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# Reliability Challenges and Performance Optimization Strategies for Superlattice Avalanche Photodiodes in Optical Communication Systems

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## Abstract:

This research paper provides a comprehensive review of avalanche photodiodes (APDs) in optical communication technology, focusing on their role in enabling high-speed data transmission. APDs, capable of operating in high electric fields, are critical to achieving high bit rate fiber optic communication systems and in long distance optical communications. APDs have become the preferred photodetector due to their inherent internal gain, which offers superior sensitivity compared to PIN photodiodes. Notable advances in APD performance have been made through research efforts, primarily focusing on material innovations and improvements in device structure. Specifically, this review delves into the intricate interplay of temperature dependence with breakdown voltages in separate regions of absorption, sorting and charge multiplication. Additionally, it examines the application of superlattice avalanche photodiodes for optical communications. In the critical wavelength range of 1.3 to 1.55 micrometer, APDs exhibit higher receiver sensitivity and dynamic range, albeit accompanied by large loss margins. The fundamental gain mechanism in APDs comes from impact ionization, although at the cost of introducing excess noise that restricts the gain-bandwidth product.

**Keywords:** *Avalanche photodiodes (APDs), impact ionization, Temperature Dependence of APDs, avalanche Punch through voltage, Breakdown voltage, optical communication, nanoscale APD.*

## Introduction:

In the past five decades, avalanche photodiodes (APDs) have served as essential components in a wide range applications spanning commercial, military and research fields. Since the mid-1970s, its use has become particularly evident in optical communications, imaging, and single-photon detection, stimulating ongoing research and development efforts. In communications, APDs have significantly outperformed PIN photodiodes due to their inherent internal gain, allowing greater receiver sensitivity and dynamic range, although accompanied by higher loss margins. The growing demand for increased transmission capacity in both trunk lines and access networks, mostly based on silica optical fibers, underscores the need for high-performance photoreceptors and premium light sources. Central to the functionality of APDs is the phenomenon of impact ionization, a stochastic process that generates excess noise compared to shot noise and thus imposes limitations on the bandwidth product. The noise power spectral density of anAPD, φ, is given by the expression φ = 2qI M2 F(M) R(ω). Here ***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.

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Our study delves into the temperature sensitivity of breakdown voltage (VBr)across a wide temperature range (-40 to 110°C) in separate absorption, grading, charge, and multiplication (SAGCM) InP/InGaAs avalanche photodiodes (APDs), encompassing various device configurations. Our experimental findings reveal a nearly linear relationship between breakdown voltage (VBr) and temperature. Specifically, we observed a temperature coefficient (ηexp) ranging from 0.13 to 0.16V, indicative of the degree of voltage changes per unit temperature variation.

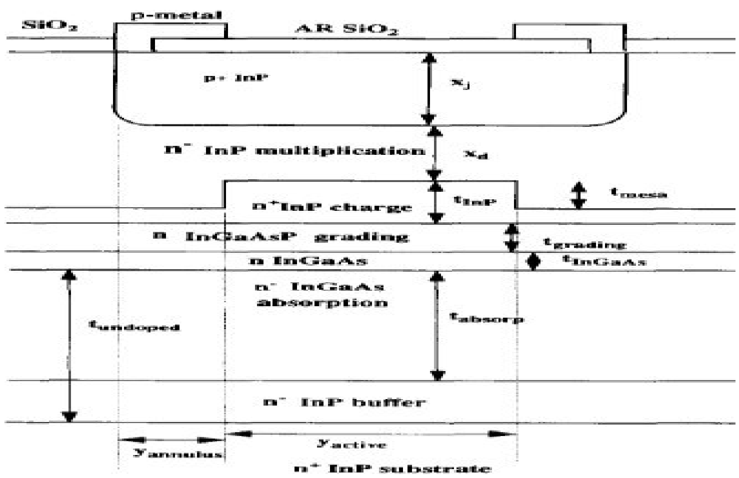


**Fig1: Seperate absorption, Charge multiplication InP/InGaAs APDS with partial charge sheet**

A physical model has been developed to elucidate the linear variation of breakdown voltage (Vbr) with temperature, demonstrating a temperature coefficient ($\eta_{exp}$) of approximately 0.155 V/°C. This model successfully accounts for the minor variations observed among different APDs and exhibits good agreement with experimental data. It proves to be an appropriate tool for modeling the temperature-dependent characteristics of any InP-based APDs.

The SAGCM (Separate Absorption, Grading, Charge, and Multiplication) InP/InGaAs avalanche photodiode (APD) has emerged as a high-performance photodetector for modern long-distance, high-bit-rate fiber-optic telecommunication systems within the wavelength range of 1.0 to 1.6 μm [1-3]. Despite the initial success in fabricating SAGCM InP/InGaAs APDs, detailed modeling of their characteristics and quantitative verification against experimental data has been lacking. Additionally, there has been a dearth of theoretical modeling concerning the temperature dependence of breakdown voltage (Vbr) in any type of InP-based APDs, despite a few early experimental works [4-7]. Planar SAGCM InP on GaAs APDs were fabricated using a two-step metal organic chemical vapor deposition (MOCVD) process, as previously described. Figure 1 provides a schematic illustration of our SAGCM APD, featuring nominal parameters.

The SAGCM structure provides independent control of the thickness of the unpublished multiplication layer and the area charge density integrated into the charge layer. Bandwidths exceeding 100 GHz have been achieved for these APDs [1]. In addition, device performance is less sensitive to changes in manufacturing parameters compared to more traditional SAGM APDs, which require doping layer thickness control to within 0.02 μm [8]. We significantly extend the work recently published in [9], focusing on the temperature dependence of the breakdown voltage (Vbr), which is an important performance parameter for APDs in unrefrigerated applications. A typical PV voltage versus bias voltage is shown in Figure 2. All well-designed APDs, including SAGCM InP/InGaAs APDs, exhibit ionization collapse at a given voltage (Vbr). However, in SAGCM InP/InGaAs APDs, there is an additional characteristic voltage that can be clearly identified from the photocurrent voltage characteristics shown in Figure 2. This is the voltage at which the electric field begins to penetrate the InGaAs layers. Using these two experimental voltages, two main parameters of the device can be extracted, such as the χ d and α charge.

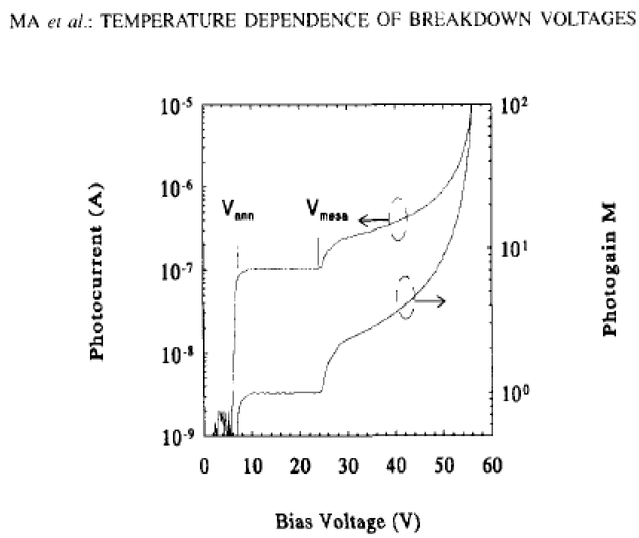


**Fig 2: Photo gain from the photocurrent-voltage curve.**

## Super lattice avalanche photodiodes for opticalcommunications:

The first type is an InAlGaAs/InAlAs polyimide-coated mesa-structured SL-APD, which achieves a high-gain bandwidth product of more than 120 GHz and a low-multiplier dark current of only a few tens of nanoamperes. Its reliability has been tested for more than $10^5$ hours at 50°C. The second type is the SL-APD flat case with a new implanted titanium protective ring, which provides a longer life than the table case and thus improves durability. The third type is a large receiving area SL-APD combined with a monolithic lens for eye-safe 1.5 µm wavelength optical measurement systems. The growing demand for higher transmission capacity in trunk lines and access networks based on silica optical fibers is driving the development of advanced SL-APD devices, essential for modern optical communications systems. To meet the increasing demand for high-performance optical receivers and high-quality light sources, advancements have been made in developing high-performance Erbium-doped fibers [10]. These developments have enabled achieving the highest reported overall receiver sensitivity in the 1.55 µm wavelength region using pin photodiodes combined with Erbium-doped fiber amplifiers (EDFAs) [11,12]. However, for applications requiring simple, low-power-consumption receiver modules in both the 1.3 µm and 1.55 µm wavelength regions, avalanche photodiodes (APDs) with internal gain remain the most sensitive semiconductor photodetectors. In these applications, InGaAs/InP heterostructure APDs, featuring an InP avalanche layer separated from an InGaAs signal-absorption layer, are preferred and now available commercially [13]. These APDs offer high sensitivity and efficiency, making them suitable for critical roles in optical communication systems. However, it is very difficult for available InGaAs/InP APDs to respond reliably to 10 Gbps (10 Gbps) band signals with moderate gain multiplication, due to their limited bandwidth (GB) products. The performance characteristics of APD, especially the GB product and the excess noise resulting from the ionization (multiplication) process, are governed primarily by the ionization rates of electrons and holes, and especially the ratio of these ionization rates in the avalanche layer itself. The ratio of InP is about 2.5 [13], which is at least an order of magnitude smaller than that of Si, and Si APDs are the most sensitive and have the highest GB product of APDs applied for wavelengths below 0.9 lm. The GB products in commercially available InGaAs/InP APDs are typically 20–50 GHz [13]. These gigabyte-limited products degrade the receiver's sensitivity to high frequencies. High-speed, high-sensitivity SL-APD transmission for use in 1.3 to 1.55 µm wavelength optical fiber communications.

Superlattice APDs and research trends in optical communications have shown that the impact ionization rate is largely determined by the semiconductor's physical properties and varies with the electric field and temperature. Advances in epitaxial growth techniques, particularly thin-multiple-layer growth, have introduced a new approach to enhancing the ionization rate using band-offsets in a multiple quantum-well (superlattice) structure. In the most successful SL-APDs, applying a reverse bias to the superlattice significantly enhances the ionization rate. As electrons travel through the hetero-interfaces from the wide-bandgap barrier layer to the narrow bandgap well layer, they gain additional energy corresponding to the large conduction-band offset energy ($\Delta E_c$). This boosts the electron ionization rate. In contrast, the hole ionization rate remains relatively unchanged due to the small valence-band offset ($\Delta E_v$) and the heavy mass of holes. As a result, a high ionization-rate ratio is achieved compared to bulk materials, making SL-APDs highly effective for optical communication applications.

## Optimization of InGaAs/InAlAs Avalanche Photodiodes:

We report a two-dimensional (2D) simulation study of InGaAs/InAlAs separate absorption, grading, charge, and multiplication avalanche photodiodes (SAGCM APDs) to examine the effects of the charge layer and multiplication layer on the operating voltage ranges of the APD.

## Key Findings:

**Punch-Through Voltage**: Increases with the thickness and doping concentrations of both the charge layer and the multiplication layer.

**Breakdown Voltage**: Decreases with increasing doping concentrations of both layers and the thickness of the charge layer and initially rapidly decreases with the increasing thickness of the multiplication layer, then slightly increases.

## Electric Field Distribution:

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For SAGCM APDs, the critical task is to adjust the electric field distribution by modifying the thickness and doping concentration of the charge and multiplication layers. When the electric field in the multiplication region is sufficiently high, carriers undergo avalanche multiplication, enabling the APD to function as intended.

## Independent Control:

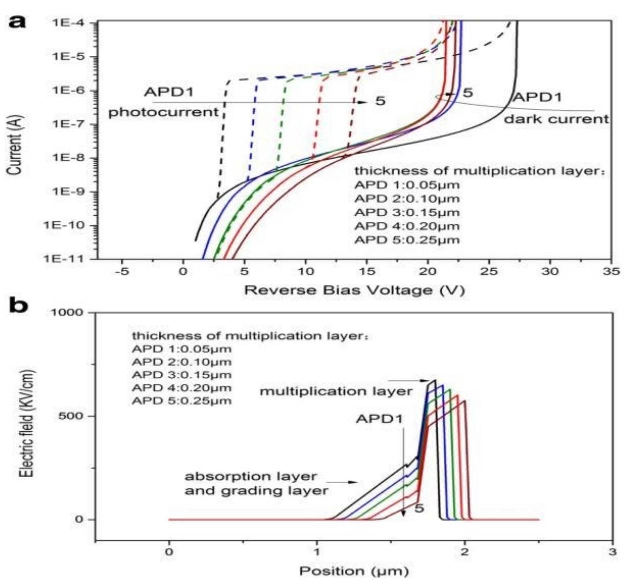
The SAGCM structure allows for independent control of the charge layer and multiplication layer parameters (thickness and doping concentration), optimizing the device's performance.

## Theoretical and Experimental Analysis:

We studied the impact of the charge and multiplication layers on the operating voltage ranges and analyzed the results based on the internal electric field distribution. The experimental current–voltage (I–V) characteristics for the top-illuminated SAGCM InGaAs/InAlAs APD were found to be in good agreement with the simulated results, corroborating the data reported in reference [15].

$$M^{n} = \frac{1-\frac{1}{k}}{\exp\left[-\alpha\left(1-\frac{1}{k}\right)x_m-\frac{1}{k}\right]}$$

To obtain smaller dark currents, larger breakdown voltage and larger gain factor, the grafting of the absorption layer is relatively larger. As the doping concentration decreases, the electric field between the absorption layer and the gradient layer increases, making the electron easier to manipulate. Through the absorption layer and classification layers, the voltage decreases due to the wedge-shaped electric field with a high gradient [12].




a. **Current–voltage characteristic of APD with different multiplication layer thicknesses.**

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**b. Distribution of electricfield, biased at 15 V**

## Reliability Challenges of Nanoscale Avalanche Photodiodes:

Avalanche photodiodes (APDs) are important components for high-performance optical receivers. The rapid growth of 100Gb/s Ethernet, along with the deployment of 2.5G and 10G APDs, has increased the demand for 25G APDs and beyond. In this short letter, we briefly review the latest developments in nanoscale APDs and highlight potential reliability challenges in the future. Solar energy is one of the major emerging renewable energy sources today [18]. The main way to utilize solar energy is through the photoelectric effect, which is the phenomenon of converting light into electrical energy [19]. In optical fiber communications, photodiodes are used as sensors to convert input light energy into electrical signals through a similar photoelectric process [20]. Avalanche photodiodes are widely used due to their performance advantages such as high receiver sensitivity, low noise, and high bandwidth [21].

The figure below shows the general device schematic and electric field distribution of an APD device. For the APD top illumination shown in the figure, the top layer is a highly doped InGaAs layer that forms an ohmic contact with the intrinsic p In0.53Ga0.47. The metal acts as an absorption layer with a bandgap energy of 0.75eV for light absorption [22]. InAlAs is widely used for field control and electric multiplication layers to achieve lattice matching with the InP substrate. The field reaches a maximum in the multiplication layer responsible for the avalanche collapse process [21]. Doping the InAlAs field control layer can affect the relative field strength between the absorption and multiplication regions.

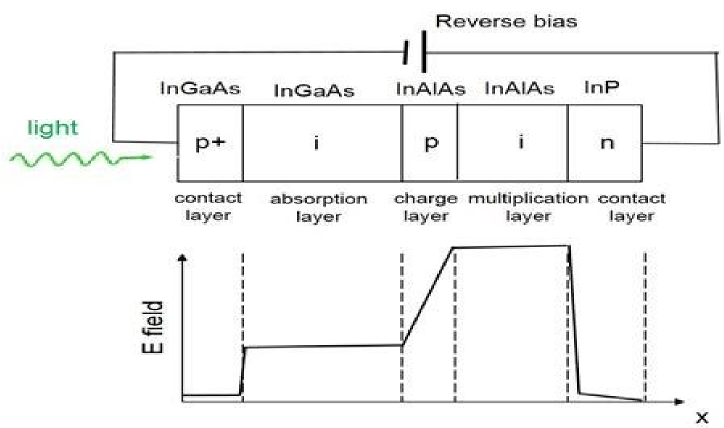


**Fig 3: Schematic cross-section and internal electric field profile of the APD structure (not in scale). In the illustration, the InGaAs absorption layer is next to the InAlAs charge controland multiplication layers**

The impact layer that may cause the avalanche collapse process [21]. The doping of the InAlAs field control layer can affect the relative field strengths in the absorption and multiplication regions. The APD feature size refers to the thickness of the multiplication layer, while the IC feature size depends on the channel length of the transistor. It has been observed that device scaling occurs in both optical and electronic devices to achieve higher performance. The first factor is the high electric field associated with the reduction of feature size, and the second factor is related to resistance and Joule heating [23-25]. Joule heating increases the device junction temperature, which can deteriorate the smoothing function in electronic ICs. The geometry during the smoothing process may cause current crowding and lead to premature reliability failures. The dark current of modern mesa-type APDs is limited to tens of nanoamperes. Voltage breakdown for the avalanche process, most of the voltage drop usually occurs in the absorption layer and the replica layer [4].

## CONCLUSIONS:

Nanoscale APDs are crucial components for high-speed, high-performance optical receivers in Lightwave communication systems. We have reviewed the key reliability aspects associated with device miniaturization, including high electric fields, Joule heating, and geometric inhomogeneity. Our findings suggest that the increase in electric field due to device miniaturization poses the most significant reliability challenge for the next generation of APDs.

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