

Dynamic Bias Characteristics of InGaAs/InP Avalanche Photodiodes under Linear Mode Operation

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Abstract—Linear mode characteristics of dynamically biased InGaAs/InP separate-absorption-multiplication avalanche photodiodes are investigated. Modulated mean gain and excess noise allow for tuning of the response to maximize the photon detection probability. A novel circuit for implementing dynamic biasing at rates up to 100 Mbps is proposed.

Keywords—Avalanche photodiodes; Mean gain; Excess noise; Impact ionization; Dynamic biasing, Optical quantum systems.

I. INTRODUCTION

Avalanche photodiodes (APDs) have high sensitivity and fast response times [1]. Their compact size, relatively low cost compared to superconducting detectors, and possible room-temperature operation make them suitable for integration into practical optical quantum systems [1], [2].

The materials used to fabricate APDs depend largely on the target wavelength range. Si APDs are widely used for visible to near-infrared wavelengths (typically up to $\sim 1 \mu\text{m}$), making them ideal for quantum circuits utilizing standard optical fibers and visible lasers. For longer wavelengths, such as those used in telecom applications ($\sim 1310 \text{ nm}$ and 1550 nm), compound semiconductors like InGaAs/InP are typically used [3].

The linear mode of APDs, under constant bias, allows for a finite, yet statistically fluctuating, gain. This mode enables the differentiation between a single photon or multiple photons arriving simultaneously. However, the statistical nature of the gain creates excess noise, which is detrimental to APD performance. In this work, we investigate the application of dynamic biasing to modulate the mean gain and excess noise factor characteristics for an InGaAs/InP APD to provide optimal conditions for photon detection.

II. DYNAMIC BIASING FOR LINEAR MODE OPERATION

Theoretical description of the avalanche multiplication process in APDs under dynamic reverse-biasing conditions has been given in [3]–[5]. Those studies indicate that periodic modulation of the electric field in the multiplication region, synchronized with the bit rate, can enhance the gain-bandwidth product by mitigating inter-symbol interference in optical receivers. Moreover, the periodic modulation of the electric field leads to similarly modulated mean gain and excess noise within the multiplication region of the APD. This effect within the device can be controlled to coordinate with the arrival of a photon. Thus, a mechanism exists for the APD to provide maximum gain when the photon arrival is expected.

To model this behavior, we consider an InGaAs/InP APD operating at 1550 nm . The working conditions were adapted from [3], and the dynamic bias of the modulating signal was chosen by taking into account the operational frequency. The modulation frequency was chosen to be 100 MHz . Moreover, we keep in mind that for InP, the impact ionization is primarily driven by holes. This means that the ionization rate for holes (β) is greater than that for electrons (α), although the ratio varies with the electric field strength. Table 1 lists main parameters used to calculate β according to Eq. (11) in [6], as well as the effective threshold ionization energy for holes E_{ih} .

Table 1. Impact ionization coefficients for InP for holes (β) [6]

	Units	
A	cm^{-1}	4.29×10^6
E_c	V/cm	2.08×10^6
M		1.12
E_{ih}	eV	2.2

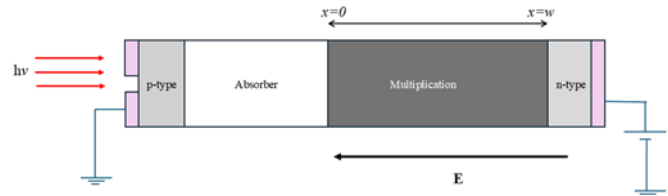


Fig. 1. Schematic illustration of a separate-absorption-multiplication APD simulated in this paper.

In this paper, we simulate a separate-absorption-multiplication avalanche photodiode (SAM APD), shown schematically in Fig. 1, similar to the device considered in [7]. The width of the absorption region is typically in the range of 500 nm and the multiplication region is kept at $1 \mu\text{m}$, which reduces the effect of the dead space multiplication that comes into play in sub-micron devices, and mitigates the effects of the stochastic nature of carriers produced by impact ionization within the multiplication region, thus making the process more deterministic [7]–[9]. Moreover, we assume a 100% injection efficiency of the incoming carriers into the multiplication region. We also assume that the change in the electric field allows the carrier populations to reach equilibrium with the electric field for each carrier, such that the ionization coefficient of a carrier depends adiabatically on the instantaneous electric

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field $E(x,t)$ at the point where and when it is ionized by impact. The electric field across the device was kept at 4.1×10^5 V/cm, and a MATLAB script was used to generate a sinusoidal pattern as a voltage input to the device.

A high-level diagram of a novel circuit for implementing dynamic biasing and recovering optical data is shown in Fig. 2. The injected dynamic biasing signal will be removed using a signal processing technique. As opposed to an earlier dynamic biasing scheme that was demonstrated to work up to 25 Gbps [4], the circuit illustrated in Fig. 2 is limited to lower bit rates (10-100 Mbps), which however are deemed sufficient for quantum computing applications. In addition, more complex error correction techniques can be implemented utilizing digital signal processing algorithms.

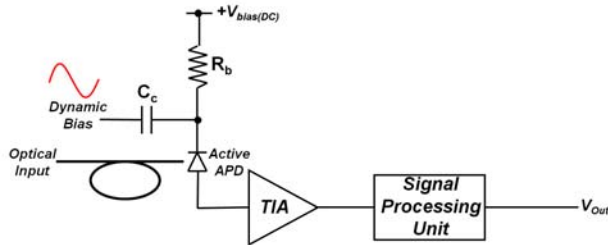


Fig. 2. A high-level circuit diagram of implementing dynamic biasing and recovering optical data (photon counting).

III. RESULTS

The statistical gain of an APD is the average multiplication factor by which the primary photocurrent is amplified through the avalanche process. The excess noise factor, on the other hand, arises from the statistical nature of the avalanche multiplication process. These parameters are crucial in quantum and optical systems, as higher gain improves detection sensitivity, but higher excess noise degrades signal-to-noise ratio and limits accuracy. We define a stochastic dynamic multiplication factor $M(x,s)$ as the total number of electron-hole pairs generated in the presence of the dynamic field by a parent carrier, where x and s represent the position and age of the parent carrier, respectively. As indicated in [7], $M(x,s) = 0.5[Z(x,s) + Y(x,s)]$, where $Z(x,s)$ ($Y(x,s)$) are the multiplication factors corresponding to an electron (hole) parent. For the special case of an InGaAs-InP SAM APD, for which holes are injected at the edge of the multiplication region at $x=w$, $G(s) = M(w,s) = 0.5[1 + Y(w,s)]$. The excess noise factor, defined in [10], is then calculated as $F(M) = kM + (1 - k)[2 - M^{-1}]$, where k is the ratio of impact ionization coefficients for holes and electrons, $k = \beta/\alpha$.

The simulated mean gain and excess noise factor characteristics for the InGaAs/InP SAM APD under 100 MHz sinusoidal bias are presented in Fig. 3. The simulated response helps us with choosing the window of input signal to ensure that the incoming carrier experiences higher gain, which in turn provides a methodology to allow for efficient photon detection at 100 MHz.

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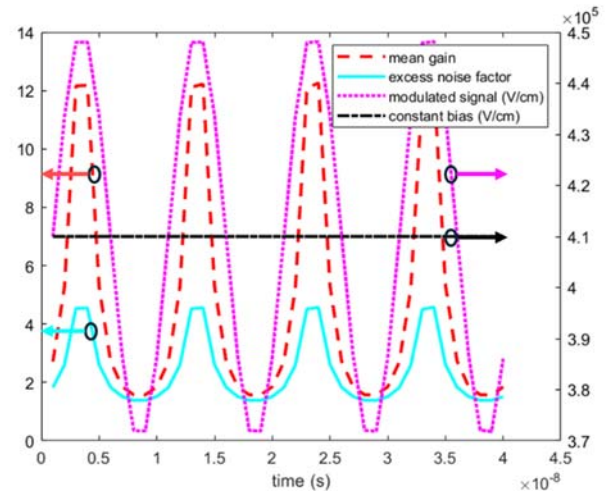


Fig. 3. Mean gain characteristics of the InGaAs/InP APD under dynamic bias with a frequency of 100 MHz.

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