High Performance Antimony-Based Avalanche Photodiodes (APDs) for Sensing Applications

John P.R. David, Xiao Jin and Harry I.J. Lewis
University of Sheffield
Department of Electronic & Electrical Engineering,
Sir Frederick Mappin Building
Mappin Street, Sheffield S1 3JD
UNITED KINGDOM
j.p.david@sheffield.ac.uk

ABSTRACT

Significant advances have been made in the development of Avalanche Photodiodes (APDs) capable of detecting light at 1550nm with low excess noise characteristics in recent years. Almost all these developments are due to novel materials that share one common characteristic, namely, the presence of antimony (Sb) in the material where the avalanche multiplication occurs. A key requirement of an APD is that the material used for the multiplication region must have a very large difference between the electron and hole impact ionization coefficients (α and β respectively). Materials with a small β/α ratio (defined as k) give rise to low 'excess' avalanche noise and have a better gain-bandwidth product, translating to higher sensitivity APDs that are capable of operating at higher speeds. These Sb containing alloys have a major advantage in that they can be grown lattice matched on InP substrates, enabling them to take advantage of InGaAs (or GaAsSb) as the light absorbing region. As they have relatively large band-gap energies (of ~1.5 eV), they can be used as the multiplication region with high electric-fields while using the narrower band-gap InGaAs to absorb light at low fields in a Separate Absorption and Multiplication region APD (SAM-APD) configuration. Unlike APDs based on materials like HgCdTe, these devices can operate uncooled at room temperature. However, the most interesting property of these Sb containing III-V alloys is the fact that they have α >> β. These alloys include AlxIn1-xAsySb1-y, AlAsSb and AlxGa1-xAsySb1-y lattice matched on InP. In all these cases, the α is similar to that seen in materials like InP and InAlAs but the β is reduced significantly, giving rise to low excess noise even at high gain values. A further advantage of these Sb containing alloys is that their ionization properties are significantly less sensitive to temperature than other III-V materials, reducing the need for temperature stabilization. This presentation will review the development of these Sb based APDs and show how their performance compares to that of commercially available InGaAs/InP based APDs. It will also explain the mechanisms responsible for the low excess noise that is observed.

1.0 INTRODUCTION

Currently, III-V based avalanche photodiodes (APDs) for the detection of short-wavelength infrared (SWIR) light comprise a narrow band-gap absorption region in combination with a wider band-gap material for avalanche multiplication, forming a separate absorption and multiplication (SAM) structure. Recent research has identified several new multiplier materials which can provide a significant improvement over current technology, displaying very low excess noise factor. All of these novel materials have in common the presence of antimony (Sb), which appears to result in a wide ratio between the electron and hole impact ionization coefficients (α and β respectively). A small β/α ratio (defined as k) results in devices with decreased noise, improved sensitivity, and high bandwidth.

The narrow band-gap absorber in a SAM-APD structure must be held at a low electric field to prevent tunneling currents. A charge grading layer is used to maintain this while eliciting a sufficiently high field in the multiplication region for carriers to undergo impact ionization, producing the avalanche gain of the device. The advantage of the use of APDs on the overall SNR of a system [1] is illustrated by equation (1):

$$\mathrm{SNR} = \frac{I_{ph}^2}{2q\left(I_{ph}+I_d\right)F(M)B+\sigma_{\mathrm{circuit}}^2/M^2} \qquad (1)$$

where I_{ph} is photocurrent, I_d is dark current, M is multiplication factor, B is the bandwidth, and $F(M)$ is the 'excess' noise factor arising due to the stochastic nature of the impact ionization process. $\sigma_{\mathrm{circuit}}^2$ is the RMS noise current in the amplification circuitry. SNR will increase with M until limited by the excess noise factor, which is expressed by McIntyre [2] as equation (2):

$$F(M) = kM + (1-k)\left(2-\frac{1}{M}\right) \qquad (2)$$

This indicates the critical importance of a low k value for significantly increasing the SNR of a system using APDs. Typical excess noise characteristics for InP, InAlAs and silicon are given in Figure 1.

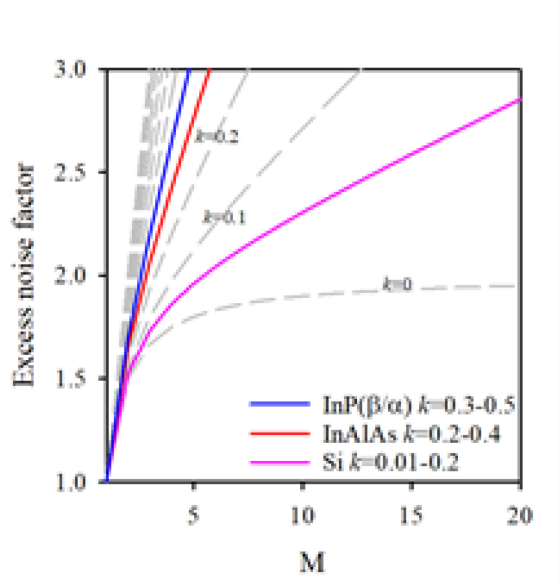


Figure 1: Excess noise characteristics of GaAs, InP, InAlAs and Si. Grey dash lines are the McIntyre local model lines [2] from *k* = 0 to 1 in steps of 0.1.

Commercially available APDs for SWIR detection use InGaAs absorbers in combination with InP or InAlAs multiplication regions. Although InAlAs represents an improvement over InP, both multiplication materials have relatively similar ionization coefficients and display correspondingly high excess noise. Silicon, for which $\alpha \gg \beta$, has very low excess noise factor and is the material of choice for APDs operating at wavelengths up to its absorption cut-off in the near infrared range.

There is now a need for high-sensitivity SWIR APDs for applications including LiDAR, gas sensing, and free-space optical communications. Until relatively recently, the only materials suitable for use at these wavelengths and exhibiting very low excess noise factor were the narrow band-gap semiconductors InAs [3] and HgCdTe [4]. Features of the band-structures of these alloys result in a suppression of β to the extent that the k value is effectively 0. However, these materials suffer from high dark currents and devices can only be operated with significant cooling. There has also been research into engineering specific device structures, such as multiple quantum well or staircase structures [5], [6], [7], in order to preferentially increase the ionization of one carrier type over the other. This approach has seen some success, but the complexity of such structures makes them more difficult to grow and fabricate reliably. The recent development of several wide band-gap antimonide alloys has opened the possibility of a highly sensitive, room-temperature SWIR APD utilizing a relatively simple device structure.

2.0 RESULTS

$Al_xIn_{1-x}As_ySb_{1-y}$ was the first of such antimonide materials to appear in the literature. Woodson *et al.* [1] presented a study of a diode structure with $x = 0.7$ and $y = 0.3$, grown on a GaSb substrate. This device showed excess noise corresponding to an effective k of 0.015 – a 20x improvement from InAlAs, which represented the state of the art for room-temperature devices at that time. In this alloy system, x and y can be controlled to produce a direct band-gap ranging from 0.3eV at $x = 0$, to 1.18eV when $x = 0.72$ [8]. This means that devices which absorb into the mid-IR (MWIR) range can be produced. Reducing the band-gap for longer wavelength absorption results in higher dark currents, but lower-aluminium compounds can be combined with higher-aluminium compounds in a SAM structure. The first $Al_xIn_{1-x}As_ySb_{1-y}$ ($x = 0.7$)/$Al_xIn_{1-x}As_ySb_{1-y}$ ($x = 0.4$) based SAM-APD was reported by Ren *et al.* [9], with noise corresponding to a k of 0.01 up to $M = 18$ and a maximum M of 50. Ionization coefficients have been reported by Yuan *et al.* [10], who showed that $\alpha >> \beta$. $Al_xIn_{1-x}As_ySb_{1-y}$ SAM structures with cut-off wavelengths up to 3.5μm have been reported [11], [12], indicating the possibility of low-noise detection well into the MWIR. A disadvantage of this alloy system is the high cost of GaSb substrates, but ongoing work in GaSb-on-Si hetroepitaxy may remove this barrier [13]. However, recent work has shown that $Al_xIn_{1-x}As_ySb_{1-y}$ can be grown on InP substrates if different compositions are used. Kodati *et al.* [14] have reported a nominally 1μm thick $Al_{0.79}In_{0.21}As_{0.74}Sb_{0.26}$ PIN structure grown on InP. The excess noise measured for this structure corresponded to an effective k of 0.018, which is similar to comparable structures grown on GaSb [1].

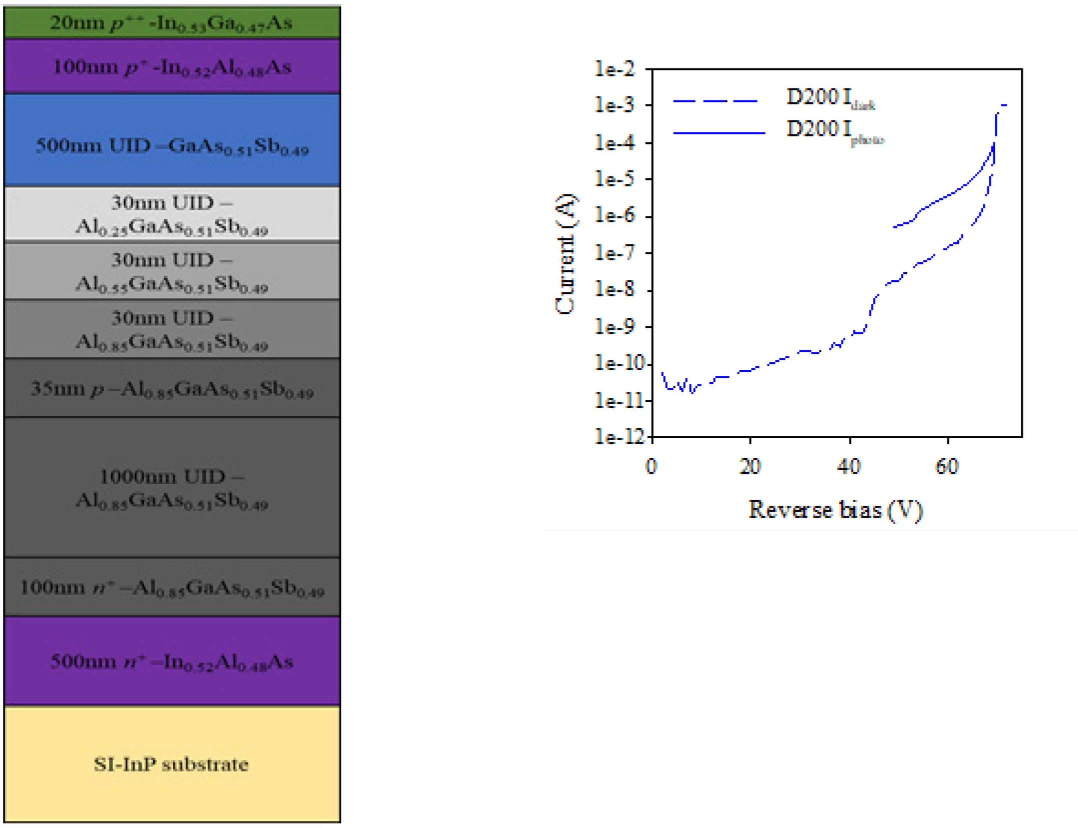
The first study to indicate the low-noise potential of $AlAs_{0.56}Sb_{0.44}$ on InP was that by Yi *et al.* [15]. Measurements on a series of 600nm-1500nm AlAsSb PIN and NIP structures showed that hole-initiated multiplication in this alloy was almost zero, while electron-initiated multiplication could be easily obtained. This indicated that the α/β ratio for this alloy was very large in thick structures. A subsequent report found extremely low excess noise in these structures, equivalent to an effective k as low as 0.005 in a 1.55μm thick PIN. However, the use of $AlAs_{0.56}Sb_{0.44}$ is problematic because its high aluminium content results in high surface dark currents and poor device reliability. The addition of small amounts of Ga may improve these problems considerably, and it has been shown that reducing the aluminium content does not significantly reduce the α/β ratio in other alloys such as $Al_xGa_{1-x}As$ and $(Al_xGa_{1-x})_{0.52}In_{0.48}P$ [16].

The first study into thick $Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ structures was by Lee *et al.* [17], who reported noise equivalent to a k of 0.01 on a 1μm thick PIN structure. Thick $AlAs_{0.56}Sb_{0.44}$ and $Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ studied up to this point had been grown as a digital alloy (DA), using alternating layers of ternary alloys to form a pseudo-quaternary structure. It was then shown by Guo *et al.* [18] and Lee *et al.* [19] that $Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ could be grown as a random alloy (RA), and similarly low noise to the DA structure was measured in an equivalent RA PIN. Electron and hole ionization coefficients for $Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ have been extracted by Guo *et al.* [18] for a wide range of structure thicknesses, showing that while α is similar to that observed in AlAsSb, β is significantly increased.

SAM-APD structures incorporating thick $Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ multiplication regions have now been reported. The first such structure, described by Collins *et al.* [20] used an InGaAs absorption region and displayed a low excess noise factor of 2.94 at a gain of 20.

A collaboration between the Ohio State University, the University of Virginia, UCLA and the University of Sheffield has now produced a SAM structure with a $GaAs_{0.56}Sb_{0.44}$ absorber and an $Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ multiplier which displays extremely low noise, with an F below 3 up to a gain of 70 and a maximum M of 278 [21]. The device schematic and dark current characteristics for this structure are shown in Figure 2, and multiplication and excess noise data for this device are shown in Figure 3. This structure also showed a very low temperature coefficient of breakdown (C_{bd}) of 11.83mV/K, indicating temperature-stable performance. Cao *et al.* also reported a very low C_{bd} of 4.31mV/K in a similar structure [22]. The C_{bd} values for these structures are shown in Figure 4 alongside those for a range of APD structures using existing materials. The use of $GaAs_{0.56}Sb_{0.44}$ for absorption may provide an advantage over InGaAs because the composition can be readily graded between the absorption and multiplication region. The device cut-off wavelength at high multiplication was above 1800nm, as shown in Figure 5.

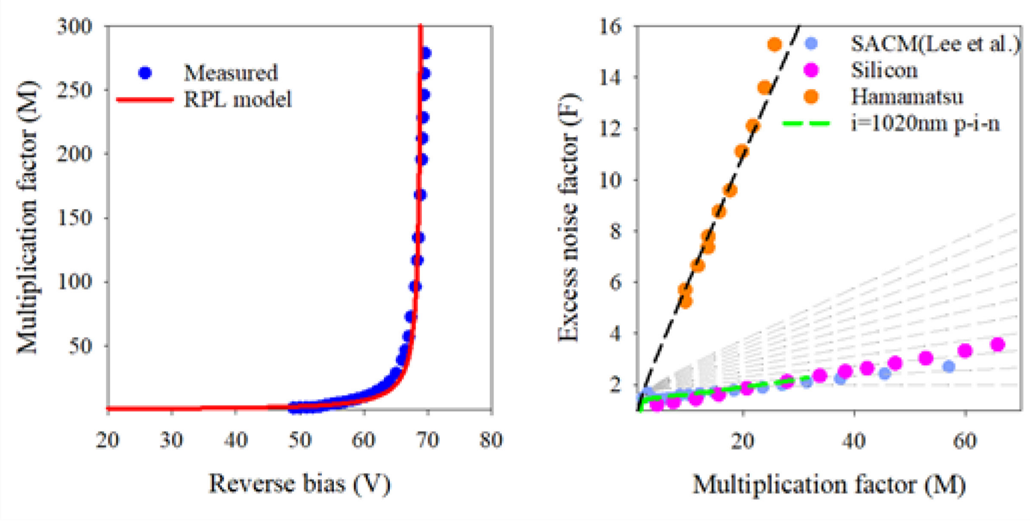
The quaternary alloy $In_xGa_{1-x}As_ySb_{1-y}$ has a band-gap which ranges from 0.7eV to 0.3eV [23], meaning that it could be used as an absorption material in a MWIR SAM-APD. $Al_xGa_{1-x}As_ySb_{1-y}$ can also be grown on GaSb with higher Sb content, allowing possible integration in such a structure. Ionization coefficients in $Al_xGa_{1-x}As_ySb_{1-y}$ on GaSb have been extracted by Grzesik *et al.* [24] for x = 0.4, 0.55, and 0.65 by measurements on a series of PIN structures. The β/α ratio was found to vary between 1.2 to 4, a result which has been corroborated by Collins *et al*. [25] who measured a series of PIN structures with $x = 0.9$.



(a)

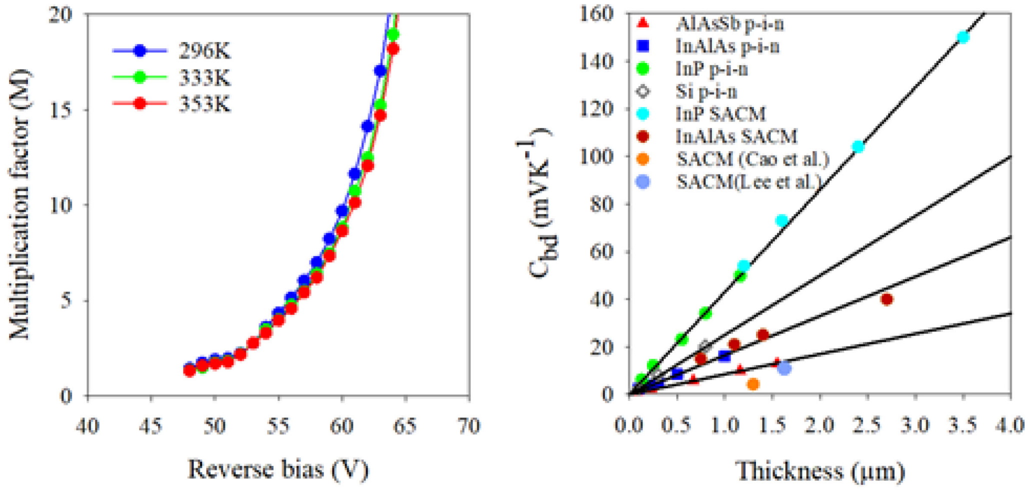
(b)

Figure 2: (a) A schematic diagram for SACM structure used in this work. (b) Dark current and photocurrent characteristics for the $GaAs_{0.56}Sb_{0.44}/Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ SAM-APD structure of Lee et al. [21], shown for a 200µm diameter device.



(a) (b)

Figure 3: (a) Measured multiplication data for the GaAs0.56Sb0.44/Al0.85Ga0.15As0.56Sb0.44 SAM-APD of Lee et al. [21], together with data simulated using a random path length model. (b) Measured excess noise data for the same structure, together with data for a commercial Hamamatsu InGaAs/InP SAM-APD, measured data for a 1020nm Al0.85Ga0.15As0.56Sb0.44 PIN structure [21], and a typical characteristic for a silicon device [21].



(a) (b)

Figure 4: (a) Bias-dependent multiplication characteristics for the GaAs0.56Sb0.44/ Al0.85Ga0.15As0.56Sb0.44 SAM-APD of Lee et al. [21] at temperatures of 296, 333, and 353K. (b) Temperature coefficient of breakdown (Cbd) for various APD structures, including the GaAs0.56Sb0.44/Al0.85Ga0.15As0.56Sb0.44 SAM-APDs of Lee et al. [21] and Cao et al. [22].

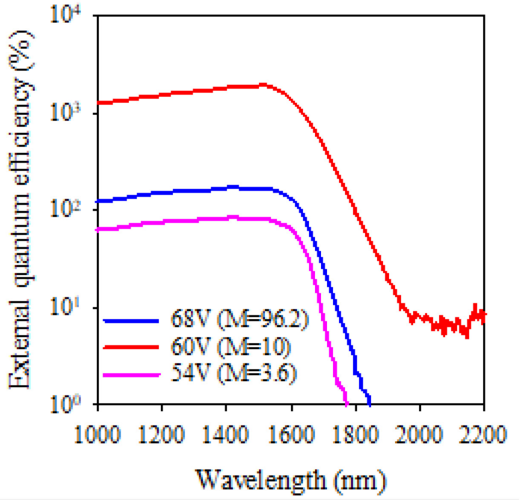


Figure 5: Effective quantum efficiency measurements for the $GaAs_{0.56}Sb_{0.44}/Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ SAM-APD of Lee et al. [21] under various reverse bias voltages, each given with the corresponding multiplication factor.

3.0 DISCUSSION

Excess noise data for various Sb-containing alloys are shown in Figure 6. The results for the $AlAs_{0.56}Sb_{0.44}$ and $Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$, and $Al_{0.79}In_{0.21}As_{0.74}Sb_{0.26}$ on InP are very low, corresponding to a k of between 0.005 and 0.02. $Al_{0.7}In_{0.3}As_{0.3}Sb_{0.7}$ on GaSb displays very low noise at low M, but this increases as the gain increases. In all of these cases the low noise is due to the suppression of hole impact ionization, such that $\alpha >> \beta$. This may be due to the large size of the Sb atom, which may result in the increase of the spin-orbit splitting energy ($\triangle_{so}$). This results in holes in the heavy and light hole bands being less likely to scatter into the split-off band, from which hole impact ionization is usually initiated in III-V alloys. This effect has been observed in GaAsBi, for which the introduction of small concentrations of Bi, a similarly large atom to Sb, suppresses hole impact ionization significantly [26]. α/β ratios for various alloys are plotted against their $\triangle_{so}$ values in Figure 7, and a strong correlation between these quantities can be observed. The decreased β in higher-aluminium compounds may also be related to the Γ band-gap being significantly larger than the X band-gap. The peak of the split-off band is close to Γ point in the Brillouin zone, and holes are likely to require a significant momentum change in the form of phonon interactions in order to impact ionize in alloys with a very indirect band-gap [16]. A notable exception to this trend is $Al_xGa_{1-x}As_ySb_{1-y}$ on GaSb, which has the highest Sb content and is the only alloy discussed here for which $\beta > \alpha$. It has been suggested that, in the ternary alloy $Ga_{1-x}Al_xSb$, a 'resonant enhancement' of the hole-initiated impact ionization may occur when the $\triangle_{so}$ is equal to the direct band-gap energy [27]. It is possible that the high Sb content in $Al_xGa_{1-x}As_ySb_{1-y}$ on GaSb leads to a similar effect, causing an increase in β.

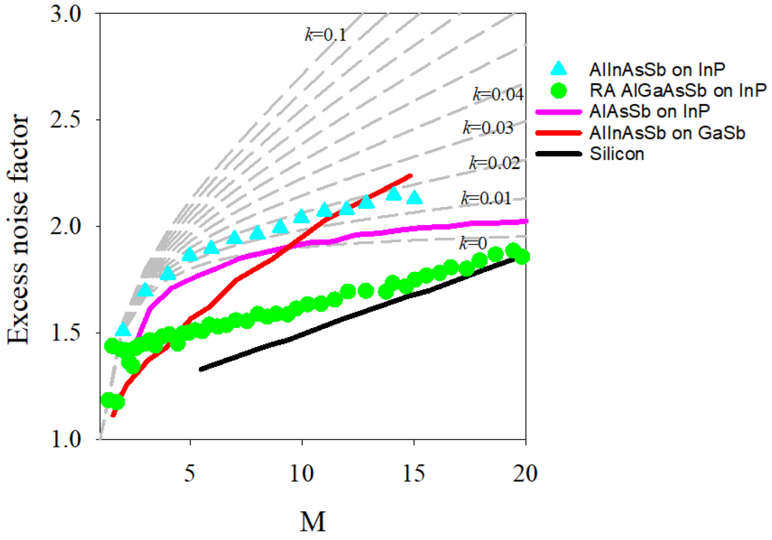


Figure 6: Excess noise characteristics for various Sb-containing alloys.

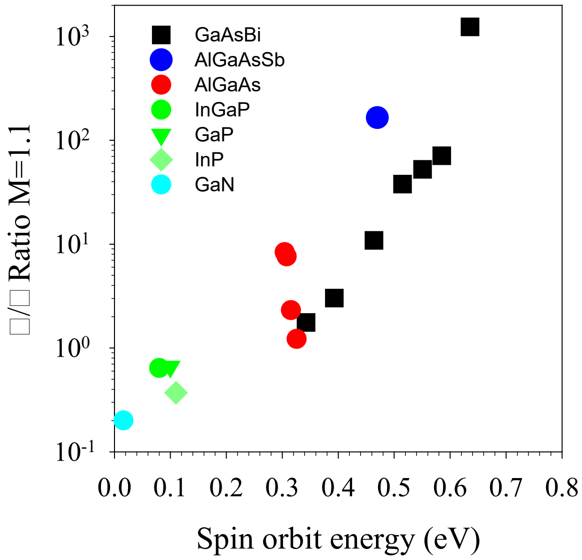


Figure 7: *α/β* ratio for various alloys, plotted against their spin-orbit splitting energy ($\triangle_{so}$).

4.0 CONCLUSIONS

In summary, the use of antimonide based alloys has enabled the development of APDs which can detect at SWIR wavelengths and multiply with low noise at room temperature, to much higher gains than current technology. Commercial development of such devices has already started. As more research is undertaken, the performance of these antinomy based APDs is expected to improve to the point where high sensitivity linear mode APDs capable of few photon detection will become available.

5.0 REFERENCES

[1] M. E. Woodson, M. Ren, S. J. Maddox, Y. Chen, S. R. Bank, and J. C. Campbell, ‘Low-noise AlInAsSb avalanche photodiode’, Appl. Phys. Lett., vol. 108, no. 8, 2016, doi: 10.1063/1.4942372.

[2] R. J. McIntyre, ‘Multiplication noise in uniform avalanche diodes’, IEEE Trans. Electron Devices, vol. ED-13, no. 1, pp. 164–168, 1966, doi: 10.1109/T-ED.1966.15651.

[3] A. R. J. Marshall, C. H. Tan, M. J. Steer, and J. P. R. David, ‘Extremely low excess noise in InAs electron avalanche photodiodes’, IEEE Photonics Technol. Lett., vol. 21, no. 13, pp. 866–868, 2009, doi: 10.1109/LPT.2009.2019625.

[4] M. A. Kinch, J. D. Beck, C. F. Wan, F. Ma, and J. Campbell, ‘HgCdTe electron avalanche photodiodes’, J. Electron. Mater., vol. 33, no. 6, pp. 630–639, 2004, doi: 10.1007/s11664-004-0058-1.

[5] K. Brennan, K. Hess, and F. Capasso, ‘Physics of the enhancement of impact ionization in multiquantum well structures’, Appl. Phys. Lett., vol. 50, no. 26, pp. 1897–1899, 1987, doi: 10.1063/1.97679.

[6] S. D. March, A. H. Jones, J. C. Campbell, and S. R. Bank, ‘Multistep staircase avalanche photodiodes with extremely low noise and deterministic amplification’, Nat. Photonics, vol. 15, no. 6, pp. 468–474, Jun. 2021, doi: 10.1038/s41566-021-00814-x.

[7] F. Capasso, Physics of Avalanche Photodiodes, vol. 22, no. PD. 1985. doi: 10.1016/S0080-8784(08)62952-X.

[8] S. J. Maddox, S. D. March, and S. R. Bank, ‘Broadly Tunable AlInAsSb Digital Alloys Grown on GaSb’, Cryst. Growth Des., vol. 16, no. 7, pp. 3582–3586, 2016, doi: 10.1021/acs.cgd.5b01515.

[9] M. Ren, S. J. Maddox, M. E. Woodson, Y. Chen, S. R. Bank, and J. C. Campbell, ‘AlInAsSb separate absorption, charge, and multiplication avalanche photodiodes’, Appl. Phys. Lett., vol. 108, no. 19, 2016, doi: 10.1063/1.4949335.

[10] Y. Yuan, J. Zheng, A. K. Rockwell, S. D. March, S. R. Bank, and J. C. Campbell, ‘AlInAsSb Impact Ionization Coefficients’, IEEE Photonics Technol. Lett., vol. 31, no. 4, pp. 315–318, 2019, doi: 10.1109/LPT.2019.2894114.

[11] A. H. Jones, S. D. March, S. R. Bank, and J. C. Campbell, ‘Low-noise high-temperature AlInAsSb/GaSb avalanche photodiodes for 2-µm applications’, Nat. Photonics, vol. 14, no. 9, pp. 559–563, 2020, doi: 10.1038/s41566-020-0637-6.

[12] A. A. Dadey, J. A. McArthur, A. Kamboj, S. R. Bank, D. Wasserman, and J. C. Campbell, ‘High-gain low-excess-noise MWIR detection with a 3.5-µm cutoff AlInAsSb-based separate absorption, charge, and multiplication avalanche photodiode’, APL Photonics, vol. 8, no. 3, p. 036101, Mar. 2023, doi: 10.1063/5.0136918.

[13] K. Akahane, N. Yamamoto, S. Gozu, and N. Ohtani, ‘Heteroepitaxial growth of GaSb on Si(001) substrates’, J. Cryst. Growth, vol. 264, no. 1, pp. 21–25, Mar. 2004, doi: 10.1016/j.jcrysgro.2003.12.041.

[14] S. H. Kodati et al., ‘AlInAsSb avalanche photodiodes on InP substrates’, Appl. Phys. Lett., vol. 118, no. 9, p. 91101, Mar. 2021, doi: 10.1063/5.0039399.

[15] X. Yi et al., ‘Demonstration of large ionization coefficient ratio in AlAs0.56Sb0.44 lattice matched to InP’, Sci. Rep., vol. 8, no. 1, pp. 8–13, 2018, doi: 10.1038/s41598-018-27507-w.

[16] H. I. J. Lewis et al., ‘Impact Ionization Coefficients in (AlxGa1-x)0.52In0.48P and AlxGa1-xAs Lattice-Matched to GaAs’, IEEE Trans. Electron Devices, vol. 68, no. 8, pp. 4045–4050, Aug. 2021, doi: 10.1109/TED.2021.3086800.

[17] S. Lee et al., ‘Low noise Al0.85Ga0.15As0.56Sb0.44avalanche photodiodes on InP substrates’, Appl. Phys. Lett., vol. 118, no. 8, pp. 0–5, 2021, doi: 10.1063/5.0035571.

[18] B. Guo et al., ‘Impact ionization coefficients of digital alloy and random alloy Al0.85Ga0.15As0.56Sb0.44 in a wide electric field range’, J. Light. Technol., pp. 1–1, 2022, doi: 10.1109/JLT.2022.3169008.

[19] S. Lee et al., ‘Random alloy thick AlGaAsSb avalanche photodiodes on InP substrates’, Appl. Phys. Lett., vol. 120, no. 7, p. 071101, Feb. 2022, doi: 10.1063/5.0067408.

[20] X. Collins et al., ‘Low-noise AlGaAsSb avalanche photodiodes for 1550nm light detection’, in Optical Components and Materials XIX, Mar. 2022, vol. 11997, pp. 51–56. doi: 10.1117/12.2608842.

[21] S. Lee et al., ‘High gain, low noise 1550nm GaAsSb/AlGaAsSb avalanche photodiodes’, Optica, vol. 10, no. 2, pp. 147–154, Feb. 2023, doi: 10.1364/OPTICA.476963.

[22] Y. Cao, T. Osman, E. Clarke, P. K. Patil, J. S. Ng, and C. H. Tan, ‘A GaAsSb/AlGaAsSb Avalanche Photodiode with a very small Temperature Coefficient of Breakdown Voltage’, J. Light. Technol., pp. 1–1, 2022, doi: 10.1109/JLT.2022.3167268.

[23] M. G. Mauk and V. M. Andreev, ‘GaSb-related materials for TPV cells’, Semicond. Sci. Technol., vol. 18, no. 5, pp. S191--S201, Apr. 2003, doi: 10.1088/0268-1242/18/5/308.

[24] M. Grzesik et al., ‘Impact ionization in AlxGa1−xAsySb1−y avalanche photodiodes’, Appl. Phys. Lett., vol. 104, no. 16, p. 162103, Apr. 2014, doi: 10.1063/1.4872253.

[25] X. Collins, A. P. Craig, T. Roblin, and A. R. J. Marshall, ‘Impact ionisation in Al0.9Ga0.1As0.08Sb0.92 for Sb-based avalanche photodiodes’, Appl. Phys. Lett., vol. 112, no. 2, p. 021103, Jan. 2018, doi: 10.1063/1.5006883.

[26] Y. Liu et al., ‘Valence band engineering of GaAsBi for low noise avalanche photodiodes’, Nat. Commun., vol. 12, no. 1, 2021, doi: 10.1038/s41467-021-24966-0.

[27] O. Hildebrand, W. Kuebart, and M. H. Pilkuhn, ‘Resonant enhancement of impact in Ga1−xAlxSb’, Appl. Phys. Lett., vol. 37, no. 9, pp. 801–803, Nov. 1980, doi: 10.1063/1.92086.