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AlAsSb avalanche photodiodes with a sub-mV/K temperature coefficient of breakdown voltage

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***Abstract*— The temperature dependence of dark current and avalanche gain were measured on AlAsSb p-i-n diodes with avalanche region widths of 80 and 230nm. Measurements at temperatures ranging from 77 to 295K showed that the dark current decreases rapidly with reducing temperature while avalanche gain exhibits a weak temperature dependence. No measurable band to band tunneling current was observed in the thinner diodes at an electric field of 1.07MV/cm, corresponding to a bias of 95% of the breakdown voltage. Temperature coefficients of breakdown voltage of 0.95 and 1.47mV/K were obtained from 80 and 230nm diodes respectively. These are significantly lower than a range of semiconductor materials with similar avalanche region widths. Our results demonstrated the potential of using thin AlAsSb avalanche regions to achieve low temperature coefficient of breakdown voltage without suffering from high band to band tunneling current.**

***Index Terms*—Avalanche breakdown, avalanche photodiodes, impact ionization, AlAsSb, temperature dependence of breakdown, tunneling.**

I. Introduction

Impact ionization has been exploited in avalanche photodiodes (APDs) and single photon avalanche diodes (SPADs) to achieve very high detection efficiency. The former provides higher sensitivity than p-i-n photodiodes in high bit rate optical communication systems while the latter has been used in quantum key distribution for secure communications [1]. It is well known that the impact ionization process is strongly dependent on temperature therefore a biasing circuit to maintain a constant gain is necessary to achieve reproducible performance. The temperature coefficient of breakdown voltage, $C_{bd} = \Delta V_{bd}/\Delta T$, where ΔV_{bd} and ΔT are the breakdown voltage and temperature differences, provides a measure of the temperature dependence of the avalanche multiplication.

In most wide bandgap semiconductors, such as Si, GaAs, $Al_xGa_{1-x}As$, $Ga_{0.52}In_{0.48}P$ (GaInP), InP and $InAl_{0.52}As_{0.48}$ (InAlAs), the avalanche multiplication reduces with increasing temperature. Massey et al. [2] reported C_{bd} varying from 20 to 1.53mV/K in Si diodes when the avalanche region width, *w*, reduces from 0.8 to 0.1μm while Groves et al. [3] observed that C_{bd} drops from 28 to 0.56mV/K in GaAs diodes as *w* reduces from 1 to 0.025μm. Ma et al. [4] and Groves et al. [5] both reported C_{bd} in $Al_xGa_{1-x}As$ diodes falls with decreasing *w* for all alloy compositions (x). The smallest change is reported for x=0.6, in which C_{bd} reduces from 20 to 3 mV/K when *w* reduces from 1 to 0.1μm. A small value of C_{bd} in thin *w* was also observed in GaInP [6] (3.68mV/K for *w* = 0.2μm), InP [7] (6mV/K for *w* = 0.1μm) and InAlAs [7, 8] (2.5mV/K for *w* = 0.13μm). These results suggest that a small C_{bd} can be obtained in materials with large bandgap and in diodes with thin *w*. The dependence of C_{bd} on *w* can be attributed to the reduced phonon scattering effects at high electric field in thin *w* leading to a weaker temperature dependence of avalanche gain (*M*).

Thin *w* is also known to improve APD performance by lowering the excess avalanche noise via the deadspace effects [9] and increasing the gain-bandwidth products, due to reduce the carrier transit time [10]. Although small values of C_{bd} can be obtained by using thin avalanche regions, the onset of the exponentially rising band to band tunneling current with electric field in thin *w* imposes a lower limit to practical avalanche region width. For instance Ong et al. [11] recently reported that to achieve the optimum sensitivity at a bit rate of 10Gb/s with a bit error rate of 10^{-12} the minimum values of *w* for telecom APDs are 180 and 150nm for InP and InAlAs avalanche regions respectively, before noise increases rapidly due to tunneling current . Therefore a material with low tunneling current should be used to fully exploit the benefit of using very thin *w* in APDs.

It is well known that the band to band tunneling is reduced in wide bandgap materials and in indirect bandgap materials. $AlAs_{0.56}Sb_{0.44}$ (AlAsSb), lattice matched to InP, has an indirect bandgap of 1.65eV, which is larger than the direct bandgaps of 1.34eV in InP and 1.45eV in InAlAs and therefore can be expected to exhibit a smaller C_{bd} as well as lower band to band tunneling current. In this work, we report for the first time the temperature dependence of current-voltage (I-V) characteristics and breakdown voltage in AlAsSb p-i-n APDs with thin *w* of 80 and 230nm.

II. Experimental Details And Results

Two p-i-n wafers were grown by molecular beam epitaxy (MBE) on semi-insulating InP substrates using Be and Si as the

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p^+ and n^+ type dopants respectively. The nominal layer details are summarized in Table I. The first wafer, PIN1, has an avalanche region of w = 100nm while the second wafer, PIN2, has a thicker w of 250nm. Circular mesa diodes with diameters, D of 50, 100, 200 and 400μm were fabricated by wet chemical etching using a 1:1:1 mixture of hydrobromic acid: acetic acid: potassium dichromate solution. Ti/Au (20nm/200nm) was deposited to form the top and bottom electrical contacts. No annealing of metal contacts was performed. Measurements and modeling of the voltage dependence of capacitance indicated that the depletion region widths are 80 and 230nm, thinner than the nominal values.

Table I: Epitaxial structure of AlAsSb p-i-n diodes

Layer	Material	Doping (/cm^3)	Thickness (nm)	Dopant
p^+ cap	InGaAs	5 x 10^{18}	50	Be
p^+ cladding	AlAsSb	2 x 10^{18}	400	Be
i-intrinsic (avalanche region)	AlAsSb	undoped	100 (PIN1) 250 (PIN2)	
n^+ cladding	AlAsSb	2 x 10^{18}	50	Si
n^+ etch stop	InGaAs	5 x 10^{18}	1000	Si
InP semi-insulating (S.I) substrate				

On wafer I-V measurements at 77, 140, 200, 250 and 295K were performed on diodes with D = 50 to 400μm on both p-i-n structures using a low-temperature probe station. For clarity only results from diodes with D = 200μm are shown in Figure 1. The dark current in PIN1 is dominated by surface leakage since the measured current scales with the diode perimeter at all temperatures. In PIN2 the dark current scales neither with the surface perimeter nor the area suggesting that both surface and bulk components are significant. The dark current in both structures reduces with decreasing temperatures with dark currents of < 10nA obtained in PIN1 and < 30nA obtained in PIN2 at 0.9V_{bd} at temperatures below 200K.

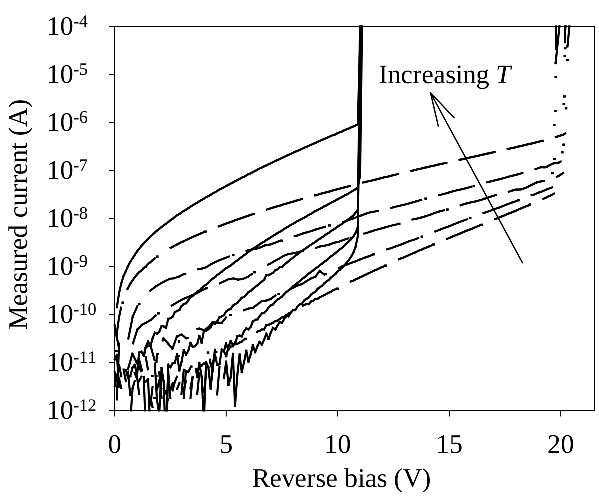

Figure 1: Measured I-V characteristic for AlAsSb diodes with D = 200μm and w = 80nm (solid lines) and 230nm (dash lines) at temperatures, T of 77, 140, 200, 250 and 295K.

Well defined V_{bd}, taken to be the voltage corresponding to the dark current of 100μA, was obtained for all devices at the temperatures measured. In PIN1 V_{bd} drops from 11.10 to 10.98V, a reduction of 1%, as the temperature reduces from 295 to 77K. Larger change in V_{bd} was observed in PIN2, with a drop from 20.4 to 19.8V, representing a reduction of 2.94%, as the temperature was varied over the same range.

In order to determine unambiguously the temperature dependence of avalanche breakdown voltage, to isolate the contribution of surface leakage current and to rule out premature edge breakdown in the diodes, the temperature dependence of avalanche gain, M, measurements were performed using phase-sensitive detection techniques. This, performed by mechanically chopping the laser beam with a wavelength of 633nm, allows the photocurrent to be measured independent of the dark current and electronic noise. The laser was focused on to the top p^+ layer at the centre of the diodes to prevent carrier generations at the sidewalls. Since the capacitance-voltage measurements showed a small increase in the depletion width with bias, the increase in the primary photocurrent due the bias dependence of the collection efficiency was estimated using the technique proposed by Woods et al. [12]. The total photocurrent was normalized to this primary photocurrent to deduce the avalanche gain.

The measured gain for PIN1 and PIN2 at 77, 140, 200, 250 and 295K are shown in Figure 2. The results show small variations of avalanche gain with temperature in these AlAsSb diodes. At a given bias the gain increases only marginally as the temperature is reduced. Consequently the temperature dependence of V_{bd} is also weak. The values of V_{bd} were estimated using linear extrapolation of the 1/M curves to 0, as shown in Figures 3(a) and 3(b) for PIN1 and PIN2 respectively. We obtained V_{bd} = 11.27V at 295K dropping to V_{bd} = 11.06V at 77K for PIN1 and V_{bd} = 20.46V at 295K to V_{bd} = 20.14V at 77K for PIN2, yielding C_{bd} values of 0.95 and 1.47mV/K respectively.

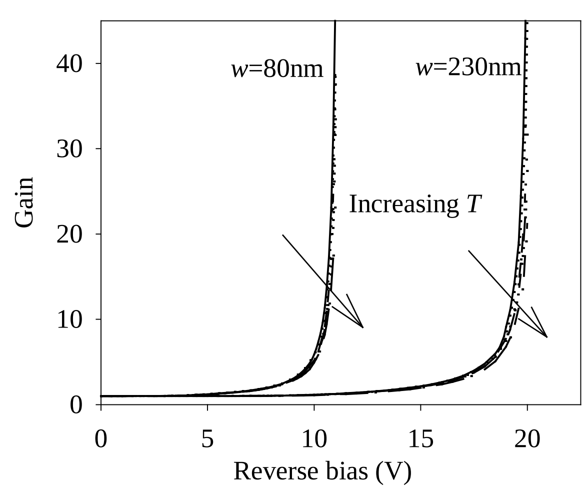

Figure 2: Avalanche gain measured using a 633nm laser on the diodes with w = 80nm and 230nm at temperatures of 77, 140, 200, 250 and 295K.

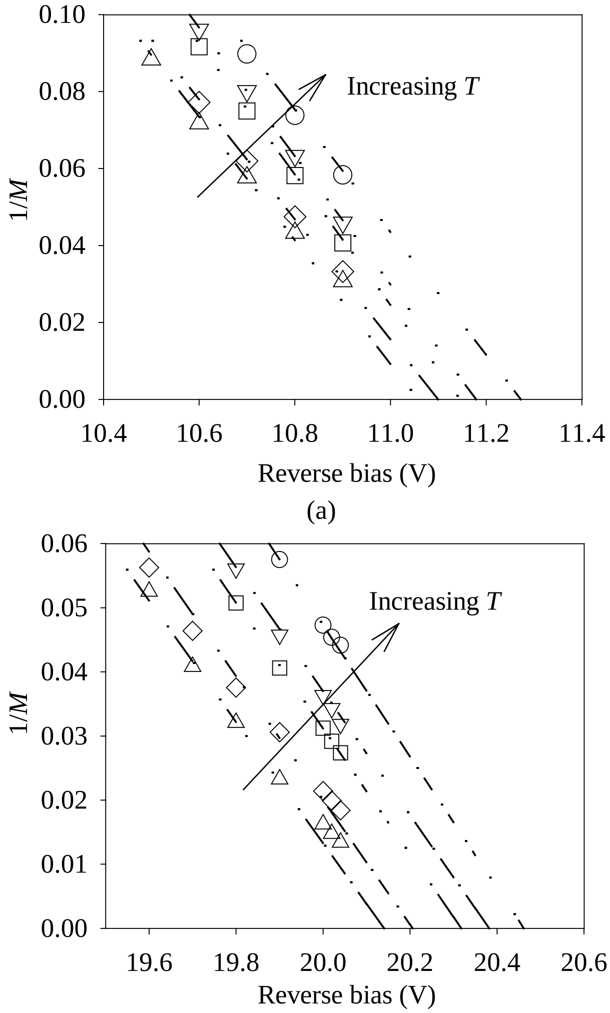

Figure 3: Extrapolation of 1/*M* to 0 (medium dash lines) for the diodes with (a) *w* = 80nm and (b) *w* = 230nm at temperatures of 77, 140, 200, 250 and 295K.

III. Discussion

The measured dark currents in both structures were found not to scale with surface area suggesting that they are predominantly surface leakage current at room temperature. This is most probably due to the absence of surface passivation, non-optimized etching procedures and the presence of high composition of Al which is known to oxidize. Despite the lack of surface passivation the dark current reduces significantly at low temperatures. The temperature dependence of dark current provides valuable data to assess whether band to band tunneling current is significant in our diodes. Band to band tunneling current can be described by [13]

$$I_{tunn} = \frac{(2m^*)^{0.5} q^3 FVA}{h^2 E_g^{\ 0.5}} \exp[-\frac{2\pi\sigma_T (m^*)^{0.5} E_g^{\ 1.5}}{qhF}] \qquad (1)$$

where m^* is the effective electron mass, q is the electron charge, V is applied reverse bias voltage, F is the electric field, A is the device area, h is the Plank's constant, E_g is the band gap and σ_T is a constant that depends on the detailed shape of the tunneling barrier. E_g is replaced by $E_g + E_p$, where E_p is the phonon energy, when modeling indirect band gap materials. Eqn. (1) shows that the band to band tunneling current increases rapidly with the reverse bias. To obtain a low tunneling probability, the effective mass and bandgap should be large and the electric field should be small.

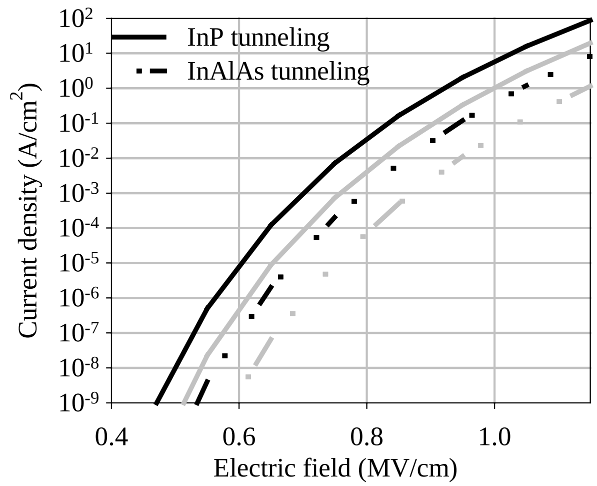

Figure 4: Calculated tunneling current density for InP and InAlAs diodes with *w* = 80nm at 293 (dark) and 14K (grey).

Figure 4 shows the calculated tunneling current using Eqn. (1) for InP and InAlAs diodes at temperature of 293 and 14K for ideal pin diodes with w = 80nm. The values of the bandgap in InP are taken from an empirical equation [7] and the band gaps at 293 and 14K for InAlAs were taken from Roura et al. [14] while the values of σ_T are 1.15 for InP [15] and 1.26 for InAlAs [16]. The results show that the tunneling current depends weakly on temperature in both materials, reducing by approximately an order of magnitude when the temperature reduces from 293 to 14K. In contrast we observed several orders of magnitude reduction in the dark currents in both PIN1 and PIN2 indicating insignificant tunneling current. The 77K dark current density in PIN1 is 10^{-5}A/cm^2 at a reverse bias of 0.95V_{bd}, corresponding to a field of 1.07MV/cm. This is not surprising since the larger band gap of AlAsSb of 1.65eV and the addition of E_p to account for the indirect band gap, will reduce the tunneling current substantially as described by Eqn. (1). Moreover a rule of thumb in Si APDs suggests that the avalanche mechanism generally dominates if the breakdown voltage is well above $6E_g/q$ [17]. In PIN1 the breakdown voltage is 11.27V which is greater than $6E_g$ (9.9V). Our data confirms that tunneling current is insignificant at least up to a field of 1.07MV/cm which is much higher than the fields where tunneling current becomes dominant in InP and InAlAs diodes. Therefore AlAsSb avalanche region as thin as 80nm has a great potential to be used in conjunction with an InGaAs absorption layer to improve the bandwidth (due to reduced carrier transit time) and excess noise (due to enhanced dead space effects in sub-micron avalanche regions) for future telecom APDs. More work will be necessary to establish the lower limit of w in AlAsSb before tunneling current becomes intolerable.

The temperature coefficients of breakdown voltage for different semiconductor materials, such as Si [2], GaAs [3],

$Al_{0.6}Ga_{0.4}As$ [5], GaInP [6], InP [7] and InAlAs [8] are plotted in Figure 5 and a comparison for diodes with w < 300nm is provided in Table II. It is clear that PIN1 with w = 80nm shows the smallest C_{bd} than all materials with a range of w, except for the thinnest GaAs diode with w = 25nm. It is worth noting in particular that the C_{bd} value of 0.95mV/K in our AlAsSb diodes is significantly lower than the values of 3.9mV/K for InP and 2.2mV/K for InAlAs diodes with the same w, estimated using extrapolation of data in Ref [7]. Further reduction of C_{bd} by reducing w is not practical in GaAs, InP and InAlAs since band to band tunneling current rapidly increases at biases close to V_{bd} in GaAs diodes with $w \leq$ 95nm [3], InP diodes with w = 130nm and InAlAs diodes with w = 100nm [11].

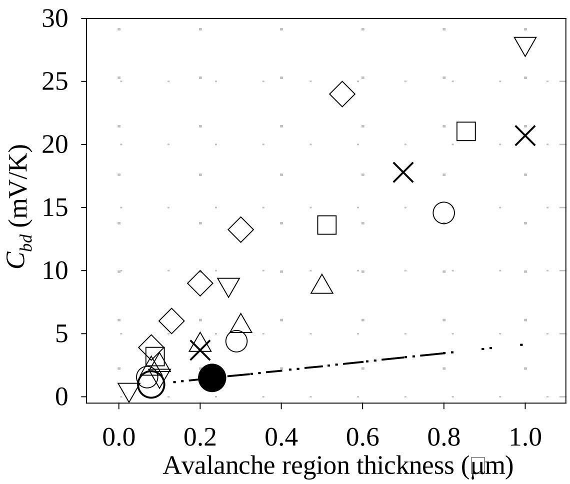

Figure 5: Comparison of C_{bd} for AlAsSb (●), Si (○) [2], GaAs (▽) [3], $Al_{0.6}Ga_{0.4}As$ (□) [5], GaInP (×) [6] InP (◇) [7] and InAlAs (△) [8] diodes with submicron avalanche regions.

Table II: A comparison of C_{bd} in diodes with w < 300nm

Material	w (nm)	C_{bd} (mV/K)	w (nm)	C_{bd} (mV/K)
AlAsSb	80	0.95	230	1.47
Si [2]	70	1.53	290	4.38
GaAs [3]	100	1.67	270	8.89
$Al_{0.6}Ga_{0.4}As$ [5]	89	3.18	--	--
GaInP [6]	--	--	200	3.68
InP [7]	80	3.9	200	6.0
InAlAs [8]	80	2.2	200	4.1

While the origin of the small C_{bd} of our AlAsSb diode is not fully understood it may be attributed to the combined effects of a very thin w of 80nm, a large phonon energy and a strong alloy scattering. In general the value of C_{bd} decreases with w due to the reduced influence of phonon scattering at high electric fields in diodes with thin w [4]. Carriers encounter fewer phonons at high electric fields and hence the population of hot carriers is less dependent on temperature at high fields leading to a smaller C_{bd}. The phonon scattering rate is proportional to the phonon occupation number $N = (exp(\hbar\omega/kT)-1)^{-1}$, where $\hbar\omega$ is the phonon energy and k is Boltzmann's constant. Clearly a material with a larger phonon energy will exhibit a smaller temperature dependence of N and hence the hot carrier population exhibits a weaker temperature dependence. Finally the alloy scattering is given by [18]

$$\frac{1}{\tau_{alloy}} = \frac{3\pi}{8\sqrt{2}}\frac{(m^*)^{3/2}}{(h/2\pi)^4}x(1-x) \times \frac{a^3}{4}(\Delta E_a)^2[\gamma(E)]^{1/2}\frac{d\gamma(E)}{dE}s^{-1} \qquad (2)$$

where x is the mole fraction of the alloy, a is the lattice constant, and ΔE_a is the alloy scattering potential, $\gamma(E) = E^*(1+\alpha E)$ is the approximation of the nonparabolicity of the conduction band and E is the carrier energy. This scattering rate is independent of temperature and we speculate that this could also contribute the small C_{bd} in our AlAsSb alloy. Modeling incorporating appropriate temperature dependence of ionization, phonon and alloy scattering rates will be necessary to quantify the small C_{bd} observed in our thin AlAsSb diodes. This is a subject of an ongoing work.

IV. Conclusion

We have grown, fabricated and measured the temperature dependence of dark current, avalanche gain and breakdown voltage of AlAsSb diodes with w = 80 and 230nm. Measurements at temperatures ranging from 77 to 295K showed that the dark current in both diodes was significantly reduced with decreasing the temperature. No band to band tunneling current was observed in the thin AlAsSb diodes. Avalanche gain exhibit a weak dependence on temperature leading to a very low temperature coefficient of breakdown voltage 0.95mV/K in the diodes with w = 80nm. The low tunneling current and very small C_{bd} shows that AlAsSb has a great potential for fabrication of APDs with sub-100nm avalanche region widths to increase the gain-bandwidth-product and to reduce the excess noise.

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