
Published paper

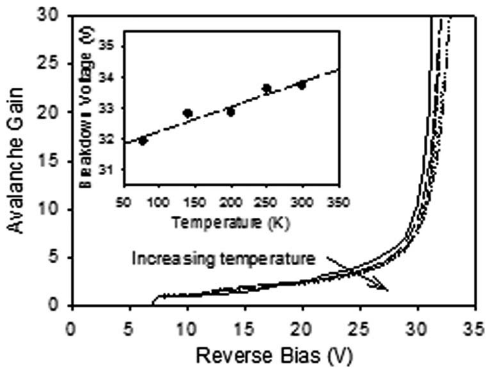
Xie, J., Ng, J.S. and Tan, C.H. (2013) An InGaAs/AlAsSb Avalanche Photodiode With a Small Temperature Coefficient of Breakdown. IEEE Photonics Journal, 5 (4). Doi: 10.1109/JPHOT.2013.2272776

IEEE Photonics Journal
An IEEE Photonics Society Publication

An InGaAs/AlAsSb Avalanche Photodiode With a Small Temperature Coefficient of Breakdown

Volume 5, Number 4, August 2013

Jingjing Xie
Jo Shien Ng
Chee Hing Tan



DOI: 10.1109/JPHOT.2013.2272776
1943-0655/$31.00 ©2013 IEEE

An InGaAs/AlAsSb Avalanche Photodiode With a Small Temperature Coefficient of Breakdown

Jingjing Xie, Jo Shien Ng, and Chee Hing Tan

Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield S1 3JD, U.K.

DOI: 10.1109/JPHOT.2013.2272776
1943-0655/$31.00 ©2013 IEEE

Manuscript received May 1, 2013; revised July 1, 2013; accepted July 2, 2013. Date of publication July 11, 2013; date of current version July 17, 2013. This work was supported in part by The University of Sheffield under Proof of Concept Awards X/004142-1 and X/005703-1 and in part by EPSRC under Grant EP/K001469/1. Corresponding author: J. Xie (e-mail: elp09jx@sheffield.ac.uk).

Abstract: Dark current and avalanche gain M on $AlAs_{0.56}Sb_{0.44}$ (hereafter referred to as AlAsSb) separate absorption multiplication (SAM) avalanche photodiodes (APDs) were measured at temperatures ranging from 77 K to 300 K. To avoid possible ambiguity in breakdown voltage due to edge breakdown and tunneling current, a phase-sensitive detection method with a tightly focused light spot in the center of the device was employed to measure M accurately. An extrapolation of $1/M$ to zero was used to deduce the breakdown voltage, from which the temperature coefficient of breakdown voltage C_{bd} was derived. The value of $C_{bd} = 8$ mV/K, obtained for AlAsSb SAM APDs, is much smaller than that for commercial Si and InGaAs/InP APDs, as well as other SAM APDs in the literature, demonstrating the potential of AlAsSb avalanche regions in improving the thermal stability of APDs.

Index Terms: Temperature dependence, avalanche photodiodes (APDs), AlAsSb.

1. Introduction

Avalanche multiplication provides the internal gain that can enhance the sensitivity of an APD-preamplifier module. As carriers traverse the high field avalanche region, they gain energy from the electric field but also lose energy via phonon scattering. At high fields if the net energy gained exceeds the impact ionization threshold energy, a hot carrier can trigger a chain of impact ionization events that produces an avalanche of new carriers. However, the phonon scattering rates, which strongly depend on temperature, control the hot carrier population and hence can have a strong influence on the avalanche gain and the breakdown voltage. This has been one of the limitations of APDs since additional control electronics are necessary to maintain the APD performance. For instance, APDs in receiver modules of optical fiber communications require adjustment to their reverse bias to maintain the avalanche gain. In airborne remote sensing differential absorption Light Distance and Ranging (LIDAR) systems for measuring water vapor in the atmosphere, the APD is mounted on thermoelectric cooler so that temperature is maintained [1]. Another important example, in which stability of gain is essential, is a photon counting system using a single photon avalanche photodiode (SPAD). The SPAD is normally biased above its breakdown voltage. A small change in the temperature can result in a change of the breakdown voltage leading to a large change in the breakdown probability. Moreover, in a material with a positive temperature coefficient of breakdown voltage, the breakdown probability decreases while the dark count increases exponentially with temperature [2]. Consequently, in most semiconductors, such as Si and InP, the

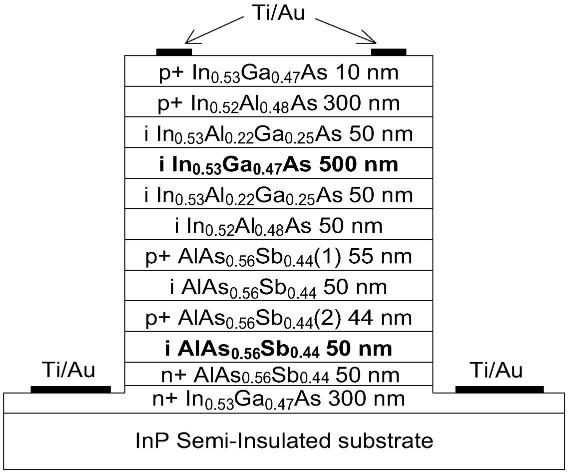


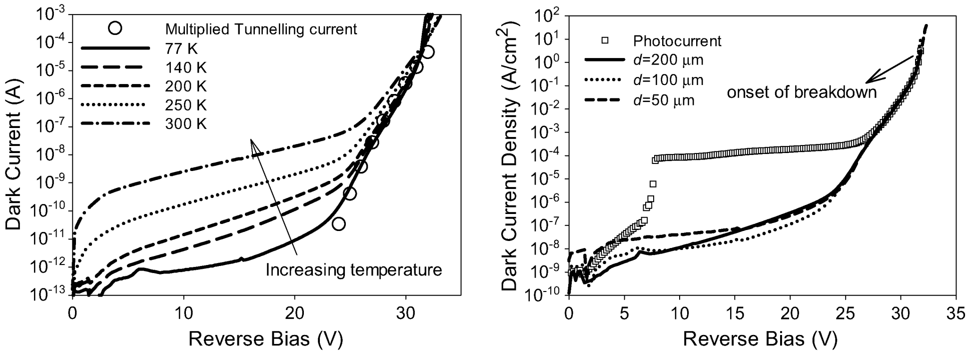
Fig. 1. Nominal structure of our AlAsSb SAM APD.

overall single photon detection quantum efficiency will reduce dramatically with increasing temperature [3]. The temperature dependence of avalanche breakdown has also been exploited in an attempt to prevent photon counting in a Si SPAD [4]. This was done by using an intense light pulse that increases the temperature of the SPAD to increase its breakdown voltage such that it operates in the analog rather than the Geiger mode. Therefore, reducing the temperature dependence of avalanche gain will reduce the influence of temperature fluctuation, on the performance of APDs and SPADs.

The temperature dependence of avalanche gain is usually characterized using the temperature coefficient of breakdown voltage, $C_{bd} = \rho V_{bd}/\rho T$, where ρV_{bd} is the fractional change of breakdown voltages and ρT is the temperature difference. The temperature dependence of breakdown voltage has been reported for a number of semiconductors and C_{bd} has been found to increase with the avalanche region width, w [5]–[10]. Small C_{bd} values that have been reported include 1.53 mV/K for Si with $w \sim 0.1$ μm [5], 6 mV/K for InP with $w \sim 0.13$ μm [9], 2.5 mV/K for InAlAs with $w \sim 0.1$ μm [9], and 0.95 mV/K for AlAsSb with $w \sim 0.08$ μm [10]. In addition to simple pin or nip diodes, C_{bd} values for InGaAs/InP SAM APDs ranging from 46 [9] to 150 mV/K [11] have been reported, with the former having $w = 0.2$ μm. Even lower C_{bd} value of 23 mV/K was obtained for an InGaAs/InAlAs APD with w of 0.15 μm [9]. It is clear that reducing w is beneficial in reducing C_{bd}. Unfortunately further reduction of C_{bd} through reduction of w is not always practical as the onset of band to band tunneling current will dominate the noise characteristics of the APD. For instance to maintain an optimum sensitivity at a bit rate of 10 Gb/s the lower limits of w are ~170 and 150 nm for InP and InAlAs [12]. Therefore, adoption of a new avalanche material is necessary to reduce C_{bd}. As described above, the thin layer of AlAsSb showed the smallest C_{bd} value among the pin and nip diodes compared [10]. An added benefit of incorporating AlAsSb is its very low excess noise corresponding to $k \sim 0.05$ [13] in the local ionization model, where k represents the "effective" ionization coefficient ratio. AlAsSb therefore has the potential to provide excess noise performance comparable to Si APDs and good thermal stability. In this paper, we present the first detailed study of the temperature dependence of avalanche gain and breakdown voltage in an InGaAs/AlAsSb SAM APD in the temperature range of 77–300 K.

2. Device Structure and Experimental Details

We recently reported an excess noise performance corresponding to $k \sim 0.1$ to 0.15, despite an un-optimized doping profile, in an InGaAs/AlAsSb SAM APD with avalanche region thickness ~40 nm [14]. In this paper, a slightly different design has been adopted, where the material used for field control layers was changed from InAlAs in reference [14] to AlAsSb, since the field control layer was



(a) (b)

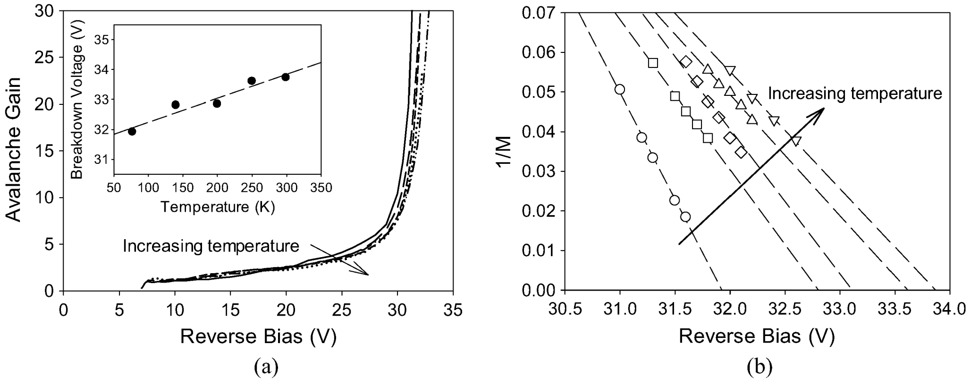
Fig. 2. (a) Measured dark current of an AlAsSb SAM APD with a diameter of 100 μm at temperatures from 77 to 300 K and (b) dark current densities at 77 K obtained from APDs with diameters, $d = 50, 100,$ and 200 μm, together with the photocurrent obtained from a 200 μm diameter APD.

designed to achieve a very high breakdown field > 1 MV/cm in AlAsSb multiplication layer while maintaining low field in InGaAs absorption layer to avoid significant tunneling current. Due to the high breakdown field required in the AlAsSb multiplication layer, the field in the charge sheet can cause excessive tunneling current if InAlAs is used. The InGaAs/AlAsSb SAM APD, lattice matched to InP and shown in Fig. 1, was grown by molecular beam epitaxy on semi-insulating (SI) InP substrate. Briefly it comprises a 500 nm InGaAs absorption layer, sandwiched between two 50 nm layers of InAlGaAs grading layer (with bandgap of 1.1 eV), another undoped 50 nm InAlAs grading layer, 199 nm thick field control p$^+$ip$^+$ AlAsSb layers and a 50 nm of AlAsSb avalanche region. The wafer was then fabricated, using standard photolithography techniques and wet chemical etching, into circular mesa diodes with annular top contacts of Ti/Au (20/200 nm) annealed at 420 °C for 60 s. The etchants used were a mixture of sulfuric acid : hydrogen peroxide : deionized water (1 : 8 : 80) to remove InGaAs, InAlGaAs and InAlAs layers, followed by a mixture of hydrochloric acid : hydrogen peroxide : deionized water (1 : 1 : 5) to remove AlAsSb layers. No surface passivation was performed.

Dark current-voltage (I–V) measurements were performed on the APDs at the temperatures of 77, 140, 200, 250, and 300 K using a low temperature Janis ST-500 probe station. A Keithley 236 source-measure-unit was used for measuring the I–V. For avalanche gain measurement, light from a 1520 nm wavelength He-Ne laser, coupled to a multimode fiber, was used to illuminate the APD to achieve pure electron injection as the light can only be absorbed in the InGaAs absorption layer. The measurement was carried out using phase sensitive detection by mechanically chopping the laser beam at the frequency of 180 Hz to unambiguously differentiate the photocurrent from the dark current and background noise. The modulated photocurrent signal was measured using an SR830 lock-in amplifier. Precaution was taken to ensure that light was focused on the center of the device to avoid edge breakdown effects. The gain measurements were also carried out on APDs with $d = 50, 100, 200,$ and 400 μm to verify that the light spot size is smaller than the device optical window. In this way light is absorbed in the center of the device and hence the influence of edge breakdown is minimized. The avalanche gain, M, was extracted by normalizing the photocurrent to that at the punch-through voltage. To minimize the influence of edge breakdown, tunneling current and surface leakage current on the deduced C_{bd}, the breakdown voltages were extracted from the extrapolation of $1/M$ to zero rather than from the I–V data.

3. Results

On-wafer temperature dependent dark current measurements for InGaAs/AlAsSb APDs were measured at 77 to 300 K, as shown in Fig. 2(a). At bias voltages below 20 V, the dark current drops by approximately four orders of magnitude as the temperature reduces from 300 to 77 K. Inspection of current densities of APDs with diameters, d of 50, 100, and 200 μm at 77 K, as shown in Fig. 2(b), suggests the presence of surface leakage current in these unpassivated APDs. At biases above 25 V



(a) (b)

Fig. 3. (a) Temperature dependence of avalanche gain measured on an APD with $d = 200\ \mu$m. (b) Extrapolation of the reciprocal of avalanche gain from AlAsSb SAM APDs at 77, 140, 200, 250, and 300 K.

the dark current, which scales with area, rises exponentially with bias and shows much less dependence on temperature, suggesting the presence of tunneling current. An even faster rise in dark current was observed at biases above 32 V, due to the onset of avalanche breakdown, although this is less obvious at higher temperature due to high dark current.

The gain was measured using different optical powers ranging from hundreds of nW to tens of μW to confirm its power independence. Upon illumination with the laser a clear increase in the photocurrent was observed. The punch through voltage was estimated to be 7.8 V, based on the sharp increase in the photocurrent as shown in Fig. 2(b). This value is consistent with our capacitance-voltage measurement, where an obvious drop in capacitance was observed at around 7.8 V.

The avalanche gains of an APD with $d = 200\ \mu$m, at 77 to 300 K, are shown in Fig. 3(a). It can be seen that the gain decreases with increasing temperature. The breakdown voltages were extracted from the linear extrapolation of reciprocal of avalanche gain versus voltage to the reverse bias axis, as shown in Fig. 3(b). Within the temperature range the breakdown voltage increases proportionally with temperature as shown in the inset of Fig. 3(a). The breakdown voltage drops from 33.7 V at 300 K to 31.9 V at 77 K, yielding $C_{bd} = 8$ mV/K.

4. Discussion

From the dark *I–V* measurements no well-defined breakdown is observed in the InGaAs/AlAsSb SAM APDs, which we attributed to high band to band tunneling current. To confirm this we estimated the electric field profile by modeling the measured capacitance-voltage characteristics.

Our modeling of capacitance-voltage characteristics suggests that the doping concentrations in the p^+ field control layers, AlAsSb(1) and AlAsSb(2) in Fig. 1, are 2.6×10^{17} and 3×10^{17} cm^{-3} lower than the intended concentrations of 5.0×10^{17} and 1.0×10^{18} cm^{-3}, respectively. Consequently, the electric field in the AlAsSb avalanche region is lower while the electric field in the InGaAs absorption layer is higher than intended. The estimated and intended electric field profiles are shown in Fig. 4. Using our estimated electric field profile the tunneling current from the InGaAs absorption layer can be modeled using [15]

$$I_{tunn} = M * \frac{(2m^*)^{0.5} q^3 EVA}{h^2 E_g^{0.5}} \exp\left[-\frac{2\pi\sigma_T (m^*)^{0.5} E_g^{1.5}}{qhE}\right] \qquad (1)$$

where q is the electron charge, m^* is the effective electron's mass, E is the electric field, A is the device area, h is the Plank's constant, E_g is the bandgap, and σ_T is a constant that depends on the detailed shape of the tunneling barrier and was found to be 1.29 to yield good fit to the measured dark current. Since the ionization coefficients for electron and hole are similar [13] in AlAsSb, we

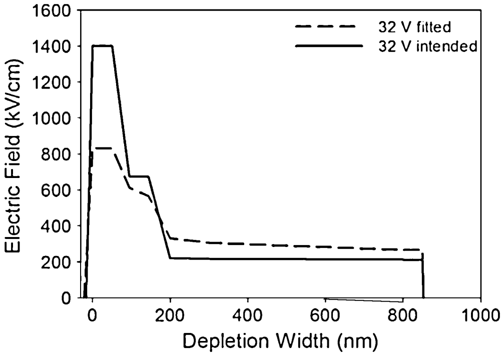


Fig. 4. Comparison between deduced and intended electric field profiles.

assume the tunneling current has the same avalanche gain as the photocurrent. A good agreement between measured and predicted tunneling currents was obtained at 77 K as shown in Fig. 2(a).

The avalanche gain shows negative temperature dependence as observed in most wide bandgap semiconductors. The increase in gain at low temperature can be explained by the increased ionization coefficients due to reduced phonon scattering [7] which is dependent on the phonon occupation number $N = [\exp(\hbar w/kT) - 1] - 1$, where $\hbar w$ is the phonon energy, k is the Boltzmann's constant and T is the absolute temperature. As the temperature rises, the increased phonon population increases the mean number of scattering events, cooling the carriers and reducing carrier ionization probability.

We noted that despite nominally thinner avalanche region of 50 nm in our InGaAs/AlAsSb SAM APD, its C_{bd} of 8 mV/K is much larger than the 0.95 mV/K from a homojunction AlAsSb p-i-n diode with $w \sim 80$ nm. For a given avalanche region width, a SAM APD exhibits a larger breakdown voltage than a p-i-n diode because an additional bias is needed to deplete the field control and absorption layers [9]. If all ionization events are confined within the avalanche region, C_{bd} in a SAM APD can be related to that of a p-i-n diode of the same avalanche region width by [9]

$$C_{bd}(\text{SAM APD}) = C_{bd}(pin) \times w_{depletion}/w \quad \text{V/K}, \tag{2}$$

where $w_{depletion}$ is the total depletion width of the SAM APD. Qualitatively our larger value of C_{bd} confirms the effect of the absorption layer. However, we are not able to perform a more rigorous analysis of the origin of our apparent larger C_{bd} value because of the following reasons. First, we do not have the C_{bd} value for a pin diode with $w = 50$ nm to be used in eqn. (2) since the thinnest w is 80 nm in [10]. The electric field profile extracted in Fig. 4 also suggests that some ionization events in the field control layer and absorption layer cannot be ruled out as the estimated fields in these layers are sufficiently high to have some small amount of impact ionizations. Detailed ionization coefficients in AlAsSb, which is a subject of an ongoing work, will be required to carry out a more accurate modeling of C_{bd}.

The C_{bd} of a Si APD, of a low temperature coefficient type, from Hamamatsu (S6045) is 400 mV/K, while an even smaller C_{bd} of a Si APD array from SensL (ArraySM-4-30035-CER) is as low as 20 mV/K. For commercially available APDs with InGaAs absorbers, AT10GC from Oclaro has one of the smallest C_{bd} values, ranging from 30 and 61 mV/K, for APDs with breakdown voltages ranging from 20 to 40 V, respectively. The lowest C_{bd} of InGaAs/InP and InGaAs/InAlAs SAM APDs reported in the literature are 46 and 23 mV/K [9]. Clearly our SAM APDs showed significantly lower C_{bd}. The very low C_{bd} in our InGaAs/AlAsSb SAM APD is attributed to the thinner absorption layer than those in reference [9] as well as the use of thin AlAsSb multiplication layer. We believe that the thin AlAsSb multiplication layer exhibits small temperature dependence due to the combined effects of the following mechanisms, the adoption a very thin multiplication region, and possibly large phonon energy in AlAsSb that may lead to less temperature dependent phonon scattering rate, and a dominant alloy scattering which is temperature independent. Temperature dependence of ionization rates and scattering rates are required to enable accurate modeling of C_{bd} and this will be a subject of our future work.

5. Conclusion

An InGaAs/AlAsSb SAM APD with a narrow nominal avalanche region of 50 nm has been fabricated, measured and characterized in this work. Temperature dependence of dark current and avalanche gain measurements were conducted at the temperatures ranging 77 to 300 K. The breakdown voltages were extracted from the avalanche gain data. The extracted coefficient of breakdown voltage of 8 mV/K in our InGaAs/AlAsSb APD, is significantly lower than Si and InGaAs/InP APDs. The results demonstrated the potential of using AlAsSb avalanche region to achieve higher avalanche thermal stability over InP and InAlAs.

Acknowledgment

J. Xie would like to thank University of Sheffield and Chinese Scholarship Council (CSC) for their Ph.D. studentships. We would like acknowledge the EPSRC National Centre for III–V. Technologies for technical contribution to wafer growth and access to fabrication facilities. We would also like to thank S. Xie for assistance in device fabrication and measurements.

References

[1] T. F. Refaat and H. E. Elsayed-Ali, "Advanced atmospheric water vapor DIAL detection system," Nat. Aeronaut. Space Admin., Langley Res. Center, Hampton, VA, USA, NASA 210 301, Jun. 2000.

[2] S. Mandai, M. W. Fishburn, Y. Maruyama, and E. Charbon, "A wide spectral range single-photon avalanche diode fabricated in an advanced 180 nm CMOS technology," *Opt. Exp.*, vol. 20, no. 6, pp. 5849–5857, Mar. 2012.

[3] G. Ribordy, J. D. Gautier, H. Zbinden, and N. Gisin, "Performance of InGaAs/InP avalanche photodiodes as gated-mode photon counters," *Appl. Opt.*, vol. 37, no. 12, pp. 2272–2287, Apr. 1998.

[4] L. Lydersen, C. Wiechers, C. Wittmann, D. E. J. Skaar, and V. Makarov, "Thermal blinding of gated detectors in quantum cryptography," *Opt. Exp.*, vol. 18, no. 26, pp. 27 938–27 954, Dec. 2010.

[5] D. J. Massey, J. P. R. David, and G. J. Rees, "Temperature dependence of impact ionization in submicrometer silicon devices," *IEEE Trans. Electron Devices*, vol. 53, no. 9, pp. 2328–2334, Sep. 2006.

[6] C. Groves, C. N. Harrison, J. P. R. David, and G. J. Rees, "Temperature dependence of breakdown voltage in $Al_xGa_{1-x}As$," *J. Appl. Phys.*, vol. 96, no. 9, pp. 5017–5019, Nov. 2004.

[7] C. Groves, R. Ghin, J. P. R. David, and G. J. Rees, "Temperature dependence of impact ionization in GaAs," *IEEE Trans. Electron Devices*, vol. 50, no. 10, pp. 2027–2031, Oct. 2003.

[8] R. Ghin, J. P. R. David, M. Hopkinson, M. A. Pate, G. J. Rees, and P. N. Robson, "Impact ionization coefficients in GaInP p-i-n diodes," *Appl. Phys. Lett.*, vol. 70, no. 26, pp. 3567–3569, Jun. 1997.

[9] L. J. J. Tan, D. S. G. Ong, J. S. Ng, C. H. Tan, S. K. Jones, Y. Qian, and J. P. R. David, "Temperature dependence of avalanche breakdown in InP and InAlAs," *IEEE J. Quantum Electron.*, vol. 46, no. 8, pp. 1153–1157, Aug. 2010.

[10] S. Xie and C. H. Tan, "AlAsSb avalanche photodiodes with a sub-mV/K temperature coefficient of breakdown voltage," *IEEE J. Quantum Electron.*, vol. 47, no. 11, pp. 1391–1395, Nov. 2011.

[11] L. E. Tarof, J. Yu, T. Baird, R. Bruce, and D. G. Knight, "Temperature measurements of separate absorption, grading, charge, and multiplication (SAGCM) InP/InGaAs avalanche photodiodes (APD's)," *IEEE Photon. Technol. Lett.*, vol. 5, no. 9, pp. 1044–1046, Sep. 1993.

[12] D. S. G. Ong, M. M. Hayat, J. P. R. David, and J. S. Ng, "Sensitivity of high-speed lightwave system receivers using InAlAs avalanche photodiodes," *IEEE Photon. Technol. Lett.*, vol. 23, no. 4, pp. 233–235, Feb. 2011.

[13] J. Xie, S. Xie, R. C. Tozer, and C. H. Tan, "Excess noise characteristics of thin AlAsSb APDs," *IEEE Trans. Electron Devices*, vol. 59, no. 5, pp. 1475–1479, May 2012.

[14] C. H. Tan, S. Xie, and J. Xie, "Low noise avalanche photodiodes incorporating a 40 nm AlAsSb avalanche region," *IEEE J. Quantum Electron.*, vol. 48, no. 1, pp. 36–41, Jan. 2012.

[15] S. R. Forrest, R. F. Leheny, R. E. Nahory, and M. A. Pollack, "$In_{0.53}Ga_{0.47}As$ photodiodes with dark current limited by generation-recombination and tunneling," *Appl. Phys. Lett.*, vol. 37, no. 3, pp. 322–325, Aug. 1980.