in band-to-band tunneling through the small-bandgap region, illustrated in Figures 8a and 8b. The resulting intensity-dependent band-to-band tunneling current manifests as an additional “photoconductive” gain, seen in Figure 8c. By deliberately enhancing electron trapping in a 2-step staircase, we have demonstrated enhanced low-voltage photoconductive gains in excess of 200, shown in Figure 9. In case of holes being trapped in the top step, the electric field is screened out of the lower steps, suppressing impact ionization in the lower steps and limiting the gain to ~2x. We have confirmed this as well by deliberately enhancing hole trapping. Preliminary noise measurements indicate that this is a very low noise gain process.

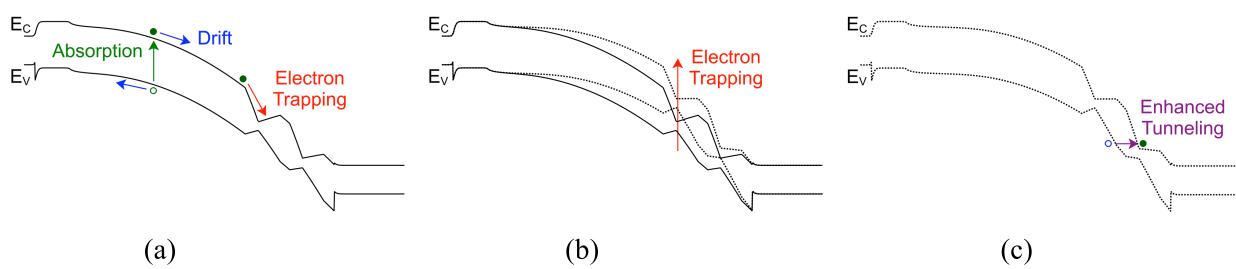
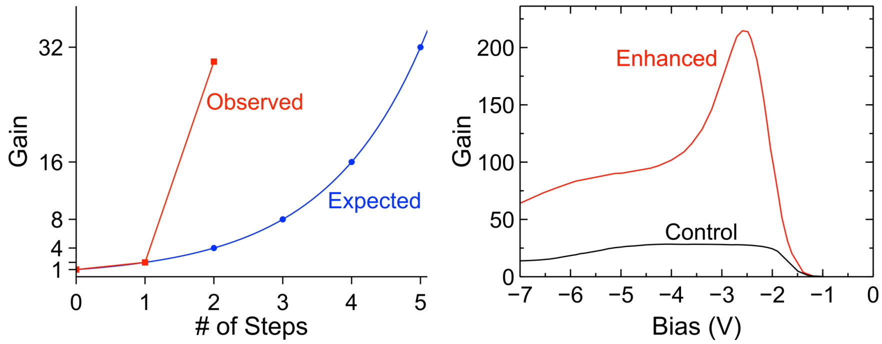


Figure 8. Illustration of the “photoconductive” gain mechanism under low bias. (a) Photogenerated electrons diffuse from the p-absorber and are captured in the top potential well and are trapped because the applied electric field is insufficient to reach the flatband “staircase” bias condition (top sketch in Figure 1), leading to (b) an increased field in the bottom staircase step.



(a) (b)

Figure 9. (a) Measured scaling of staircase APDs with the number of steps (red), compared with the expected scaling (blue). (b) By changing the grading rate of the staircase to increase the depth of the potential wells at the bottom of each staircase, we were able to enhance the gain at low biases.

While this phenomenon relies on carrier trapping, which limits its applications to either low frequencies or high light intensities, the benefits of achieving large gains at low biases for low-power imaging applications is clear. Moreover, the experiment above to confirm the photoconductive gain mechanism was only our first attempt at increasing the photoconductive gain and only employed a conservative increase in the grading rate. Additionally, we have not experimentally attempted to reduce the bias needed to achieve gain. We are confident that significant opportunities exist to further increase the gain levels at further reduced bias.

Based upon Poisson-Schrodinger and Monte Carlo studies, we believe that the grading rate between staircase steps, as well as the spacing between the steps are the most promising first parameters to investigate. For example, the Monte Carlo studies shown in Figure 10 illustrate another promising parameter, the spacing between each staircase step, w.

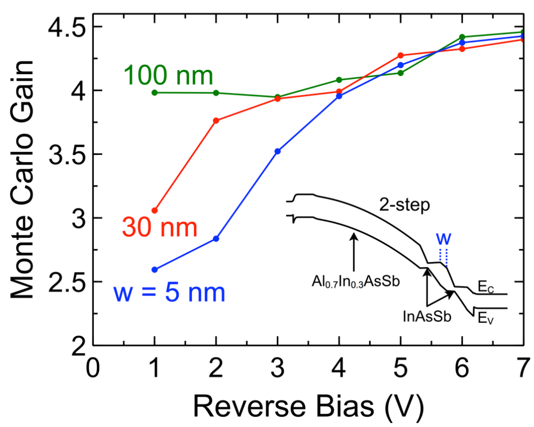


Figure 10. Monte Carlo calculations illustrating one example of how we plan to increase the gain at reduced biases. In particular, we find that increasing the width between steps should yield substantial improvement. Inset: band diagram defining the spacing between steps, w.

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