Recent Advances in Avalanche Photodiodes

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(Invited Paper)

***Abstract*—Until the early 2000's, the avalanche photodiode (APD) was widely deployed in high-performance optical receivers that operated up to 10 Gb/s. In subsequent years, the use of APDs for high-capacity systems declined as a result of their limited gain bandwidth, the transition to coherent detection, and the development of high-efficiency modulation techniques. Recently, the rapid growth of optical-fiber communications systems that utilize baud rates up to 25 Gb/s represented by a 100-Gb/s Ethernet has led to a resurgence of research on APDs and the development of low-noise APDs with enhanced gain bandwidth. This paper presents a brief review of APD fundamentals and describes some of the recent advances.**

***Index Terms*—Avalanche photodiode, photodetector, photodiode.**

I. Introduction

OVER the past five decades, avalanche photodiodes (APDs) have been utilized for a wide range of commercial, military, and research applications. From the mid 1970's to the present, optical communications, [1] imaging, [2], [3] and single photon detection [4], [5] were the primary driving forces for research and development of APDs. In the communication area, relative to PIN photodiodes, the internal gain of APDs provides higher receiver sensitivity and dynamic range with concomitant increases in loss margins [6]–[9]. The origin of the APD gain is impact ionization, a stochastic process that results in excess noise, relative to shot noise, and limits the gain-bandwidth [10]–[12]. The noise power spectral density of an APD, ϕ, is given by the expression $\phi = 2\mathrm{qIM^2F(M)R(\omega)}$ where q is the charge on an electron, I is the current, M is the avalanche gain, F(M) is the excess noise factor caused by the random nature of the multiplication process, and R(ω) is the device impedance [10], [11]. The benefit of an APD is strongly dependent on whether it has sufficient gain-bandwidth, which is closely tied to the excess noise [12]. The factors that establish low noise tend to also yield high gain-bandwidth. Consequently, increasing the gain-bandwidth while reducing the excess noise has been a focus for APD research and development. It should also be noted that while the incremental cost of utilizing APDs is modest, APDs do require more complex epitaxial wafer structures and bias circuits. The most important performance parameters for an APD are gain, bandwidth, gain-bandwidth product, and excess noise factor.

There are three ways to achieve low noise and high gain bandwidth: selecting a semiconductor with favorable impact ionization coefficients, scaling the multiplication region to exploit the non-local aspect of impact ionization, [13]–[27] or impact ionization engineering using appropriately designed heterojunctions [28]–[34]. For bulk multiplication regions, the highest performance is achieved with materials such as Si [35]–[38], $Hg_{0.7}Cd_{0.3}Te$, [39], [40] or InAs [41]–[45] in which k, the ratio of the hole ionization coefficient, β, to that of the electron, α, approaches zero. This is due to the fact that the excess noise factor, F(M), is low when k $<<$1. For other materials systems, enhanced performance can be achieved through designs optimized for low noise. This paper will review recent advances in materials and structures that have enabled improved performance for fiber optic communications.

II. Separate Absorption, Charge, and Multiplication (SACM) APDs

Since the first generation of optical fiber communication systems operated in the wavelength range 800 to 900 nm owing to the operating wavelength of the available $Al_xGa_{1-x}As$ lasers, the optical receivers utilized Si PIN and APDs [46]. However, the attenuation and dispersion characteristics of optical fibers favor operation in the now standard telecommunication wavelength range of 1.3 to 1.6 μm. Consequently, subsequent generations of fiber optic systems employed materials appropriate for longer wavelength operation, primarily those lattice-matched to InP. One such material, $In_{0.53}Ga_{0.47}As$ (referred to in the following as InGaAs), which has bandgap energy of 0.75 eV, is widely used as the absorbing layer in a wide range of telecommunication detectors. However, the narrow bandgap, which enables high responsivity in the short wavelength infrared spectrum also results in excessive dark current due to tunneling at the high electric fields required for impact ionization [47], [48]. This led to the development of SACM APD structures. An important design consideration is to maintain low electric field in the InGaAs absorption region in order to minimize tunneling, which causes high dark current if the electric field strength exceeds ~200 kV/cm. This is accomplished by placing the p-n junction and thus the high-field multiplication region in a wide bandgap semiconductor such as InP or $In_{0.52}Al_{0.48}As$, which is lattice-matched to InP, where tunneling is inconsequential. The relative field strength between the absorber and multiplication regions is controlled with a high-low doping profile in the multiplication region [49]–[51] similar to the reach-through structure that has been widely used for Si APDs [52]. In this structure the

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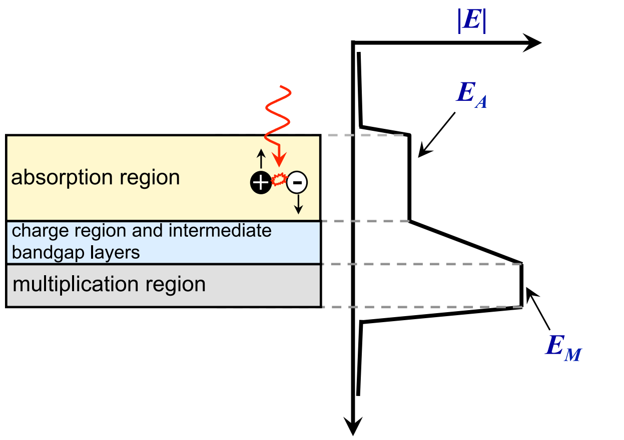

Fig. 1. Layer structure of an SACM APD with internal electric field profile. E_A and E_M are the electric fields in the absorber and multiplication regions, respectively.

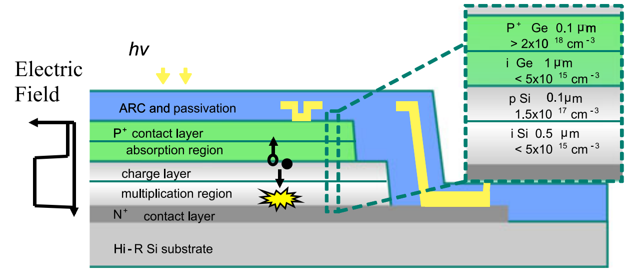

Fig. 2. Schematic cross section of Ge on Si SACM APD [68].

wide-bandgap multiplication region consists of a lightly-doped (usually unintentionally doped) layer where the field is high and an adjacent, doped charge layer or field control region. In order to prevent charge accumulation at the heterojunction interface the absorber and multiplication regions are separated by a transition region consisting of one or more latticed-matched, intermediate-bandgap $In_xGa_{1-x}As_{1-y}P_y$ [53], [54] or InAlGaAs [55]–[58] layers. A schematic cross section of the SACM APD and the internal electric field are illustrated in Fig. 1.

The InP/InGaAsP/InGaAs SACM APDs have been the most widely commercialized for telecom receivers. While these APDs have achieved excellent receiver sensitivities up to 10 Gb/s [59]–[61] there are three factors that limit their performance at higher bit rates. Since they operate under normal incidence and since the absorption coefficient of InGaAs at telecom wavelengths is $\sim 10^4$ cm^{-1}, [62], [63] the absorption region must be approximately 2.5 μm thick in order to obtain external quantum efficiency $> 90\%$. The associated transit time limits the bandwidth to $\sim$10 GHz at low gain. At higher gains, the relatively low gain-bandwidth product ($<$100 GHz) restricts the frequency response. In addition, the ionization coefficients yield a k factor of 0.4 to 0.5, [64], [65] which results in significantly higher excess noise than Si. Much of the recent work on APDs has focused on developing new structures and incorporating alternative materials that will yield lower noise and higher speed while maintaining adequate gain levels.

III. Ge on Si APDs

The SACM structure has been successfully applied to a monolithically grown Ge/Si APD in which light absorption and carrier multiplication occur inside Ge and Si, respectively [66]–[69]. A schematic cross-section of a Ge on Si APD is shown in Fig. 2 [66]. A 1 μm-thick Ge absorber was grown on the Si multiplication layer (0.5 μm) by chemical vapor deposition. A Si charge layer was used to maintain low electric field at the Si-Ge interface. Of particular note, these APDs achieved gain-bandwidth product of 340 GHz, which is two to three times higher than InP/InGaAs APDs. The effective noise factor, k, was only 0.09. Optical receivers built with these APDs demonstrated sensitivity of -28 dBm at 10 Gb/s and bit error rate (BER) of 10^{-12} [66]. Using a similar structure, Huang *et al.*, reported 18 GHz at a gain of 8, responsivity = 0.55 A/W at 1310 nm, and successful operation at 25 Gb/s; the receiver sensitivity was –20 dBm [68]. Two issues for this type of APD are (1) the lattice mismatch between Si and Ge creates deep-level traps that give rise to high dark current and (2) the absorption coefficient of Ge drops rapidly with increasing wavelength beyond $\sim$1.55 μm. Using a waveguide structure enables the thickness of the Ge layer to be reduced, which will reduce the number of traps and decrease carrier transit times yielding higher bandwidths. This approach also increases the optical absorption path length in order to maintain high responsivity at longer wavelengths. Kang *et al.* [67] reported waveguide Ge on Si SACM APDs with 400 nm-thick Ge absorbing layer have been reported. The internal responsivity and bandwidth were 0.8 A/W and 29 GHz, respectively. A 10 Gb/s optical receiver achieved –30.4 dBm sensitivity at BER of 10^{-12}. An open eye diagram was obtained at 40 Gb/s.

IV. Submicron Scaling of the Multiplication Region

It has been shown for a wide range of materials including InP, [20]–[23] GaAs, [22], [28], [70]–[73] $In_{1-x}Al_xAs$, [22], [23], [74] Si, [75], [76] $Al_xGa_{1-x}As$, [22], [23], [77]–[80] SiC, [81] GaP, [82] and GaInP [83] that submicron scaling of the multiplication thickness can significantly reduce the excess noise factor. This is due to the non-local nature of impact ionization, as manifest in the "dead space" effect. The dead space refers to the distance that a carrier travels before gaining enough energy to impact ionize. When the dead space becomes a significant fraction of the multiplication layer thickness, the probability distribution function, which is the probability per unit length that a carrier ionizes at a specific distance from the injection point or the point where it was created by another impact ionization event, narrows. The result is that the gain process becomes more deterministic and the excess noise decreases. It should be noted that there are two competing effects associated with decreasing the multiplication layer thickness. The thinner layers decrease carrier transit times, however, the dead space effect counterbalances this to a small degree.

While shrinking the multiplication region thickness is an effective approach to noise reduction, it should be noted that this is relative to the characteristic noise of the bulk (thick) material. Thus, lower noise can be achieved by beginning with

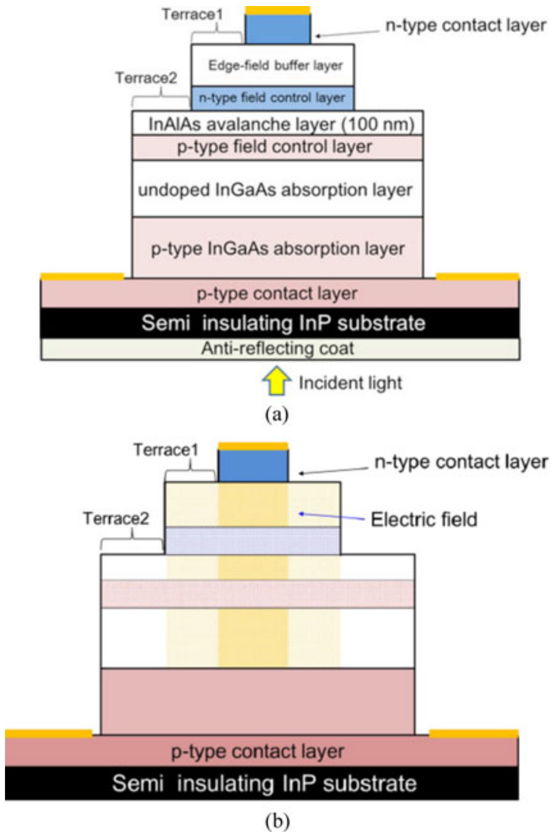

Fig. 3. (a) Schematic cross section and (b) electric field profile of triple mesa p-down InAlAs/InGaAs APD [57].

"low-noise" semiconductors. For this reason, $In_{0.52}Al_{0.48}As$ (referred to below as InAlAs), which has lower intrinsic noise than InP has become an attractive candidate to replace InP in telecommunications APDs. Thin layers of InAlAs have been incorporated into the multiplication region of SACM APDs. Li *et al.* [84] reported that mesa-structure undepleted-absorber InAlAs APDs with 180 nm-thick multiplication regions exhibited excess noise equivalent to $k = 0.15$ and a gain-bandwidth product of 160 GHz. Several planar InAlAs/InGaAs SACM APDs have also been developed. An AlInAs/InGaAs planar SACM APD without a guard ring has achieved gain > 40, high external quantum efficiency (88%), 10 GHz low-gain bandwidth, and a gain-bandwidth product of 120 GHz [56]. Higher operating bandwidth and gain-bandwidth product have been achieved with a triple mesa p-down InAlAs/InGaAs APD [57], [85]. A schematic cross section of the structure is shown in Fig. 3(a). Light is incident through an InGaAs absorber. Above the absorber are a p-doped InAlAs field control layer, an undoped 100-nm InAlAs avalanche layer, n-doped InP field control layer, lightly n-doped InP edge-field buffer layer, and n-doped InP contact layer. The top mesa contains the n-type contact layer; the second mesa contains the edge-field buffer and n-type field control layers; and the other layers are within the third mesa. As illustrated in Fig. 3(b), the triple mesa structure restricts the high electric field regions to the space directly underneath the top mesa thus obviating the need for a guard ring. The electric field is low at the outside edges of the regions labled terrace 1 and terrace 2, which not only prevents edge breakdown but also reduces surface leakage, a common issue for mesa-structure APDs. In order to optimize the transit time, the InGaAs absorber consists of two regions, an undepleted p-type layer and an undoped depleted layer; this absorber doping profile is similar to that in high-power modified uni-traveling carrier photodiodes [86] for which this type of absorber has been employed to suppress the space-charge effect, a primary limitation on output power and saturation current. For APDs space charge can reduce the internal field, which will result in lower gain and a corresponding decrease in dynamic range. The partially depleted absorber in the triple mesa APD has enabled linear response up to 1.5 dBm. The 100 nm InAlAs multiplication layer enabled a gain-bandwidth of 235 GHz. Devices designed for 25 Gb/s have achieved 72% external quantum efficiency, bandwidths of 23 GHz and 18.5 GHz at gain of M = 4.47 and 10, respectively, and excess noise factor corresponding to k = 0.2. A four channel receiver utilizing these APDs demonstrated 100-GbE over 50 km; all channels achieved receiver sensitivities better than –20 dBm at 10^{-12} BER. By decreasing the thicknesses of the absorbing and multiplication regions to reduce the transit time component of the bandwidth, operation at 50 Gb/s was achieved with a gain of 4.6 [87].

V. Impact Ionization Engineering

A third method that has been employed to achieve higher performance utilizes impact ionization engineering (I^2E) [28]–[34]. Structurally, I^2E is similar to a truncated multiple quantum well (frequently mislabeled as "superlattice") APD, [88], [89] however, operationally there is a fundamental difference in that these APDs do not invoke heterojunction band discontinuities. While the distinction is somewhat subtle, the I^2E devices achieve low noise through abrupt changes in the threshold energy for impact ionization as carriers transit from materials with wide bandgaps to those with much narrower bandgaps. Carriers gain energy from the electric field in the wide bandgap material and quickly impact ionize when they enter the narrow bandgap layer. Initial work that demonstrated the efficacy of this approach utilized the $GaAs/Al_xGa_{1-x}As$ material system [28]–[30]. Excess noise equivalent to k < 0.1 has been demonstrated [90]–[92]. Duan *et al.*, reported an MBE-grown $In_{0.52}Al_{0.48}As/In_{0.53}Al_{0.3}\ Ga_{0.17}As$ (InAlAs/InAlGaAs below) I^2E SACM APD [33]. A cross section of the epitaxial layer structure of an InAlAs/InAlGaAs I^2E SACM APD is shown in Fig. 4. The absorber is a 1.5 μm-thick layer of InGaAs. The I^2E multiplication region consists of unintentionally-doped layers of InAlAs (130 or 180 nm) and InAlGaAs (100 nm). Two 50 nm-thick InAlAs and InAlGaAs p-type layers are used for the charge region. Monte Carlo simulations show that there are relatively few ionization events in the InAlAs multiplication layer, owing to the combined effects of "dead space" and the relatively high threshold energy in InAlAs. Fig. 5 shows the excess noise factor, F(M), versus gain for two wafers, one having an InAlAs layer 130 nm (▲) thick and the other 180 nm (♦). The solid lines in Fig. 5 are plots of F(M) for k = 0 to 1 using the local field model [10], [11]. For low gain values, it appears

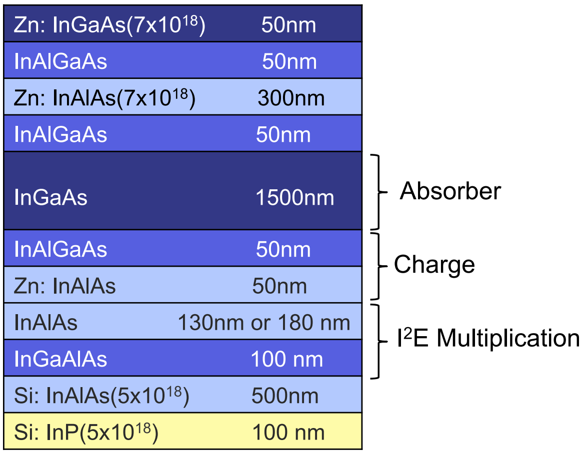

Fig. 4. Schematic cross section of $In_{0.52}Al_{0.48}As/In_{0.53}Al_{0.3}Ga_{0.17}As$ I^{2}E SACM APD.

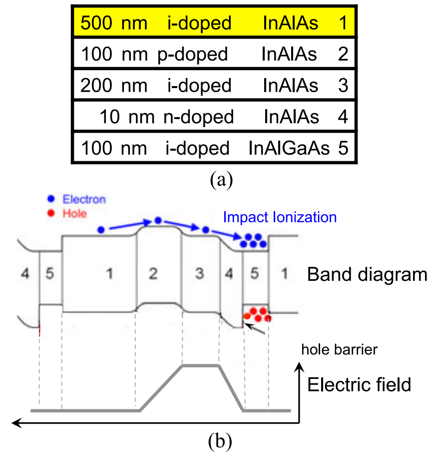

Fig. 6. (a) Epitaxial layer structure and (b) band diagram of three cell of a tandem I^{2}E InAlAs/InGaAs APD.

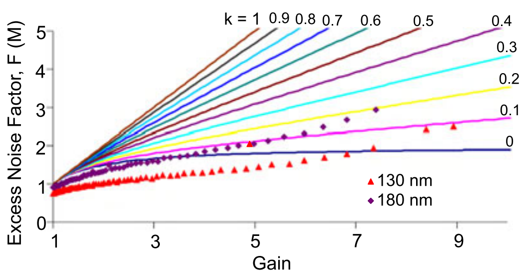

Fig. 5. Excess noise factor, F(M), versus gain, M, for an $In_{0.52}Al_{0.48}As/In_{0.53}Al_{0.3}Ga_{0.17}As$ I^{2}E SACM APD.

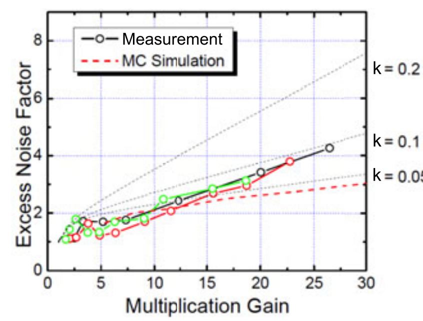

Fig. 7. Measured and simulated noise of the tandem I^{2}E InAlAs/InGaAs APD in Fig. 6.

that k < 0, which is unphysical and simply reflects the inapplicability of the local field model for this type of multiplication region. A photoreceiver for LIDAR applications based on the InAlAs/InAlGaAs I^{2}E SACM APD exhibited a noise equivalent power of 150 $fW/\sqrt{\mathrm{Hz}}$ over 1 GHz bandwidth at 1.06 μm [93]. This type of APD has also been incorporated into free space laser communication terminals for small, unmanned airborne platforms. Receiver sensitivity of –47 dBm was achieved at 155 Mb/s.

A technique that has been proposed to further reduce the excess noise of APDs is to cascade low-noise gain regions within an APD [94], [95]. Recently this approach has been applied to I^{2}E APDs [34], [96]. The connection between two adjacent multiplication cells is critical to the performance of this type of APD. A well-designed structure can significantly enhance impact ionization of the carrier type with higher ionization rate, and suppress impact ionization of the carrier with lower ionization rate. Williams *et al.*, have reported a five-stage I^{2}E InAlAs/InGaAs tandem APD that achieved k ≤ 0.1 for gain, M < 20 [97]. Clark *et al.* have successfully demonstrated a three-stage tandem I^{2}E InAlAs/InGaAs APD [34]. Both structures have been designed to enhance electron ionization while suppressing that of holes. The structure of each I^{2}E multiplication cell in Ref. [34] contains a 100 nm InAlAs hole relaxation layer, a 100 nm p-type InAlAs layer in which the electric field increases, a 200 nm InAlAs "acceleration" layer, a 10 nm InAlAs layer with decreasing electric field, and a 100 nm InAlGaAs (band-gap = 0.92 eV) impact ionization layer. At high gain, the excess noise of this structure degrades due to increased hole ionization as holes surmount the hole barrier. To suppress hole-initiated ionization, Sun *et al.*, have used Monte Carlo simulations to show that increasing the thickness of the relaxation layer in the multiplication cells from 100 to 500 nm has the benefit of allowing the holes to cool before they enter the InAlGaAs multiplication layer [98]. The epitaxial layer structure and band diagram of a single cell are illustrated in Fig. 6(a) and (b), respectively. Fig. 7 shows the simulated [98] and measured excess noise for this structure. The simulated k factor for the thicker hole relaxation layer is less than 0.05 for gain values up to ~30. For gain less than 15 the measured excess noise agrees with the simulation. At $M = 25$ the equivalent k value increases to 0.08. Simulations that address variations in the thickness and doping of the p-type relaxation layer show that 20% variation in the thickness-doping product can account for the slight increase in excess noise. It should be noted that the compound multiplication region of the tandem APD, while yielding very low excess noise, is also characterized by reduced gain-bandwidth product. Fig. 8 shows the simulated bandwidth versus gain for a single stage I^{2}E APD and a three-stage tandem APD. The gain-bandwidth product decreases by approximately a factor of N, where N is the number of stages in the tandem APD.

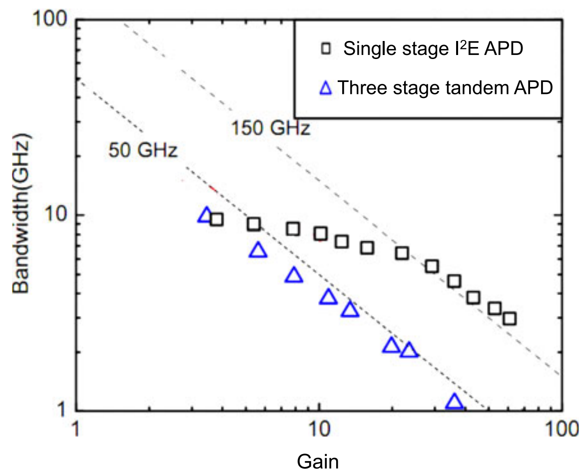

Fig. 8. Bandwidth versus avalanche gain for single- and three-cell tandem APDs [98].

VI. 2 μM APDs

Interest in extending the transmission of optical communications into the 2-μm band has been stimulated by the expected "capacity crunch" by 2020. The development of hollow core photonic bandgap fibers and thulium-doped fiber amplifiers are timely enabling components. Detectors that operate at wavelength longer than 2 μm are not as advanced as those in the standard telecommunications spectrum. One approach involves utilizing $In_xGa_{1-x}As$ epitaxial layers on InP to extend the operating wavelength into the MWIR. Using highly strained $In_{0.83}Ga_{0.17}As$ quantum wells on InP Dries *et al.* [99] extended the operating wavelength to 2.01 μm, however, the quantum efficiency was $< 30\%$. Thick (2.5 μm) mismatched $In_{0.71}Ga_{0.29}As$ absorption layers on relaxed buffer layers yielded external quantum efficiency $> 80\%$ from 1to 2 μm with cutoff wavelength of 2.6 μm [100], However, these devices exhibited high dark current owing to defects related to the lattice-mismatched layers. A more promising approach has been to use type II quantum wells in the absorption region of an SACM APD. Type-II quantum wells are formed between materials with staggered band offsets. When thin layers of these materials are grown adjacent to each other, the electrons and holes are confined in adjoining layers. This allows spatially indirect tunneling-assisted emission or absorption. The type-II band line-up leads to a narrower effective bandgap and allows longer wavelength operation. Sidhu *et al.*, reported an SACM APD with InP multiplication region and an absorbing region consisting of 150 pairs of type-II $Ga_{0.47}In_{0.53}As$-$GaAs_{0.51}Sb_{0.49}$ quantum wells [101]. A schematic cross section of the epitaxial layer structure and a band diagram for the type II superlattice absorption region are shown in Fig. 9. These APDs exhibited cutoff wavelength of 2.4 μm, quantum efficiency $> 40\%$ for wavelengths < 2.1 μm, dark current density near breakdown of less than 0.66 mA/cm^2, and gain > 35 at room temperature. Ong *et al.*, have reported a similar SACM APD with type II $Ga_{0.47}In_{0.53}As$-$GaAs_{0.51}Sb_{0.49}$ quantum well absorber except the multiplication region is InAlAs instead of InP [102]. These APDs had the following characteristics: 2.5 μm cutoff wavelength, 32% external quantum efficiency at 2.0 μm, gain > 60, and 30 mA/cm^2 dark current near breakdown. Another approach for 2 μm APDs utilizes InAs as the gain material. InAs APDs have demonstrated k $\sim$ 0 with moderate dark current at room temperature [41], [43]. InAs APDs employing 10 μm-thick intrinsic regions and AlAsSb blocking layer to suppress electron diffusion current achieved gain as high as $\sim$300 at 15 V bias. The gain-bandwidth product was >500 GHz, however, the bandwidth was transit-time limited in the range 2 to 3 GHz independent of gain owing to the thick depletion width required to minimize the tunneling component of the dark current [43].

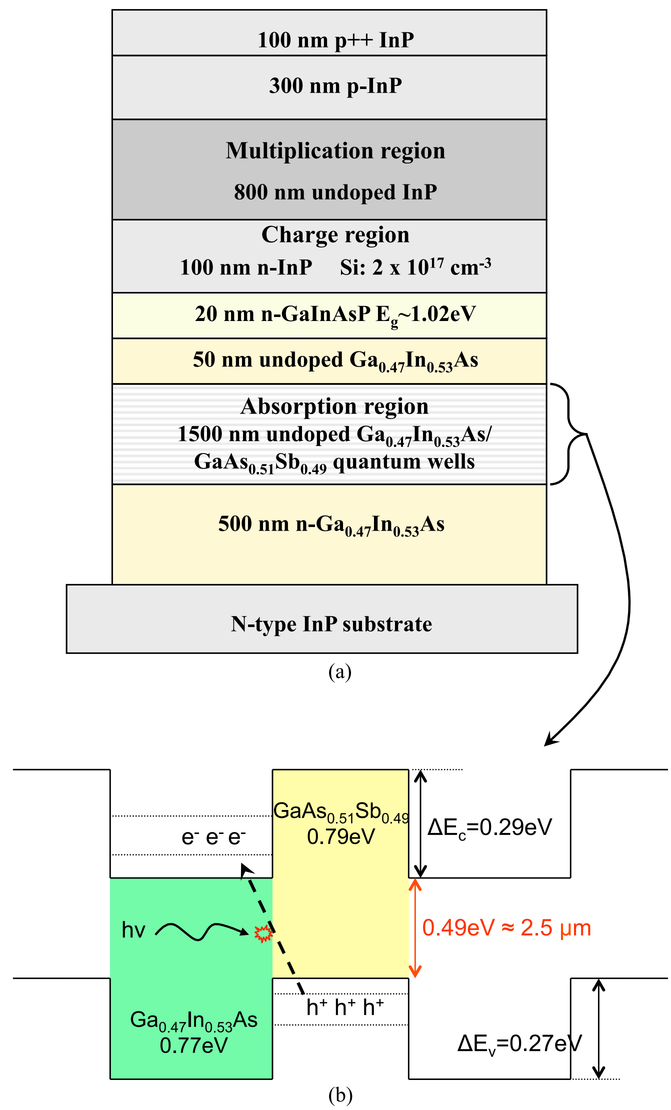

Fig. 9. (a) A schematic cross section of the epitaxial layer structure and (b) a band diagram for the type II superlattice absorption region.

VII. Summary

In the past decade the performance of APDs for optical fiber communication systems has improved as a result of improvements in materials and the development of advanced device structures. Techniques to reduce the excess noise and increase the gain-bandwidth product have enabled operation at higher bit rates and set the stage for future systems that will benefit from the compact size, low cost, and high sensitivity that APDs provide.

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