Mid Infrared Avalanche Photodiodes.

A.R.Marshall, C.H.Tan, J.S.Ng, J.P.R.David and M.Hopkinson
Department of Electronic and Electrical Engineering,
The University Of Sheffield,
Mappin Street, Sheffield, S1 3JD

Abstract

Photomultiplication measurements were performed on MBE-grown InAs diodes to study impact ionization characteristics in InAs. Our measurements showed that significantly higher gain was obtained by injecting a mixture of electrons and holes than that of pure hole injection. This indicates that electron ionization coefficient is much higher than hole ionization coefficient in InAs contrary to the only previously reported coefficients in 1976. Useful gain was obtained at low fields in the region of 60-70kV/cm. Results of this work suggest that InAs is a potential material for low voltage mid infrared avalanche photodiode.

Keywords: Avalanche photodiode, Impact ionisation, Infrared, Narrow bandgap

Introduction

The mid infrared spectral range between the 1.55µm – 3.5µm has seen increasing interest for applications including military imaging, gas sensing, free space communications, and satellite based sensing. InAs can offer good detection efficiency in this spectral range. Furthermore the unique bandstructure of InAs can be exploited to achieve very high avalanche gain at very low reverse bias. In this material the L and X valleys are 0.73eV and 1.02eV above the Γ valley minima. This means that electrons may undergo many scattering events without significant change in direction since the dominant scattering mechanism is polar scattering in the Γ valley. As a result electrons can acquire energy much higher than the bandgap of 0.36eV before transferring to the satellite valleys. This, coupled with the relatively flat heavy-hole band will significantly enhance the probability of electron initiated impact ionisation, leading to preferential electron ionisation and high avalanche gain at low reverse bias.

Theoretical work by Dumke [1] showed that the ionisation rate in InAs rises above $10^9 s^{-1}$ at field as low as 1.6kV/cm indicating that avalanche gain can be achieve at low electric field and hence low reverse bias. To date the only reported impact ionisation coefficients in InAs come from Mikhailova et al. [2]. However they did not account for change in carrier collection efficiency in their pn diode and possibility of photon recycling effect. They concluded that the hole ionisation coefficient, β, is much larger than the electron ionisation coefficient, α, in both InGaAs and InAs. It is now well known that the electron ionisation coefficient is larger than the hole ionization coefficient in InGaAs. Therefore their reported ionisation coefficients for InAs are questionable. Moreover first principle Monte Carlo simulations by Brennan et al. [3] suggest that electron ionisation coefficient is much higher than that reported by Mikhailova, raising further doubts on the accuracy of their measured ionisation coefficients.

Recently Cadmium-Mercury-Telluride (CMT) has been reported to demonstrate close to ideal avalanche property where virtually no excess avalanche noise was measured [4]. However, growth and fabrication in CMT are significantly more challenging than conventional III-V compound semiconductors. CMT (with 30% mercury) has a small bandgap and large intervalley separation energies [3], suggesting that these features may be the reason for its ideal avalanche behaviour. InAs having very similar bandstructure to CMT is therefore a potential material for low voltage low noise avalanche photodiodes, which are particularly suitable for low voltage applications. Importantly InAs can be grown and fabricated using established III-V technologies, providing a low cost high performance two-dimensional array alternative to CMT.

Growth and Fabrication

Three InAs wafers were grown using Molecular Beam Epitaxy (MBE). Our growth procedures are as follows. First the temperature was ramped up to ~510 °C under high As overpressure, followed by a wait period of 15mins. Then a short ramp of ~1min to 540°C was followed by immediate cooling to 510°C. Initiation of InAs growth started at 510°C. Pyrometer readings of temperature and heater input were used to maintain the temperature at 500-510 °C. Table 1 summarises our structures.

Layer	**Structure**	**i-region thickness (µm)**
InAs4	n^+ip^+	2
InAs5	n^+ip^+	1
InAs6	p^+in^+	2

Table 1: *Summary of InAs grown using MBE.*

The grown wafers were then fabricated into circular mesa diodes. AuZnAu and InGeAu alloys were deposited to form the p-type and n-type contacts, respectively. Solution of Sulphuric acid: Hydrogen peroxide: Deionised water (1:8:80) was used to etch away unwanted material to create the mesas.

Results and Discussion

The fabricated devices were assessed using standard current-voltage (IV) measurements at room temperature. The forward IV characteristics indicated a very low built-in voltage in the region of 0.05V, an ideality factor of around 1.4 and acceptable contact resistances. The reverse dark current results for InAs4 and InAs5 are shown in figure 1. Figure 1 shows that at room temperature, with the fabrication process used, the dark current is high. Some of the smaller devices also show an area dependant ‘breakdown’. This is a hard device failure, and is believed to be a defect-dominated breakdown, not an avalanche breakdown. Normalising the dark current to the device area and perimeter shows that the measured dark currents are due to a combination of bulk and surface components.

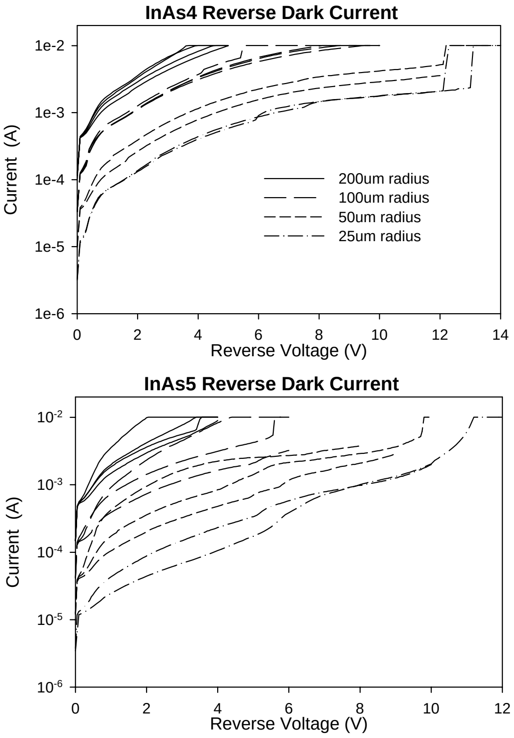

Figure 1: *Reverse dark IV characterisation results from the two n^+ip^+ diodes*

The nip samples InAs4 and InAs5 were also given a simple test (some time after initial fabrication) at a reduced temperature using liquid nitrogen (we estimated the temperature to be > 77K), to give an initial indication of the potential for dark current reduction. The results are shown in figure 2. Note that the dark current is reduced by more than 4 orders of magnitude at 8V when cooled by liquid nitrogen.

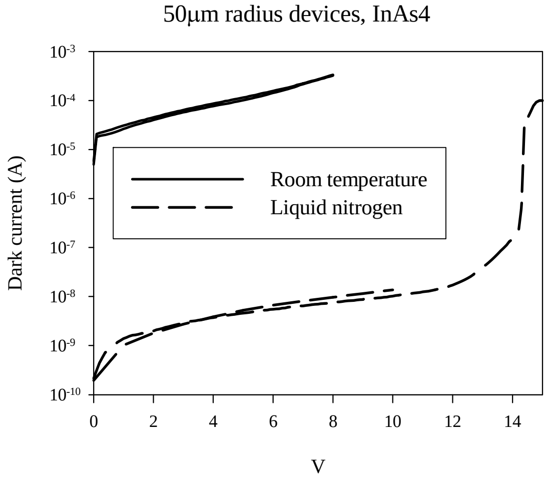

Figure 2: *Reverse dark IV characteristics at room temperature and with liquid nitrogen cooling on InAs4.*

As shown in figure 1 reverse dark currents were significant at room temperature, which necessitated the use of a lock-in amplifier and phase sensitive detection, to accurately measure the primary and multiplied photocurrent. Using this technique, adequate results could be obtained, with only the pin devices on InAs6 being significantly limited by their dark current. Lasers with wavelengths of 3.4µm and 1.15µm were focused onto the top of the mesa diodes. The 3.4µm wavelength gives a mixture of electrons and holes injection while the 1.15µm wavelength gives predominantly hole injection in the n^+ip^+ diodes and predominantly electron injection in the p^+in^+ diode.

In the InAs4 and InAs5 n^+ip^+ diodes the gain due to the 3.4µm wavelength light is significantly higher than those due to 1.15µm, as shown in figure 3. In contrast the InAs6 p^+in^+ diode (not shown) shows higher gain when 1.15µm wavelength light was used.

As discussed in Introduction, the published data shows that $\beta > \alpha$, which appeared to be contradictory to our measurements at room temperature. The multiplication characterisation performed during this study confirms that, at room temperature, $\alpha > \beta$, in contradiction to the published result. The results also confirm that usable gain is achievable at low fields in the region of 60-70kV/cm.

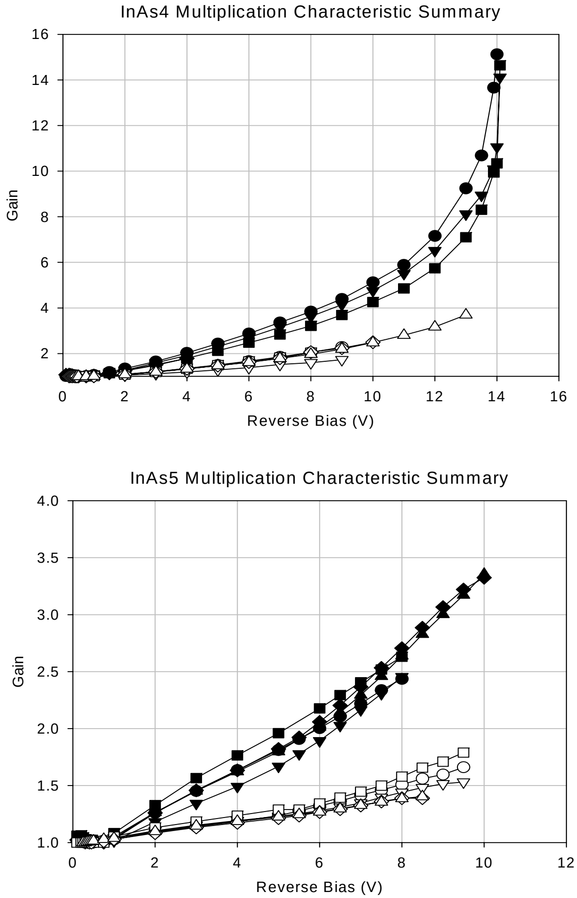

Figure 3*: Room temperature gain for the n^+ip^+ diodes using 1.15µm (open symbols) and 3.4µm (closed symbols) wavelengths.*

In results for the n^+ip^+ diodes (figures 3) it can be seen that photocurrent generated by the 3.4µm wavelength laser, which is absorbed throughout all three layers of the structures, experiences a relatively high gain. The photocurrent from 1.15µm wavelength lasers however, which is predominantly absorbed in the n-type capping layer, undergoes a lower gain. This indicates that the injection of predominantly holes to the (relatively) high field intrinsic region, obtained with the 1.15µm wavelength, initiates less gain than the more mixed injection of electrons and holes obtained with the 3.4µm wavelength

Although the results for the p^+in^+ diode (not shown) are limited to low gains, due to very high dark current, they confirm the trend seen in the n^+ip^+ diodes. In this case the shorter wavelengths are again predominantly absorbed in the cap, however now they inject electrons into the high field intrinsic region. It is observed that multiplication initiated by this electron-dominated injection is higher than the multiplication initiated by the more mixed injection obtained with the 3.4µm wavelength.

Conclusion

In this study two n^+ip^+ diodes and one p^+in^+ diode were fabricated into circular mesa diodes for electrical and optical measurements. From the IV measurements it was found that the dark current of the diodes is high. The high dark current is attributed to the absence of wide bandgap minority carrier blocking layers and proper surface passivation. Some defect-related breakdown was also observed. The dark current was found to decrease remarkably by > 4 orders of magnitude from room temperature when cooled with liquid nitrogen, showing that it can be reduced by lowering the operating temperature. However optimisation of growth conditions to minimise defect level and optimisation of fabrication and passivation procedures are still required to yield low dark current diodes.

Photocurrent measurements using laser wavelengths of 1.15µm and 3.4µm were performed to deduce the gain-voltage characteristics of InAs. The results showed that higher gain was achieved when mixed injection of electrons and holes were used than that of predominant hole injection. This proves that electron ionisation coefficient is larger than hole ionisation coefficient, in contrast to reported data in 1976. Our results also showed that useful gain can be obtained at low electric fields of 60-70kV/cm, showing the potential of using InAs to achieve low operating voltage high gain avalanche photodiodes. Lower voltage operation can be achieved using thinner avalanche regions or using pn junctions with carefully controlled doping.

In conclusion, we have demonstrated that electron ionisation coefficient is higher than hole ionisation coefficient in InAs and useful gain can be obtained at very low fields. However more work to obtain accurate ionisation coefficients is required to design robust InAs mid infrared avalanche photodiodes that operate at low CMOS voltages.

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