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Study of avalanche statistics in very low noise AlGaAsSb APDs using a multi-channel analyzer

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ABSTRACT

The usefulness of avalanche photodiodes (APDs) resides in their ability to produce internal gain via impact ionization without generating excessive noise. This process is stochastic and the gain values fluctuate around a mean value, giving rise to the so-called excess noise. In this work, we evaluate the gain fluctuations in APDs using a multi-channel analyzer (MCA). Two $Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ APDs, one *p-i-n* and one *n-i-p* were used. Illuminated with a pulsed light source, the APDs were connected to a charge-sensitive amplifier, counting the number of charges created by each avalanche event initiated by the light pulse. The signal was subsequently sent to an MCA, recording the gain values and outputting a gain spectrum. Both APDs were investigated for mean gains up to ~ 9. For a given mean gain, the gain distribution for the *n-i-p* diode was found to be significantly broader than for the *p-i-n* diode, as expected from the excess noise values previously measured in those devices. The coefficient of variance (*CoV*), defined as the ratio of standard deviation to mean value of the gain peaks, was found to be low for the *p-i-n* APD, consistent with the low excess noise values in this material. For higher mean gain values, the *CoV* of the *n-i-p* APD gave higher values than for the *p-i-n* APD, again corroborating the conventional excess noise measurements.

Keywords: Avalanche Photodiodes, avalanche gain, excess noise, multi-channel analyzer

1. INTRODUCTION

Avalanche photodiodes (APDs) are widely used in applications where detection of very weak light signals is required. APDs make use of the impact ionization process to create internal gain, called avalanche gain, *M*. For each impact ionization event, the number of electron-hole pairs created fluctuates around a mean value. The fluctuations give rise to avalanche noise (typically characterized by excess noise factors, *F*) and degrade the signal-to-noise ratio. Experimental methods for avalanche noise usually involve measurements of the noise power within the APD with and without avalanche gain. In this work, we present a direct method of experimentally obtaining the fluctuations of the avalanche gain in thin $Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ (lattice-matched to InP) APDs, by utilizing a multi-channel analyzer (MCA).

2. DEVICE STRUCTURES AND CHARACTERIZATION

2.1 Device structures

The study was carried out using two AlGaAsSb homojunction APDs grown on InP substrates by Molecular Beam Epitaxy, with nominal *i*-region (avalanche region) width of 200 nm. One of them has a *p-i-n* diode structure and the other has a *n-i-p* diode structure. The details of the layer structure are given in Figure 1 (left). The diodes were fabricated into mesa structures, using wet chemical etching. Ti/Au top contacts and bottom grid contacts were deposited by thermal evaporation. To prevent light injection onto the sides of the mesa devices, a metal mask was deposited on top of the samples. The final aspect of the devices is shown in Figure 1 (right).

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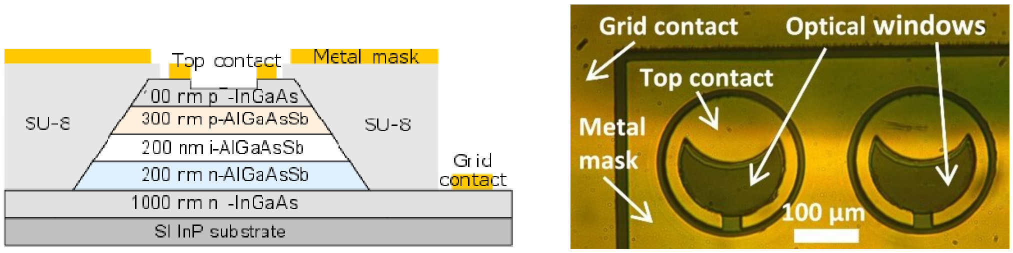

Figure 1. (Left) Schematic of the *p-i-n* device used. (Right) Top view of the fabricated diodes, showing the metal contacts, metal mask, and optical windows.

2.2 Dark current

Characterization of the devices started with dark current measurements as a function of the reverse bias voltage. The *I-V* curves of the *p-i-n* and *n-i-p* diodes are presented in Figure 2. Both APDs show low dark current values and a sharp breakdown at ~ 15.5 V.

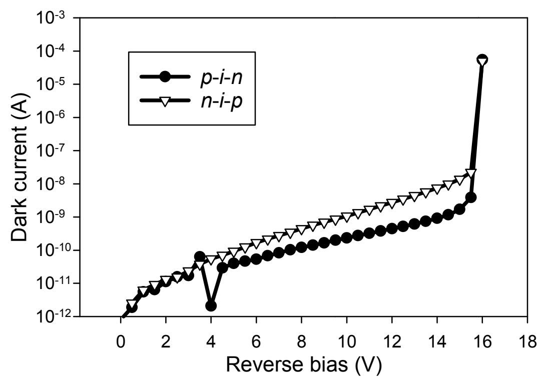

Figure 2. Dark current of the *p-i-n* and *n-i-p* diodes.

2.3 Avalanche gain

The avalanche gain characteristics $M(V)$ of both APDs under pure injection conditions (pure electron injection for the *p-i-n* and pure hole injection for the *n-i-p* diode) are shown in Figure 3.

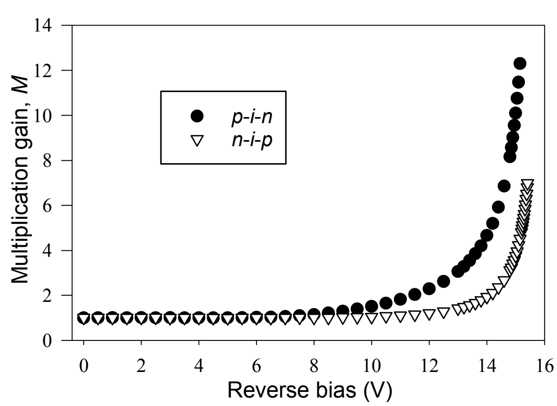

Figure 3. Avalanche gain versus reverse bias voltage for the *p-i-n* diode (for pure electron injection) and the *n-i-p* diode (for pure hole injection). Data adapted from [1].

For higher reverse bias voltage, the *p-i-n* APD gain is higher than the *n-i-p* at a given voltage, illustrating the dissimilar ionization coefficients for the electrons and holes, as discussed in [1].

2.4 Excess noise factors

The fluctuations of M from one avalanche event to the other gives rise to an extra noise contribution from the APD, the so-called excess noise. This excess noise is commonly quantified via the excess noise factor, F. F is deducted from the ratio of the shot noise of an APD and the noise of an ideal, non-avalanching photodiode. $F(M)$ characteristics are shown in Figure 4 [1]. The results showed much higher F values for the *n-i-p* diode than for the *p-i-n* diode of same thickness. This is due to a much higher impact ionization coefficient for the electrons than for the holes. The excess noise factor can also be defined as:

$$F = \frac{\langle M^2 \rangle}{\langle M \rangle^2},$$

where <M> denotes the average values of M. From this expression, it is clear that higher excess noise in the *n-i-p* APD will translate into more fluctuations in the M values from one impact ionization event to the other.

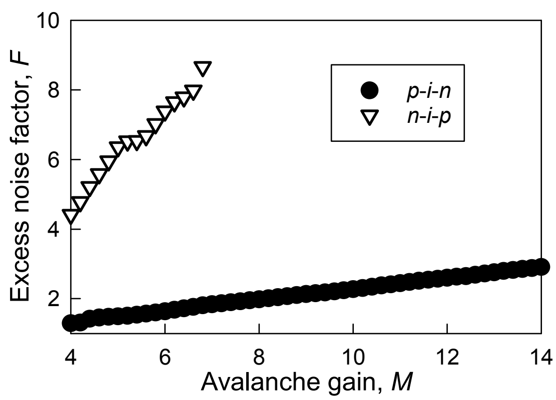

Figure 4. Excess noise factor versus avalanche gain for the *p-i-n* diode (for pure electron injection) and the *n-i-p* diode (for pure hole injection). Adapted from [1].

3. EXPERIMENTAL METHOD

Using light pulses from an LED with emission wavelength of 420 nm, pure electron (hole) injection was achieved in the *p-i-n* (*n-i-p*) APD, which was reverse-biased. APD current pulses due to light absorption were amplified by a charge-sensitive preamplifier, giving a voltage pulse V_{out} with amplitude proportional to the number of created charges, Q, via a feedback capacitor, C_f. The signal was subsequently sent to a shaping amplifier. For a given reverse bias, an MCA recorded the total number of charges produced in the APD, yielding a histogram of M. The block diagram of the setup is presented in Figure 5.

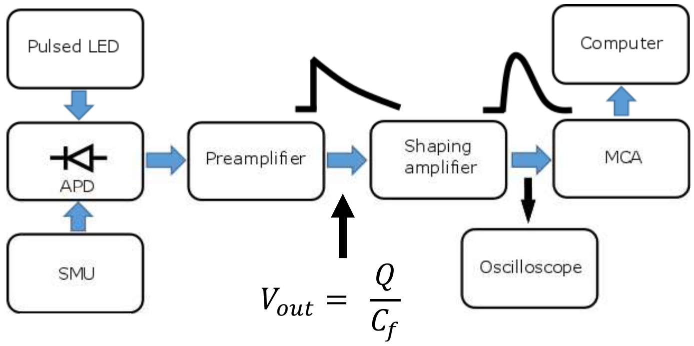

Figure 5. Schematic of the setup used to record the gain distribution spectra.

4. RESULTS AND DISCUSSIONS

The gain spectra obtained by this method are presented in Figure 6.

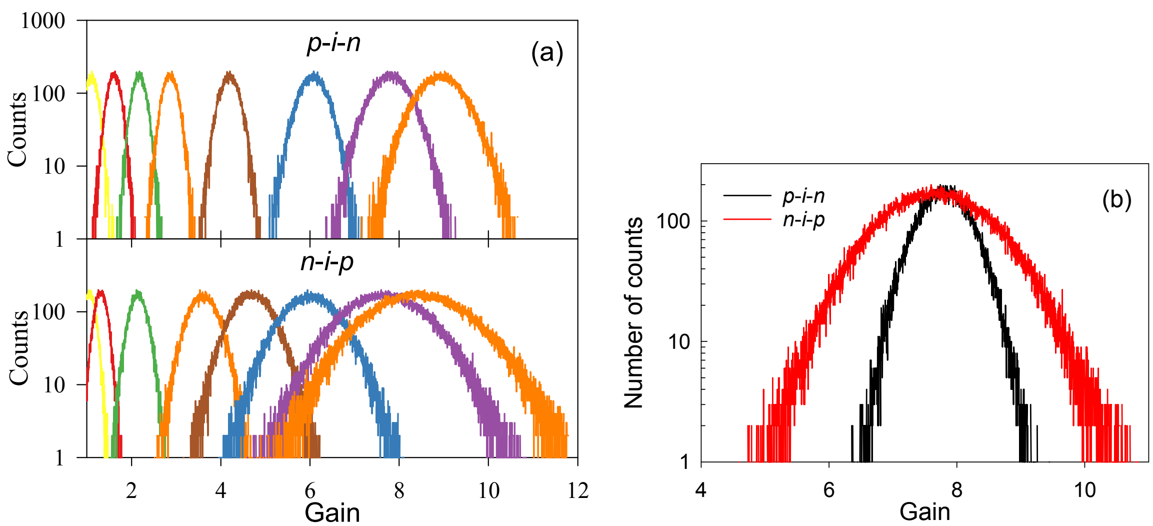

Figure 6. (a) Gain distribution spectra for several bias voltages, for (top) the *p-i-n* diode and (bottom) the *n-i-p* diode. (b) *p-i-n* (black) and *n-i-p* (red) gain distribution for a same mean gain of ~ 8.

For each reverse bias voltage, the gain spectrum shows a Gaussian-like distribution of M around a mean value $\langle M \rangle$, with a well-defined standard deviation. Spectra for mean gains up to ~ 9 have been recorded. At a similar gain value, the gain distribution peak is significantly broader in the *n-i-p* APD than in the *p-i-n* APD. Figure 6 (b) shows that for $\langle M \rangle \sim 8$, the *p-i-n* diode's gain spreads from approximately 6.3 to 9.3, whereas the *n-i-p* diode's gain spreads from 4.7 to 10.8. This is consistent with the $F(M)$ characteristics in Figure 4. Gaussian peak fittings to the data in Figure 6 (a) yield a coefficient of variation (CoV) of the distribution, defined as the ratio of standard deviation to mean. The values of CoV versus avalanche gain are plotted in Figure 7.

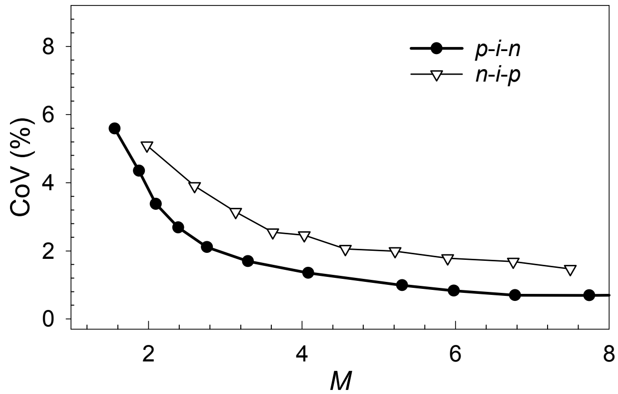

Figure 7. *CoV* values the *p-i-n* diode (closed symbols) and the *n-i-p* diode (open symbols).

The *CoV* values are small (between 0.7 and 6%), consistent with the very low excess noise factors of AlGaAsSb APDs reported in [1]. For $M > 3$, the *CoV* values are generally lower in the *p-i-n* APDs (between 0.7 and 1.7%) than in the *n-i-p* APD (1.5-2.5%), again consistent with the reported comparison of excess noise factors obtained through conventional measurement method.

5. CONCLUSIONS

We demonstrated an experimental method to visualize the fluctuations in the avalanche gain of APDs using an MCA. The observed gain spectra show a broadening with increased reverse bias, indicating increased fluctuation of the values of individual gain M around a mean gain $\langle M \rangle$. This broadening has been found to be notably larger in the *n-i-p* APD than in the *p-i-n* APD, corroborating previous excess noise measurements.

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