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$Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ avalanche photodiodes with high immunity to temperature fluctuation

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ABSTRACT

Avalanche gain and breakdown voltage in most wide bandgap semiconductor materials are dependent on temperature and most instruments utilizing APDs rely on temperature stabilization or voltage compensation circuitry to maintain a constant avalanche gain. The complexity in operation circuitry can be reduced by incorporating material with inherently superior temperature stability in its avalanche gain and breakdown voltage. In state of the art APDs, the temperature dependence of avalanche breakdown voltage is quantified by the temperature coefficient of avalanche breakdown, C_{bd}. We report on the temporal and temperature stability of avalanche gain and breakdown voltage of 100 nm thick avalanche layers of $Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ (AlGaAsSb). The C_{bd} (1.60 mV/K) is smaller compared to state of art InP and InAlAs APDs for similar avalanche layer thickness. The temporal stability of avalanche gain for the AlGaAsSb APD was also evaluated in temperature ranges of 294 K to 353 K. The APD was biased at room temperature gain of 10 and maximum fluctuation of ±0.7% was recorded at 294 K which increases to ±1.33% when the temperature was increased to 353K. The promising temperature stability of gain indicates the potential of AlGaAsSb lattice matched to InP in achieving higher tolerance to temperature fluctuations and reduction of the operational complexity of circuitry. The dark currents are robust and do not show significant thermal degradation after gain measurements at elevated temperatures.

Keywords: Avalanche gain, breakdown, alloy scattering, Photodiodes

1. INTRODUCTION

Avalanche photodiodes (APDs) are sensitive light sensors capable of converting extremely weak light to strong electrical signal through an inherent process called avalanche gain. The avalanche gain increases rapidly as the reverse bias approaches the breakdown voltage. The avalanche gain and breakdown voltage in most wide bandgap semiconductors are strongly dependent on temperature. The temperature coefficient of avalanche breakdown ($C_{bd} = dV/dT$, expressed in mV/K) is an important performance metric and APDs with small C_{bd} are preferred. InP with bandgap of 1.46 eV at 294 K is the most common III-V material for APDs owing to its compatibility with InGaAs absorber layer providing detection at low loss telecom window of 1550 nm. For a 130 nm thick InP layer, a C_{bd} of 6 mV/K has been recorded. Recently InAlAs has been proposed as replacement for InP owing to its reduced C_{bd} (2.5 mV/K for 100 nm thick avalanche layer)[1] and an even wider bandgap. The wider bandgap values are beneficial in mitigating the band-to-band tunneling currents for high electric field values[2]. In addition to wide bandgap and reduced C_{bd} value[3], InAlAs avalanche layers also offer reduced avalanche excess noise compared to InP[1].

Recently a wider bandgap material, AlGaAsSb (1.59 eV at 294 K) lattice matched to InP substrate has been proposed and it has demonstrated the smallest C_{bd} value (in the range of 0.86 – 1.08 mV/K) without the signs of excessive band-to-band tunneling[3]. These quaternary layers have also demonstrated reduced avalanche excess noise compared to InP and InAlAs[4] APDs demonstrating their potential to replace these APDs. AlInAsSb APDs lattice matched to GaSb substrates have been proposed with promising low noise[5] and temporal stability of avalanche gain[6]. Quaternary layers of AlGaAsSb have been reported elsewhere[7,8] however these layers are lattice matched to GaSb substrates with narrower bandgaps (0.7 – 1.2 eV), are several microns thick avalanche layers[9] and exhibit C_{bd} on the order of 30 mV/K. In this work, we report on the temperature dependence of avalanche breakdown voltage and temporal fluctuations of avalanche gain of AlGaAsSb APDs lattice matched to InP substrates. We record the temperature dependence of avalanche breakdown voltage in temperature ranges of 294 K – 353 K. The temporal stability of avalanche gain is recorded at elevated temperatures up to 353 K and a study on the robustness of dark currents is conducted to ascertain possible influence of thermal degradation.

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2. DEVICE FABRICATION AND EXPERIMENTAL DETAILS

Mesa avalanche photodiodes were processed on wafer layer structure shown in Fig.1. The layer structure is composed of a 100 nm thick un-doped AlGaAsSb layer sandwiched between oppositely doped quaternary layers where Te and Be are used as *n*- and *p*-type dopants respectively. The layers are grown on and lattice matched to InP substrate through Molecular Beam Epitaxy (MBE). The mesa APDs are processed through standard UV-Photolithography and wet chemical etching. Citric acid hydrochloric acid solutions[10] diluted with hydrogen peroxide are used to etch the InGaAs contact layers and quaternary AlGaAsSb layers respectively [ref]. Ti/Au layers (20/200 nm thick) are used for metallization of the diodes. Negative resist SU-8 is used to preserve the mesa sidewalls. The snapshot of processed APDs is shown in Fig.1 (b).

(a)

100 nm *p* - $In_{0.47}Ga_{0.53}As$, 5 x $10^{18} cm^{-3}$
300 nm *p* - $Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$, 2 x $10^{18} cm^{-3}$
100 nm *i* - $Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$
100 nm *n* - $Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$, 2 x $10^{18} cm^{-3}$
1 µm *n* - $In_{0.47}Ga_{0.53}As$, 5 x $10^{18} cm^{-3}$
n- InP substrate

(b)

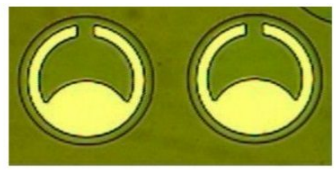

Figure 1 (a) Device layer structure and (b) top view of the D = 220 um mesa diodes characterized in this work.

Different sized mesa diodes were processed (420, 220, 120 and 70 µm diameters) where 220 µm mesas are selected for a majority of electrical and optical characterization. Standard current voltage (*I-V*) characterization was done to select APDs with well-defined breakdown voltages and low surface leakage currents for subsequent gain characterization. A He-Ne laser (633 nm) was used to illuminate the diodes where phase sensitive detection (PSD) technique was used to collect photocurrents from mesa diodes at a reference frequency of 180 Hz which was provided by a mechanical chopper externally modulating the laser light. The maximum fluctuations in laser beam power was recorded at ±0.5% by recording the photocurrent of a commercial Si photodiode (BPX-65). For gain measurements at elevated temperatures, the device under test (*DUT*) was placed on a copper plate which was heated through a variable current supply allowing the plate temperature to be increased up to 373 K. A LABVIEW program was used to collect the photocurrent in *DUT* as a function of time for temporal stability characterization at room and elevated temperatures.

3. RESULTS AND DISCUSSION

Fig. 2 shows the dark currents of 29 mesa APDs (220 µm) in reverse bias. The devices show a presence of surface leakage component prior to breakdown. However the breakdown voltages remain uniform across these devices. Out of these devices, 4 robust devices (blue lines in Fig. 2) are selected for subsequent gain characterization.

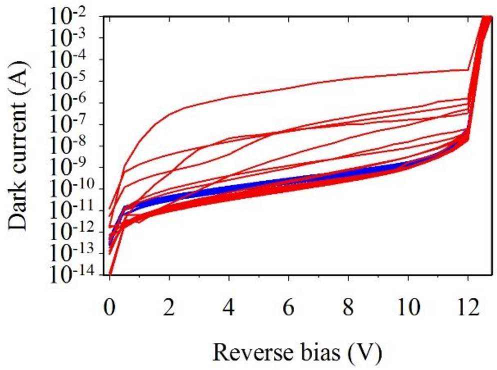

Figure 2. Dark currents of 29 APDs (D = 220 µm) recorded at room temperature. The blue lines show four selected APDs.

The dark current in Fig. 2 are not influenced by premature edge breakdown effects and this was confirmed by recording the photocurrents of two different size mesa diodes (220 um and 120 um) which yielded similar values. The four selected APDs are labelled APD-1 through 4.

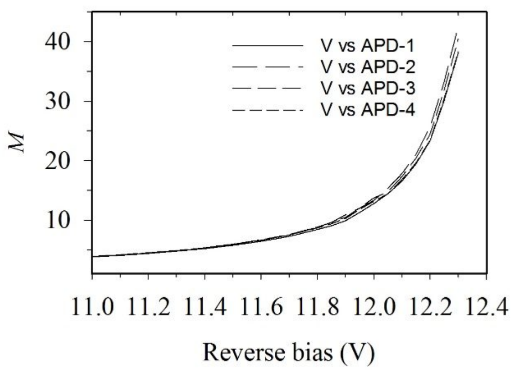

Figure 3. Avalanche gain versus reverse bias for the four selected APDs at room temperature.

Fig.3 shows the avalanche gain recorded with phase sensitive detection for APD-1 through 4. The avalanche gain shows uniformity for the selected APDs. As the reverse bias increases the avalanche gain increases owing to the increase in the impact ionization coefficients which increase with electric field. The gain rises abruptly as the reverse bias approaches the breakdown voltage. The breakdown voltage can be extracted by extrapolating the inverse of gain, $1/M$ to zero, i.e. avalanche gain of infinity. Such an approach gives accurate value of the breakdown voltage and repeating the extrapolation at different temperatures can yield the temperature coefficient of avalanche breakdown voltage.

Increase in the breakdown voltage as a function of temperature is shown in Fig. 4 for APD-1 through 4. The breakdown voltage increases with increase in temperature owing to increase in the lattice vibration (phonon scattering) which increases the mean free path between impact ionizing collisions hence reducing the impact ionization and avalanche gain. As the temperature increases the breakdown voltage increases. This phenomenon can be explained by increase in the phonon scattering at higher temperatures which impedes the ballistic transport of impact ionizing carriers. To offset this reduction of impact ionization, higher reverse bias is usually applied, hence increasing the breakdown voltage. The increase in the mean breakdown voltage for APD-1 through 4 with temperature is fitted by $V_{bd} = C_{bd}\, T + 12.36$ where mean C_{bd} = 1.60 mV/K.

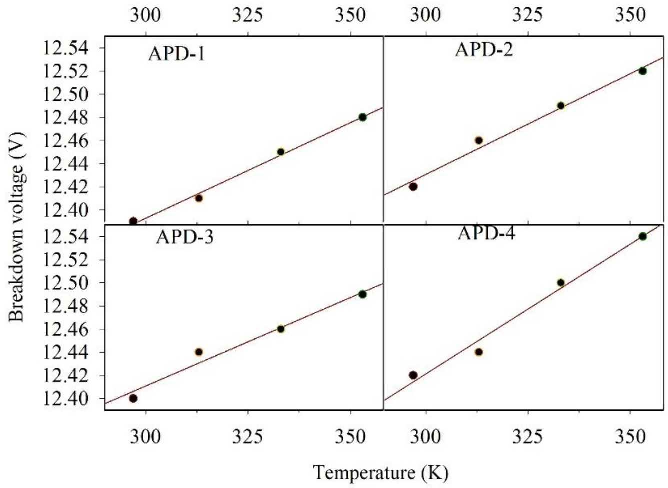

Figure 4. Breakdown voltage as a function of temperature for APD-1 through 4. Dots represent the breakdown voltage and solid lines shows linear fit to the data

This is smaller compared to wide bandgap III-V materials InP and InAlAs with comparable thicknesses. The temperature insensitivity of avalanche breakdown voltage for AlGaAsSb may be due to a combination of dominance of alloy scattering potential and reduced phonon scattering at high electric field values (~1000 kV/cm) for thin avalanche layers[11]. Fig. 5 shows the data for temporal stability of avalanche gain for the selected APDs. The data is represented as percentage fluctuations relative to mean gain at 11.9 V at corresponding temperatures. The percentage fluctuations are within ±1.1% for all devices over the temperature range of study except APD-1 which shows a maximum fluctuation of ±1.33% at 353 K. No trend of temporal drift in avalanche gain was observed.

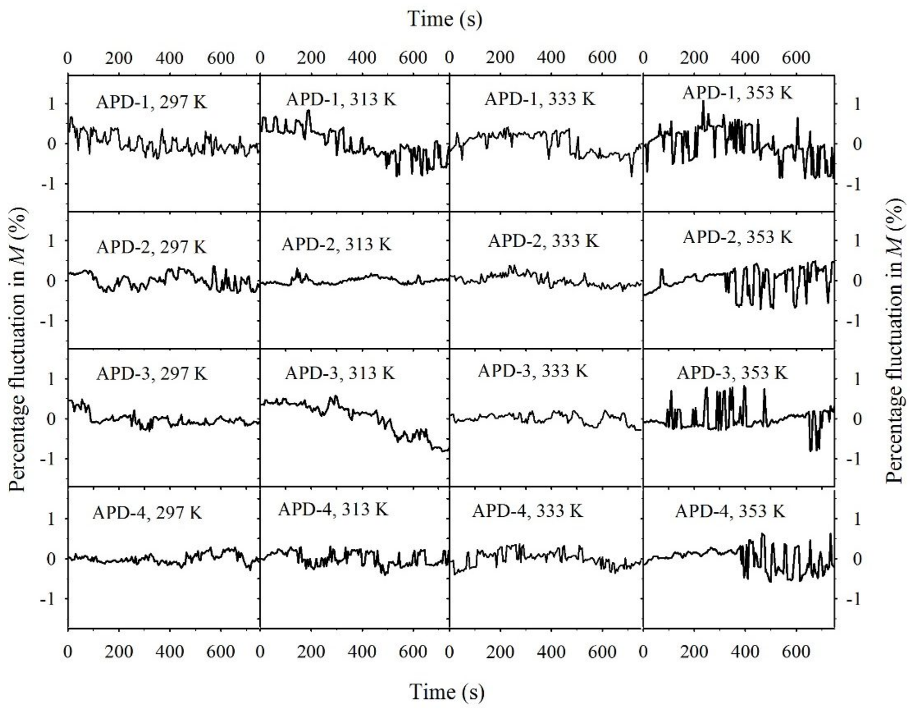

Figure 5. Fluctuations in *M* as function of time for 297, 313, 333 and 353 K with reference to mean gain at corresponding temperatures at reverse bias of 11.9 V.

To assess the influence of a possible thermal degradation, the dark currents of the selected APDs were recorded before and after the gain measurements at elevated temperatures. Fig. 6 shows that no significant thermal degradation is observed indicating the robustness of AlGaAsSb APDs.

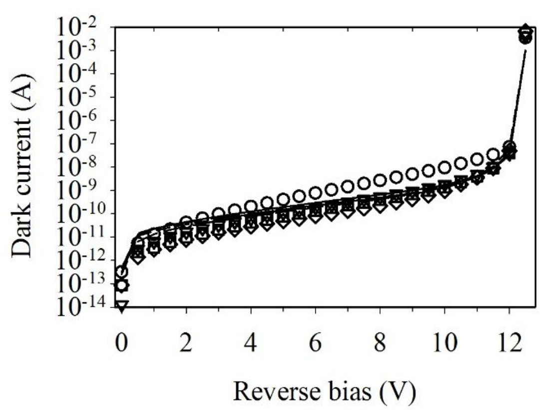

Figure 6. Dark currents for the four selected APDs before (solid lines) and after (symbols) gain measurements at elevated temperatures.

4. CONCLUSION

Temperature and temporal stability of avalanche breakdown and avalanche gain were investigated for AlGaAsSb APDs in the temperature range of 294 K to 353 K. The temperature coefficient of the avalanche breakdown was found to be the lowest among other III-V materials (1.60 mV/K). The APDs show a maximum fluctuation of ±0.5% when operated at a mean gain of $M = 10$ at 294 K for 12.5 minutes. Subsequent temporal stability measurements at 313, 333 and 353 K showed a maximum fluctuation in avalanche gain of ±1.33% at 353 K at 11.9 V reverse bias. No significant thermal degradation in dark current was observed. The results suggest that thin avalanche layers of AlGaAsSb can be used in APDs with higher temperature immunity to temperature fluctuations.

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