AlInAsSb on GaSb avalanche photodiodes for eSWIR detection

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***Abstract*—The ionization coefficients in $Al_{0.7}In_{0.3}AsSb$ lattice matched to GaSb have been systematically measured over a wide range of avalanching widths. When combined with $Al_{0.3}In_{0.7}AsSb$ as an absorber, we can show detection up to 2 µm at room temperature with low excess noise. Such avalanche photodiodes are very promising for extended short-wave infrared (eSWIR) applications such as LiDAR.**

Keywords—Avalanche Photodiode (APD), impact ionization, AlInAsSb, excess noise, eSWIR

I. INTRODUCTION

In photon-starved applications, avalanche photodiodes (APDs) are often used due to their exceptional sensitivity and signal-to-noise ratio (SNR) performance. For some gas sensing applications, the widely used InGaAs is insufficient, as its wavelength detection does not extend beyond 1650 nm. HgCdTe can cover this spectral region, but it requires cooling to reduce the dark currents, which adds complexity and cost to the sensing system [1]. In this presentation we report on an alternative quaternary digital alloy system $Al_xIn_{1-x}AsSb$ which delivers a large ionization coefficient ratio at large Al compositions and can detect up to 2000 nm at low Al compositions, thereby allowing the development of an extended short wavelength infrared (eSWIR) APD capable of room temperature operation.

Previous work on the AlInAsSb alloy system for APDs has been reported in several papers [2-5]. These have all been grown as digital alloys with avalanche multiplication thicknesses of between 500 nm to 1000 nm. To date, no systematic investigation into the effect of the width of the avalanching region on the multiplication (M) and excess noise (F) has been undertaken. This work presents such a systematic investigation on a series of p-i-n (PIN) diodes with varying i-region thicknesses from 100 nm to 1500 nm (as shown in Table 1), and also reports on a separate absorption, charge, and multiplication (SACM) structure as shown Fig. 1. The 1 µm Al = 0.3 composition absorber on the top ensures a high quantum efficiency up to 2 µm while the 500 nm Al=0.7 composition multiplication region ensures low excess noise and low voltage operation.

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From measurements of the electron and hole-initiated multiplication characteristics, we deduced the ionization coefficients of the $Al_xIn_{1-x}AsSb$ (x=0.7) over a wide electric field range. Excess noise measurements on these test structures show that the thickest 1500 nm i-region diode demonstrates the lowest F under pure electron injection with F<2 when M=20.

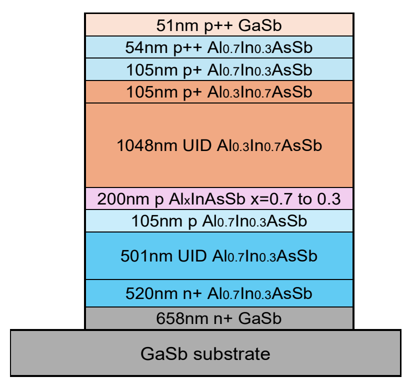

Figure 1 SACM APD layout

II. PRINCIPLE

APDs achieve internal gain through the impact ionization process. As carriers traverse the high electric field. Carriers gain sufficient energy to initiate impact ionization. Each ionization event generates an electron-hole pair, and both the original and newly generated carriers can continue to drift within the field, potentially triggering further ionization events. The hole ionization results in a large variance in the gain distribution giving rise to the excess noise factor (F). The F is related to the ratio of the hole to electron ionization coefficients and was shown by McIntyre [6] to be equation (1) for pure electron-initiated multiplication.

$$F(M) = kM + (1-k)(2-\frac{1}{M}) \quad (1)$$

III. EXPERIMENTS

The experiment was conducted using phase-sensitive detection (PSD), where a mechanical chopper modulated the incident illumination at a frequency of 180 Hz. The resulting photocurrent was then measured using a lock-in amplifier (LIA) to accurately obtain the photocurrent values. Electron-initiated multiplication (Me) was obtained by illuminating the top optical window while hole-initiated multiplication was obtained by illuminating the mesa side (M_h)

Wafer	PIN1	PIN2	PIN3	PIN4
i-region thickness(nm)	100	500	940	1500
Breakdown Voltage(V)	8.5	25	38	61

Table 1 PIN diodes i-region thickness and breakdown voltage

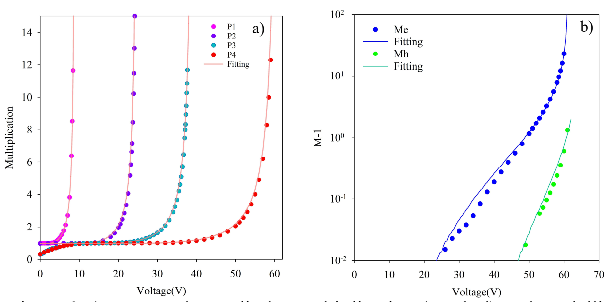

Figure 2 a) measured PIN diodes multiplication (symbol) and modelling (line). b) PIN4 M_e, M_h results and fittings

Table 1 demonstrates the i-region thickness and breakdown voltages of devices P1, P2, P3, and P4 respectively. These gain results in Fig. 2a enable the determination of ionization coefficients. The modelling fitting in Fig. 2a using published ionization coefficients [7] gives very good agreement, which demonstrates a large α/β ratio across a wide electric field range, spanning from 140 kV/cm to 850 kV/cm. Fig. 2b illustrates the pure electron-initiated ionization multiplication (M_e) and side injection multiplication (M_h) with their fittings on P4. The side injection technique employs a 450 nm laser illumination on the floor of the n+ cladding layer which will result a mixed carriers injection. The pure hole injection gain could only be even lower. The significant difference of M-1 indicates a large α/β ratio of this material system.

Fig. 3 illustrates the spectrum-response measured across a wavelength range from 1200 nm to 2200 nm using a monochromator. Due to the narrow bandgap of the $Al_{0.3}In_{0.7}AsSb$ absorption layer, the absorption remains high until approximately 1900 nm, after which it begins to decrease significantly. At a bias voltage of 18 V, the device has just fully punched-through. At 38 V, which approaches the breakdown voltage, the response maintains high at a wavelength of 2 µm, demonstrating a large internal gain.

IV. CONCLUSION

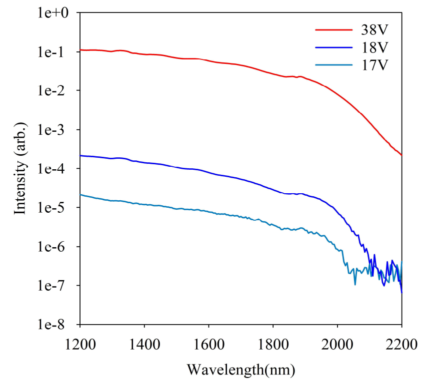

Figure 3 SACM APD spectrum-response

The measured M_e agrees well with the ionization coefficients previously reported in the literature. The observed M_h is however lower than the expected M_h. The measured F decreases with increasing intrinsic layer thickness, suggesting that the α/β ratio increases as the electric field decreases.

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