Temperature Dependence of Avalanche Breakdown in InP and InAlAs

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***Abstract*—Simple analytical expressions for temperature coefficients of breakdown voltage of avalanche photodiodes (APDs) utilizing InP or InAlAs are reported. The work is based on measurements of temperature dependence of avalanche breakdown voltage in a series of InP and InAlAs diodes at temperatures between 20 and 375 K. While avalanche breakdown voltage becomes more temperature sensitive with avalanche region thickness for both materials, the InAlAs diodes are less sensitive to temperature changes compared to InP diodes.**

***Index Terms*—Avalanche breakdown, avalanche photodiode (APD), impact ionization, InAlAs, InP, temperature dependence, tunnelling.**

I. Introduction

Avalanche multiplication is an important process in several types of semiconductor electronic devices. This avalanche multiplication is the result of the impact ionization process, which is temperature dependent via the phonon scattering mechanism. Avalanche multiplication limits the operating power of high electron mobility transistors, heterojunction bipolar transistors, and other power devices which generally operate above ambient temperatures. Avalanche photodiodes (APDs) and single-photon avalanche diodes (SPADs) are also operated over a wide temperature range. In particular, SPADs are often cooled to suppress the dark counts for photon-counting applications [1].

Telecommunication wavelengths InGaAs/InP separate absorption multiplication (SAM) APDs utilize InP as the avalanche medium in order to achieve low dark current and low noise [2]. These SAM APDs are usually specified to operate between −40 °C and 85 °C. The bias of the SAM APD is controlled to maintain the gain of the device despite temperature fluctuations. Knowledge of how avalanche breakdown voltage, V_{bd}, changes with temperature would thus be useful. InAlAs is considered as an alternative multiplication material because it is lattice matched to InP and has lower excess noise characteristics [3]. In addition there have been reports of weak temperature dependence of SAM APD breakdown voltage when InAlAs is used [4], [5]. It is therefore of interest to compare the avalanche breakdown temperature dependence of these two materials.

This paper reports expressions for breakdown voltage temperature dependence of two SAM APDs utilizing InP or InAlAs multiplication region. The expressions were obtained from results of avalanche breakdown voltage of a series of InP and InAlAs *p-i-n* diodes at temperatures between 20 and 375 K. Results of the tunneling current in InP diodes as a function of temperature are also included in this study.

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TABLE I
Summary of Diodes Studied in This Work

Material	Nominal w (μm)	RT V_{bd} (V)	$\Delta V_{bd}/\Delta T$ (mV/K)
InP	1.70	64.7	73
	0.80	36.4	35
	0.55	26.9	24
	0.25	15.9	11
	0.13	11.4	6.0
InAlAs	1.00	51.7	16
	0.50	32.8	8.7
	0.30	19.5	5.6
	0.20	15.6	4.1
	0.10	10.2	2.5

II. Experimental Details

The *p-i-n* diodes were grown by molecular beam epitaxy (MBE) and metal organic vapor phase epitaxy (MOVPE) on InP substrates. The wafers comprised of an InP or InAlAs buffer, a doped p^+ (n^+) layer, an undoped *i*-region, a doped n^+ (p^+) top layer, and a thin 30-nm InGaAs contact layer. Circular mesas with diameters of 50, 100, 200, and 400 μm with annular top contacts for optical access were fabricated using standard photolithography and wet chemical etching. The nominal values of the *i*-region thickness of the diodes are summarized in Table I. C-V measurements of these diodes showed that the doping in the cladding layers were high (10^{18} cm^{-3}) compared to the unintentional doping (10^{15} cm^{-3}) in the intrinsic layer. The two SAM APDs were similar in their structures, except for the material used in the multiplication region. The InP-based SAM APD has a 0.2-μm InP multiplication region while the InAlAs SAM APD has a 0.15-μm InAlAs multiplication region. Both SAM APDs have a 1.0-μm InGaAs absorber.

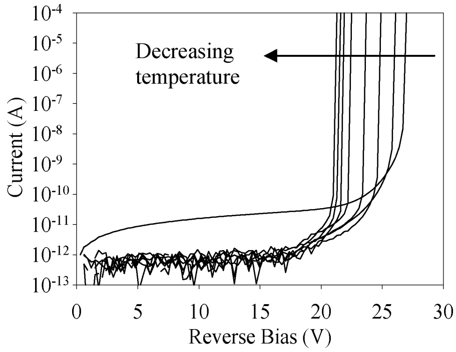

Fig. 1. Reverse dark current characteristics measured on a 200-μm diameter, $w = 0.55$ μm InP device at temperatures of 20, 50, 77, 100, 150, 200, 250, and 290 K.

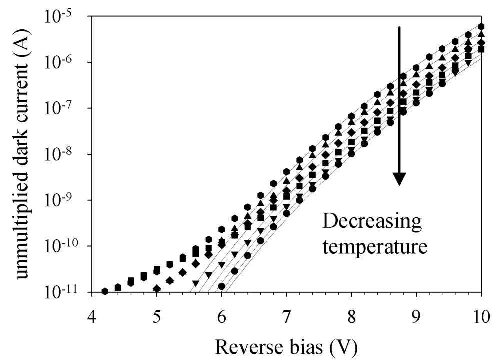

Fig. 2. Unmultiplied dark current (symbols) on the $w = 0.13$ μm InP diode (diameter $= 400$ μm) at temperatures of 20, 77, 150, 200, 250, and 290 K. Solid lines are the fitted tunnelling currents.

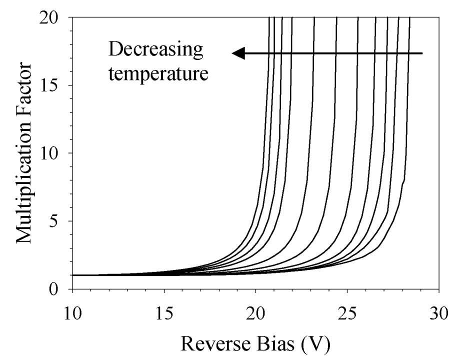

Fig. 3. Measured M(V) characteristics for the $w = 0.55$ μm InP p-*i*-*n* diode at temperatures of 20, 50, 77, 100, 150, 200, 250, 290, 325, 350, and 375 K.

Avalanche breakdown voltage was determined from photomultiplication measurements. For these measurements, carriers were created in the diodes by illuminating the top surface of the devices with 542-nm CW wavelength laser light. Multiplication factor versus reverse bias, $M(V)$, was given by the ratio of photocurrent to the injected primary photocurrent. The measured photocurrent was normalized for the bias-dependent collection efficiency by applying the correction used by [6]. For devices with high dark currents, phase-sensitive detection techniques were used in the measurement of photocurrent. This involved using a modulated optical signal and a lock-in amplifier to detect the electrical signal with the modulation frequency. The measurements were repeated on a number of devices for each wafer to ensure reproducibility. In addition, the incident laser power was varied to give photocurrents ranging from 100 nA to 10 μA to ensure that the multiplication was independent of laser power.

Photomultiplication measurements at and below room temperature were performed either by placing samples bonded onto TO-5 headers in a closed cycle liquid helium cryostat, which cools the headers down to 20 K, or by placing unbonded devices into a Janis low-temperature probe station, which cools samples down to 77 K. Measurements at higher than room temperature were performed by placing the devices on a heated stage.

Avalanche breakdown voltage was deduced from experimental $M(V)$ by fitting the Miller expression [7] $M(V) = 1/(1-(V/V_{bd})^c)$, where c is a dimensionless constant, to the data. In cases where the dark current breakdown was abrupt, breakdown voltage could also be determined from the dark current characteristics. The dark current breakdown voltage was defined as the voltage at a dark current of 100 μA. The values from the dark current and photomultiplication breakdown are indistinguishable.

III. Results

Fig. 1 shows reverse dark current characteristics of a 200-μm diameter InP $w = 0.55$ μm *p-i-n* diode from 20 to 290 K. Dark current breakdown appears abrupt at all temperatures. It should be noted that the dark currents at 290 K are not bulk but edge leakage. However the breakdown is a bulk mechanism as confirmed by photocurrent measurements. The breakdown voltage is also found to increase with temperature. These curves are typical of other InP and InAlAs diodes measured, with the exception of the InP $w = 0.13$ μm diode and the InAlAs $w = 0.1$ μm diode, where tunnelling currents are significant. Unmultiplied dark currents (measured dark current divided by the multiplication factor) of the InP $w = 0.13$ μm diode at 20 to 290 K are shown in Fig. 2. In our previous work [8], the InP diode tunnelling current at room temperature was fitted using a band-to-band tunnelling current expression [9]. σ_T, which is the constant that defines the shape of the tunnelling barrier, was found to be 1.15.

The band gap was adjusted as a function of temperature to give best fits to the measured current. The values of the band gap are 1.350, 1.365, 1.380, 1.393, 1.413, and 1.420 eV at 290, 250, 200, 150, 77, and 20 K, respectively. They are in agreement with the empirical equation for InP bandgap temperature dependence [10].

Fig. 3 shows $M(V)$ for the $w = 0.55$ μm InP diode from 20 to 375 K. Avalanche breakdown voltage was then deduced from $M(V)$. The $M(V)$ curves for the other InP and InAlAs diodes are similar. Increasing the temperature reduces the multiplication factor for a given reverse bias. This is expected as higher electric fields are needed to offset any carrier cooling due to increased phonon scattering at higher temperatures. Fig. 4 compares the breakdown voltage of a $w = 0.55$ μm InP diode and a $w = 0.50$ μm InAlAs diode. There is a linear dependence of breakdown voltage with temperature above 100 K and the temperature coefficient, $\Delta V_{bd}/\Delta T$, can be extracted for each diode. Fig. 5 plots $\Delta V_{bd}/\Delta T$ for the InP and InAlAs diodes with different avalanche region thickness. The temperature dependence

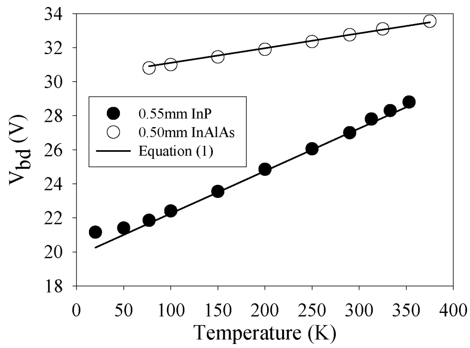

Fig. 4. Breakdown voltage of two InP and InAlAs diodes at different temperatures. Solid lines shows calculated breakdown voltage using (1).

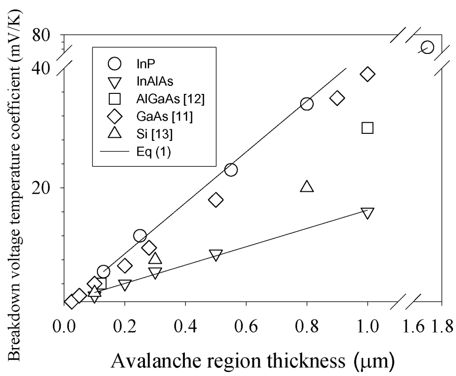

Fig. 5. Comparison of breakdown voltage temperature coefficient between InP (O) and InAlAs (▽) diodes of this work. Data of other semiconductor materials GaAs (◇) [10] and $Al_{0.8}Ga_{0.2}As$ (□) [12], Si (△) [13]) are also shown for comparison. Solid line shows the linear fit of (1).

of avalanche breakdown voltage increases with avalanche region thickness for both avalanche materials.

IV. Discussion

The increased temperature dependence with avalanche region thickness can be explained as follows [11]. Inelastic carrier scattering at the fields typical of the ionization process is dominated by phonon scattering. An increase in temperature increases the phonon population and hence the phonon scattering rate. Therefore ionization coefficients decrease with temperature. Phonon scattering is relatively less dominant at high fields as carriers can acquire the ionization threshold energy faster, scattering from fewer phonons along the way, and consequently the temperature dependence of the ionization coefficient is reduced.

Fig. 5 compares the breakdown voltage temperature coefficient for the InP and InAlAs diodes measured. For a given avalanche region thickness, InAlAs diodes have $\Delta V_{bd}/\Delta T$ smaller than those of InP by factors of two to three. This advantage, however, decreases with decreasing avalanche region thickness. $\Delta V_{bd}/\Delta T$ for other semiconductor materials such as GaAs [12], $Al_{0.8}Ga_{0.2}As$ [13], and Si [14] are also shown in Fig. 5 for comparison. $\Delta V_{bd}/\Delta T$ for InP is similar to GaAs. InAlAs is the most temperature-insensitive material of the group compared in Fig. 5. Alloy scattering reduces the sensitivity of the carrier ionization coefficient to temperature because it is temperature independent [15]; this may contribute

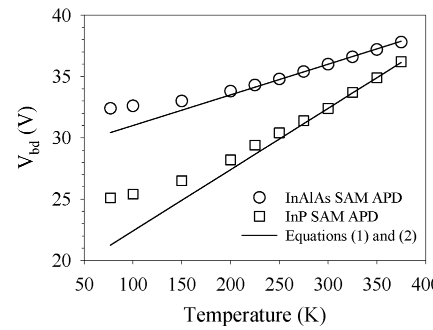

Fig. 6. V_{bd} as a function of temperature for a InP and InAlAs SAM APD. Solid line shows calculated breakdown voltage using (1) and (2).

to InAlAs insensitivity. However, how much more alloy scattering contributes to the temperature insensitivity is still not well understood.

Fig. 5 also suggests that there exists a linear dependence on the $\Delta V_{bd}/\Delta T$ with the avalanche region thickness for both InP and InAlAs diodes. Empirical fittings yield

$$\frac{\Delta V_{bd}}{\Delta T} = (42.5 \times w) + 0.5 \text{ for InP} \tag{1a}$$

$$\frac{\Delta V_{bd}}{\Delta T} = (15.3 \times w) + 1.0 \text{ for InAlAs.} \tag{1b}$$

The units for $\Delta V_{bd}/\Delta T$ and w are millivolts per Kelvin (mV/K) and microns (μm), respectively. These expressions are valid only for w between 0.1 and 1.7 μm. In addition, (1) assumes that the electric field in the multiplication region is uniform, as it is in our devices.

Osaka *et al.* [16] reported low-temperature impact ionization coefficients in InP. Fig. 1 of their work showed multiplication factor as a function of bias voltage. Although no avalanche region thickness was stated [16], this could be deduced from $M(V)$ at 293 K to be ~1.4 μm. The experimental $\Delta V_{bd}/\Delta T$ was thus ~62 mV/K, which compares well with 60 mV/K from (1a). There was insufficient details in [17] and [18] for comparison.

V. SAM APDs

Fig. 6 compares the measured V_{bd} of the InP and InAlAs SAM APDs with similar avalanche region and absorption region thickness at different temperatures. Dark current breakdown is sharp for these devices, and breakdown voltage is taken when the current reaches 100 μA. $\Delta V_{bd}/\Delta T$ for the InP SAM APD was ~ 46 mV/K, larger than the 23 mV/K of the InAlAs SAM APD. There have been reports in the literature concerning $\Delta V_{bd}/\Delta T$ for InP and InAlAs SAM APDs [4], [5], [19]–[22]. Ishimura *et al.* [19], Rouvie *et al.* [5], and Levine *et al.* [4] reported a $\Delta V_{bd}/\Delta T$ ~ 21, 25, and 15 mV/K for their respective InAlAs SAM APDs while Hyun and Park [20] showed $\Delta V_{bd}/\Delta T$ ~ 50 and 70 mV/K for two InP SAM APDs with different multiplication region thicknesses. Tarof *et al.* [21] and Ma *et al.* [22] also reported $\Delta V_{bd}/\Delta T$ of ~ 150 mV/K for InP SAM APDs with similar structures. These SAM APDs utilized InGaAs as the absorber region. There are also reports for InP and InAlAs SAM APDs using type II superlattice as the absorber region [23], [24]. Sidhu *et al.* [23] and Goh *et al.* [24] reported a

TABLE II
PARAMETERS USED IN CALCULATING THE THEORETICAL $\Delta V_{bd}/\Delta T$ FOR VARIOUS SAM APDs REPORTED IN THE LITERATURE. THE EXPERIMENTAL AND CALCULATED $\Delta V_{bd}/\Delta T$ ARE ALSO SHOWN

	Material	w_m (μm)	$w_{depletion}$ * (μm)	Experimental $\Delta V_{bd}/\Delta T$ (mV/K)	Calculated $\Delta V_{bd}/\Delta T$ (mV/K)
Levine *et al* [4]	InAlAs	0.13	~0.75	15	17
Rouvie *et al* [5]	InAlAs	0.2	1.4	25	28
Ishimura [19]	InAlAs	0.2	1.10	21	22
Goh *et al* [24]	InAlAs	1.0	2.7	40	44
Hyun and Park [20]	InP	0.15–0.40	1.60–1.90	50 – 70	73-83
Tarof *et al* [21]	InP	0.2 – 0.4	3.5 – 3.7	150	160
Ma *et al* [22]	InP	~0.5	3.5	~150	150
Sidhu *et al* [23]	InP	0.8	2.4	~100	104
This work	InP	0.2	1.2	46	54
This work	InAlAs	0.15	1.15	23	25

$\Delta V_{bd}/\Delta T \sim 100$ and 40 mV/K for a InP – Type II and InAlAs – Type II SAM APD, respectively.

The wide range of $\Delta V_{bd}/\Delta T$ values in the literature is due to the sensitivity of $\Delta V_{bd}/\Delta T$ to device structure. For example, SAM APDs with identical multiplication region thickness but different absorption region thickness would yield very different $\Delta V_{bd}/\Delta T$ because the voltage dropped across the absorption regions would be very different although the breakdown electric field in the avalanche regions would be identical (assuming no impact ionization occurs in the absorber region).

It has been shown in Fig. 4 that V_{bd} varies linearly with temperature in simple *p-i-n* structures. Therefore the breakdown electric field, $\Im_{bd}$, also varies linearly in a SAM APD, provided that no impact ionization occurs outside of the multiplication region. Since $\Im_{bd}$ depends on the multiplication region thickness, w_m, we can express $\Delta V_{bd}/\Delta T$ for any SAM APD structure as

$$\frac{\Delta V_{bd}}{\Delta T}(SAMAPD) = \frac{\Delta \Im_{bd}}{\Delta T} \times w_{depletion} \text{ or}$$
$$\frac{\Delta V_{bd}}{\Delta T}(SAMAPD) = \frac{\Delta V_{bd}}{\Delta T}(pin) \times \frac{w_{depletion}}{w_m} \quad (2)$$

where $(\Delta V_{bd}/\Delta T)\,(pin)$ is the breakdown voltage temperature coefficient for a *p-i-n* photodiode with an avalanche region thickness of w_m and $w_{\mathrm{depletion}}$ is the total depletion width of the SAM APD. Coupled with (1a) and (1b), we can calculate $\Delta V_{bd}/\Delta T$ for any SAM APD structure that utilize InP or InAlAs multiplication region, assuming that there is no impact ionization in the absorber and that the electric field is uniform in the multiplication region.

Using (1) and (2), $\Delta V_{bd}/\Delta T$'s were calculated and compared to the experimental values of [4], [5], [19]–[24] and this work, as shown in Table II. The parameters used to calculate $\Delta V_{bd}/\Delta T$ are also summarized in the same table. There is good agreement between the calculated and experimental $\Delta V_{bd}/\Delta T$ despite uncertainties in depletion layer thickness. It can also be seen that it is not critical as to what the material and thickness of the absorber is, as (2) has already factored the voltage drop across the absorber. Values calculated for the two SAM APDs used in this work are also plotted in Fig. 6. The calculated values agree with the data for temperatures above 150 K.

VI. CONCLUSION

The breakdown voltage temperature coefficient was investigated in two SAM APDs with InP and InAlAs avalanche material. Compared to the InP SAM APD, the InAlAs SAM APD V_{bd} was found to be approximately two times more temperature insensitive. This difference can be traced to InP and InAlAs *p-i-n* diodes measured at temperatures between 20 and 375 K. It has also shown that the temperature dependence of breakdown voltage reduces with decreasing avalanche region thickness. Simple analytical expressions were developed to calculate the breakdown voltage temperature coefficient for any InP- and InAlAs-based SAM APD. These were validated with reported work.

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