Recent Advances in Low-Noise Avalanche Photodiodes

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***Abstract*— This paper discusses the improvements in excess noise that have been achieved with Sb containing III-V compound quaternaries.**

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I. Introduction

Recently, two bulk quaternary materials, $Al_xGa_{1-x}As_ySb_{1-y}$ lattice-matched to InP and $Al_xIn_{1-x}As_ySb_{1-y}$ to InP or GaSb have exhibited very low excess noise. There are several, as yet not fully resolved explanations for the dominance of electron impact ionization relative to holes in these materials. Contributing factors include the influence of Sb, which can give rise to large phonon scattering rates and increased effective hole mass, resulting in a large reduction in β[i,ii] and the energy separation between the heavy hole and light hole valance bands and the split-off band. While exhibiting noise characteristics comparable to that of Si avalanche photodiodes, by changing the Al content to modify the bandgap energy these III-V compound materials have exhibited photoresponse from the visible to the mid-wavelength infrared. The bandgap tunability has also been utilized to demonstrate staircase APDs with 2^n gain scaling, where n is the number of staircase steps.

II. AlInAsSb APDs

The growth of $Al_xIn_{1-x}As_ySb_{1-y}$ for Al concentrations greater than 30% has proved difficult owing to a wide miscibility gap.[iii,iv] This can be circumvented, however, using molecular beam epitaxy (MBE) to grow $Al_xIn_{1-x}As_ySb_{1-y}$ (referred to below by the Al concentration as $Al_xInAsSb$) as a digital alloy, a short-period super-lattice structure composed of four binary alloys.[v] The bandgap of $Al_xInAsSb$ on GaSb is direct for x = 0 (E_g = 0.23 eV) to x = 0.8 (E_g = 1.3 eV). AlInAsSb can also be lattice matched to InP with bandgap energies from 1.44 eV to 1.93 eV.

M. Ren et al., have reported $Al_xInAsSb$ PIN-structures with x = 0.7 to 0.3.[vi] The gain normalized dark current was $5x10^{-5}$ A/cm^2 and $1.8x10^{-4}$ A/cm^2 for the x = 0.7 and x = 0.3 devices, respectively. The 70% PIN-structure APDs exhibited gains as high as 100 and excess noise characterized by *k* values in the range 0.01 and 0.06, which is comparable to that of Si APDs. For lattice matching to InP, S. Kodati et al.,[vii] have reported $Al_{0.75}In_{0.25}As_{0.76}Sb_{0.24}$ grown as a random alloy with excess noise corresponding to a *k* of 0.02, which appears to indicate that the low noise in this material system is not attributable to growth as a digital alloy. We note that the thickness of the multiplication layers for the AlInAsSb on GaSb and InP was ~ 1 µm, an indication that the low noise is a bulk characteristic and not due to non-local effects.

While the $Al_xInAsSb$ on GaSb exhibits lower noise for x = 0.6 to 0.8, lower Al compositions (x ≤ 0.5) that absorb at the optical communications wavelengths (1.3 to 1.6 µm) exhibit excessive dark current due to tunneling at the high electric fields required for impact ionization. This has been addressed by using a separate absorption charge and multiplication (SACM) structure with a lower Al content layer for absorption and higher Al layers for the multiplication region. An $Al_{0.7}In_{0.3}As_{0.3}Sb_{0.7}/Al_{0.4}In_{0.6}As_{0.3}Sb_{0.7}$ SACM APD has achieved $6x10^{-3}$A/cm^2 dark current density at 95% breakdown, which is approximately 100x lower than that of Ge on Si APDs[Error! Bookmark not defined.,Error! Bookmark not defined.] and comparable to that of AlInAs/InGaAs APDs.[viii] The maximum gain was 90 and the excess noise was the same as that of the 70% homojunction APD.

Impact ionization is affected to a great extent by phonon scattering, which results in variation of the gain and thus breakdown on temperature. This frequently necessitates temperature stabilizing techniques in optical receivers, an added cost and power penalty. Reducing this limitation can simplify receiver design. The variation of the breakdown voltage of AlInAsSb APDs with temperature, $\Delta V_{bd}/\Delta T$, is approximately 3 mV/K, which is less than a quarter that of AlInAs APDs and almost an order of magnitude lower than $\Delta V_{bd}/\Delta T$ for InP and Si.

III. Staircase APDs

The noise of APDs can be reduced even further by incorporating new materials and impact ionization engineering (I^2E) with appropriately designed heterostructures.[ix-xv] The structure that relies entirely on heterojunctions, specifically the conduction band discontinuity, for impact ionization is the staircase APD. In the early 1980's Capasso and co-workers proposed the staircase APD as a solid-state analog of the photomultiplier tube.[xvi] The staircase APD structure consists of sequential bandgap graded regions, which

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under reverse bias creates a series of steps. Electrons that move from the wide to narrow bandgap regions acquire excess energy, which enables immediate, localized impact ionization. These discontinuities are somewhat analogous to dynodes in a photomultiplier, creating a more deterministic gain process with a resultant reduction in gain fluctuations, and thus lower excess noise. Ideally, the probability of impact ionization is unity at each step, generating a gain of 2^n where n is the number of steps.

Initially $Al_xGa_{1-x}As/GaAs$ was used to fabricated the staircase band structures.[xvii,xviii] Unfortunately, the $Al_xGa_{1-x}As/GaAs$ conduction band discontinuity is not sufficient to impact ionize GaAs, particularly for high-energy electrons scattered to satellite valleys.[xix] The $Al_xIn_{1-x}As_ySb_{1-y}$ material system, on the other hand is well suited for the staircase APD structure. The direct bandgap is widely tunable from 0.24 (x=0) to 1.25 eV (x=0.8)[xx] and the change in bandgap occurs almost entirely in the conduction band.[xxi] As an example, for the $Al_{0.7}In_{0.3}As_{0.31}Sb_{0.69}/InAs_{0.91}Sb_{0.09}$ heterojunction, the conduction band discontinuity is ~0.6eV, which is 2.4x the bandgap energy of $InAs_{0.91}Sb_{0.09}$. It follows that an electron will have sufficient energy to ionize as it crosses the step from the wide bandgap $Al_{0.7}In_{0.3}As_{0.31}Sb_{0.69}$ to the narrow bandgap $InAs_{0.91}Sb_{0.09}$.

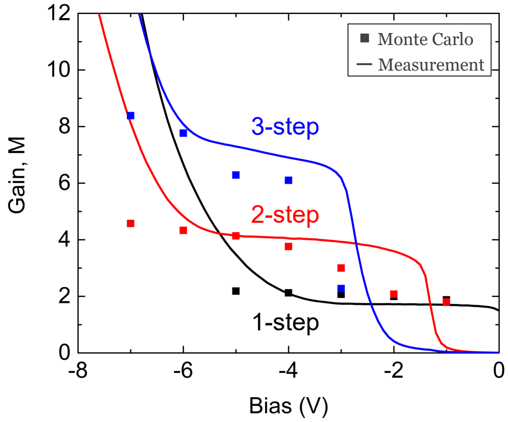

Figure 1. Measured and Monte Carlo simulated gain for 1-, 2- and 3-step staircase APDs versus bias voltage at 300K.

Using 1-, 2-, and 3-step AlInAsSb staircase structures, March et al.,[xxii] have successfully demonstrated 2^n gain scaling. Figure 1 shows the measured gain and Monte Carlo simulations for 1-, 2- and 3-step staircase APDs at 300K. The average measured gains for the 1-, 2-, and 3- step structures were 1.77, 3.97, and 7.14, and the average Monte Carlo simulated gains were 2.01, 3.81, and 6.71, respectively. Fitting the gain versus step count yielded gain of 1.92^n and 1.95^n for measured data and Monte Carlo simulations, respectively, which provides confirmation of gain scaling with step count.
Similar to a photomultiplier tube (PMT) the gain mechanism of the staircase APD is spatially deterministic. This results in excess noise factors ≅ 1 for both the PMT and the staircase APD, which contrasts with a "perfect" k = 0 APD with excess noise factor = 2.

IV. Conclusion

While APDs have been successfully deployed for a wide range of applications, the quest to reduce the noise associated with the random nature of impact ionization has continued for more than four decades. This is, of course, understandable since the gain-related excess noise can limit the receiver sensitivity of digital optical receivers, degrade signal to noise performance, and restrict the operating bandwidth. Recently, quaternary III-V compounds have presented the possibility of low excess noise from the visible to the mid-wavelength infrared that previously was only achievable with Si APDs in the visible. Further, the advantageous use of novel materials and heterojunctions may enable the long-sought solid-state photomultiplier.

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References

[i] M. E. Woodson, et al., Appl. Phys. Lett., vol. 108, no. 8, p 081102 (4 pp.), 22 Feb. 2016.
[ii] Xin Yi, et al., Sci. Rep. vol. 8, pp. 9127-9133, 2018.
[iii] G. W. Turner, et al., J. Cryst. Growth, vol. 175–176, Part 2, pp. 825-832, 1997.
[iv] A. N. Semenov, et al., J. Cryst. Growth, vol. 278, no. 2, pp. 2003-2008, 2005.
[v] S. J. Maddox, et al., ACS Crystal Growth & Design, vol. 16, no. 7, pp. 3582–3586, 2016.
[vi] Min Ren, et al., Lightwave Tech., vol. 35, no. 12, pp. 2380-2384, 15 June 2017.
[vii] S. H. Kodati, et al., Appl. Phys. Lett., vol. 118, no. 9, p 091101 (March 1, 2021).
[viii] M. Nada, et al., 2014 European Conf. Opt. Comm., p. 3, 2014.
[ix] P. Yuan, et al., IEEE Photon. Tech. Lett., vol. 12, pp. 1370-1372, 2000.
[x] O.-H. Kwon, et al., IEEE J. Quantum Electron., vol. 39, no. 10, pp. 1287-1296, 2003.
[xi] C. Groves, et al., IEEE J. Quantum Elect., vol. 41, no.1, pp. 70-75, 2005.
[xii] S. Wang, et al., IEEE J. Quantum Electron., vol. 39, pp. 375-378, 2003.
[xiii] S. Wang, et al., IEEE Photon. Tech. Lett., vol. 14, pp. 1722-1724, 2002.
[xiv] Ning Duan, et al., IEEE Photon. Tech. Lett., vol. 17, no.8, pp. 1719-1721, 2005.
[xv] W. R. Clark, et al., Proc. SPIE Vol. 6796, 67962H, 2007.
[xvi] F. Capasso, et al., IEEE Trans. Electron Dev. Vol. 30, pp. 381–390, 1983.
[xvii] G. F. Williams, et al., IEEE Electron Dev. Lett., vol. 3, pp. 71–73, 1982.
[xviii] G. Ripamonti, et al., Nuclear Inst. and Methods in Physics Research, vol. 288, no. 1, pp. 99-103, Mar 1 1990
[xix] I. K. Czajkowski, et al, Electron. Lett., vol. 26, no. 16, p 1311-1313, Aug 2 1990
[xx] Scott J. Maddox, et al., Crystal Growth and Design, vol. 16, no. 7, pp. 3582-3586, July 6, 2016
[xxi] Jiyuan Zheng, et al., Appl. Phys. Lett., vol. 115, no. 12, 122105, Sept. 16, 2019.
[xxii] S. D, March, et al., Nat. Photonics vol 15, pp. 468–474, 2021.