# InGaAs Avalanche Photodiodes (APDs) Outcompete PIN Diodes

*T.C. Wu, M. Riaziat*

InPhOE Technologies, Inc.
Santa Clara, California
September 2024

## Introduction

Among standard semiconductor photodetectors, the Avalanche Photodiode (APD) stands out in that it provides internal gain. As a result, APDs are the most sensitive solid state photodetectors on the market. Up to about 8dB of higher sensitivity has been shown at 10Gbps over PIN diodes operating at 1550nm wavelength [1]. Some APDs (Geiger mode) detect single photons [2]. Avalanche multiplication can amplify a small initial photocurrent by any factor up to a few hundred. Commercially available silicon APDs are responsive to wavelengths as long as 1100 nm, while products built on InP that use InGaAs for detection, operate in the near infrared region between 1000 - 1650 nm. This range is what is commonly known as the fiber optic communications range. Silicon-Germanium APDs can also be used for communications range wavelength detection, though they are not as commonly available yet. Long wavelength APDs have applications in telecom and datacom, passive optical networks (PON), and LIDAR among others.

The first APDs built in 1950's and 60's were simply PIN photodiodes (Figure 1) that were biased at a voltage close to breakdown of the junction. These devices provided gain, but with a high excess noise factor. They operated at a relatively high bias voltage and their reliability was questionable. Significant progress has been made in the design and fabrication of APDs since then. Modern APDs have high reliability and very low noise. Common 10Gbps InGaAs APDs operate at bias voltages ranging from 25V to 50V. These voltages are routinely available from inexpensive DC/DC converter chips. Feedback in the bias network provides constant APD gain over temperature.

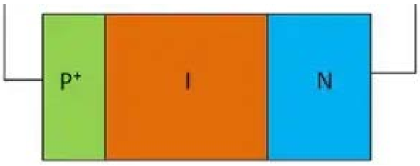

**Figure 1.** Early avalanche photodiodes were simply PIN diodes biased near breakdown.

## Noise

The onset of avalanche is a random process with its associated broad gain distribution over time for charge carriers. The broad distribution is caused by both the uncertainty in avalanche onset, and by long avalanche chains that randomly form. This broad distribution translates into increased shot noise in the circuit. The noise can be reduced by narrowing the gain distribution width through a combination of the following measures: Using one-carrier type multiplication (only electrons) significantly narrows the gain distribution. Other parameters that reduce the gain distribution are a thinner multiplication region, and a lower operating bias. The development of SAM devices (Separate Absorption and Multiplication) was a major step in reducing the excess noise of the APD. These devices suppressed hole multiplication, and confined the avalanche to a thin layer outside of the absorption region. This combination reduced the randomness of the avalanche and lowered the associated noise (Figure 2). In addition, the multiplication region is made of a higher bandgap semiconductor that reduces the dark current.

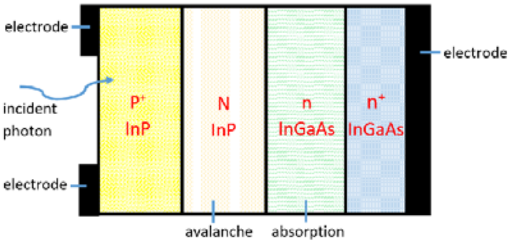

**Figure 2.** Separate Absorption and Multiplication (SAM) APDs have lower noise and lower dark current.

## Impact Ionization Coefficients

The impact ionization coefficients for electrons and holes are referred to as (α) and (β) respectively. They measure the average expected impact ionizations per unit length. Typically, α is either larger or almost equal to β. Their ratio ($k = \beta/\alpha$) is an important predictor of excess noise, and low values close to zero are desirable. The excess noise $F_e$ of the APD may be estimated by the following simple expression for $k<1$ [3]:

$$F_e = kM + (1 - k)[2 - 1/M]$$

Where $M$ is the multiplication factor. For small $k$ and low $M$: *Fe ~ 1 which is ideal*. For high k of close to unity: *Fe ~ M* which is quite high. $k$ is a characteristic of the multiplication material though its value is also a function of the electric field and temperature. Very low excess noise APDs may be fabricated using antimonide alloys as the multiplication layer. Some representative $k$ values as shown in the table below.

| Material | α (cm$^{-1}$) | β (cm$^{-1}$) | k |
|---|---|---|---|
| Si | 20,000 | 3,500 | 0.17 |
| GaAs | 12,000 | 9,000 | 0.75 |
| InP | 3000 | 1000 | 3.0 |
| AlInAs | 1000 | 80 | 0.08 |
| AlAsSb | 1000 | 0.6 | 0.0006 |

**Table 1.** Impact ionization coefficients are field and temperature dependent [4]. The values in this table are for an electric field of approximately 300 kV/cm at room temperature. This value is close to the breakdown field of the semiconductors we are considering (~ 500 kV/cm). The last two rows of the table are materials lattice matched to InP.

## Responsivity and Bias

Higher responsivity in general requires a thicker absorption region (I layer of the PIN diode). In early APDs, any extra thickness required a proportionally higher voltage to maintain the internal field close to breakdown. Newer APDs employ a “charge” layer that localizes the high breakdown field to the avalanche region. These devices are known as SACM (Separate Absorption, Charge and Multiplication) devices. A high field is not needed in the absorption region, and thus responsivity is decoupled from the bias voltage this way.

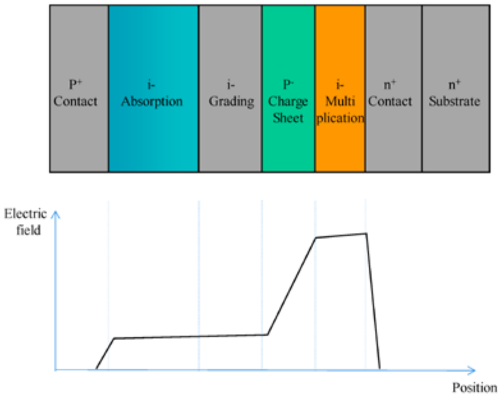

**Figure 3.** Lower bias voltages are achieved in Separate Absorption, Charge and Multiplication (SACM) APDs, and responsivity is decoupled from bias voltage. The corresponding electric field distribution shown in the lower image, is at its maximum in the multiplication layer.

Among the absorption materials commonly used (Si, Ge, InP, InGas), InGaAs offers the highest responsivity for any thickness of the absorption region. The absorption coefficient for InGaAs is higher than either silicon or germanium over standard communication wavelengths as shown in Figure 4.

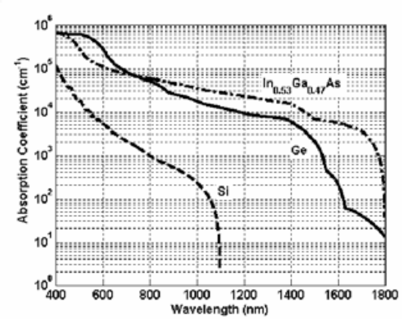

**Figure 4.** The absorption coefficient of InGaAs is favorable over a broad range of wavelengths. [5]

## Speed

The speed of the photodiode is limited by: (1) Carrier transit time in the absorption region, (2) Intrinsic and parasitic capacitances of the device, and (3) Avalanche delay

The optimization of the first two factors is similar to optimizing the high-speed performance of any PIN diode. Reducing transit time increases intrinsic capacitance and vice versa. There is a happy medium where neither one is dominant.

Avalanche delay on the other hand is independent of the other two and used to be a major data rate limitation in early APDs. The delay became controllable with the advent of SAM and SACM devices. Avalanche delay spreads a pulse by two mechanisms: the uncertainty of avalanche onset, and the pulse broadening due to the multiplication of both electrons and holes. Referring to Figure 3, if the multiplication region is thin, and the *k* factor for the multiplication material is zero, no broadening of a pulse due to avalanche is expected. The pulse stops when all the holes in the absorption region are collected. Faster electrons including the ones generated by impact ionization will be swept out before all the holes are collected. For higher values of k, trailing edge of the pulse will be extended in order to collect the multiplied holes. This avalanche delay will be significant in slowing down the device.

As we can see, high speed APDs employ relatively thin multiplication layers to minimize avalanche delay. Here the tradeoff is between avalanche gain that requires a thicker multiplication layer and speed that requires a thinner layer to limit the avalanche uncertainty. To increase the gain somewhat without sacrificing the speed, it is possible to employ multiple thin gain layers.

A material growth challenge with using thinner layers is that they are more susceptible to dopant penetration into the adjacent absorption and multiplication regions during epitaxial growth.

## Device Structure and Fabrication

### Diffusion vs Mesa

At present, two main types of device isolation techniques are used in avalanche photodiode fabrication: Zn diffusion, which allows the structure to remain planar, and mesa etch which is inherently a nonplanar structure. In the planar structures, the epitaxial layers are typically deposited on a doped conductive substrate that forms the bottom electrode, and the top contact layer is formed by a Zn diffusion process as shown in Figure (5).

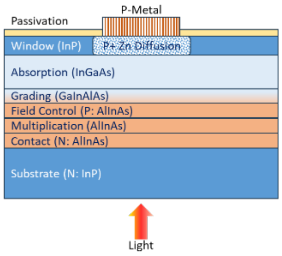

**Figure 5.** The structure of a backside illuminated Zn-diffused APD (SACM).

In the mesa structures, there is typically no diffusion process, and the periphery of each device is defined by mesa isolation (Figure 6).

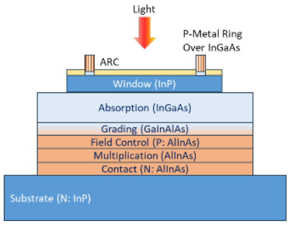

**Figure 6.** The structure of a frontside illuminated mesa type APD (SACM).

The diffusion process continues to have some issues with uniformity and stability, particularly in large arrays, while the mesa structure is more repeatable over the entire wafer. On the other hand, the diffusion process gives a distinctly lower dark current.

The extra dark current of the mesa-type APD is mainly due to surface leakage of the etched mesa. Proper treatment and passivation of the surface, limits the dark current to tens of nA while the planar structure typically achieves dark currents close to 1nA. Of course, the dark currents of both devices types are low enough for all telecom and datacom applications, and any noise generated by the dark current of either type is negligible.

### Top vs Bottom Illumination

The other major differentiator of APDs is the side of the device that is illuminated. Top illuminated devices are easier to assemble and work with, while bottom illuminated devices need to be flip chip mounted and they are not easy to test in wafer form (Figures 5 and 6).

On the other hand, bottom illuminated devices can collect more light and can implement double pass absorption by reflection from the top surface for higher responsivity. The optical aperture of the bottom illuminated device may be made larger and even lensed for easier optical coupling. The larger bottom aperture does not directly increase the capacitance of the device, while for top illuminated devices the capacitance scales with aperture size.

## Advanced Concepts

impact-ionization engineering or $I^2E$ has been used to achieve high APD gain, and wide dynamic range, while minimizing excess multiplication noise. This is typically done by implementing multi-gain-stage amplification that prevents the formation of impact ionization chains and thereby forces the gain distribution of the APD to be narrow [6]. Multi-gain stages can be formed in AlInAs for example, by growing successive doped and undoped homojunction layers that act as cascaded charge control and multiplication regions. The excess noise for these devices is typically much lower than noise generated by the same gain in a single multiplication layer.

Another advanced concept that has not yet gained widespread commercialization is the non-planar APD. Nonplanar structures that are typically formed by ion implantation in silicon APDs, can confine the high electric field regions inside the device and prevent their extension to the edges of the device where they can cause high dark current [7].

## Conclusion

With recent advances in APD design and fabrication these devices have become highly robust and reliable and their prices have fallen to a level that they can easily replace standard PIN diodes in many fiber optic applications. Their need for higher bias levels can easily be met by readily available DC to DC converters that are integrated on PC boards.

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