High gain InAs avalanche photodiodes

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Abstract

We report on the physics, design, development and characterisation of high gain InAs avalanche photodiodes. A parameterised expression for tunnelling current is presented and it is shown that high gain can be achieved without significant tunnelling current in structures with wide depletion regions. Converse to the accepted trend for established APDs, increasing the depletion width actually reduces the bias voltage required to generate avalanche gain. This relationship makes high gain APDs operating at low readout IC compatible biases achievable in a III-V material. This, in conjunction with the extremely low noise characteristics of avalanche gain demonstrated in InAs, makes InAs avalanche photodiodes ideally suited to applications in focal plane arrays and an attractive alternative to the HgCdTe APDs already exploited in this emerging field.

Introduction

Making use of avalanche photodiodes (APDs) instead of simple unity gain pin photodiodes can improve the overall sensitivity of light detecting systems. However due to their material properties and initial development for the telecommunications market, established infrared APDs only detect in the near or short wave infrared (NIR or SWIR). They also require relatively high operating biases of the order of 30V or more and suffer from high levels of avalanche noise when operated at high gains. Furthermore they are not ideally suited to applications in the emerging field of single photon detection. For these reasons they have had limited implementation in defence applications such as laser range finders and active or passive imaging cameras. Indeed high sensitivity is an important requirement in such systems, due for example to the need for short frame integration times or the spreading of captured optical power in hyperspectral systems. However for the potential benefits of APDs to be exploited new APDs must be developed to overcome a number of issues.

1. Multiplication noise must be kept to a minimum allowing high gains to be used.
2. Operating biases must be reduced to simplify ROIC design and if possible achieve compatibility with existing low operating bias designs.
3. The spectral response range must be extended to support new applications beyond 1.7µm.

The first demonstration that these issues could be addressed successfully came with the reports of near ideal APD characteristics in HgCdTe, with operating voltages below 10V [1]. Similar HgCdTe APDs have been employed in FPA applications to facilitate high sensitivity active and 3D imaging [2], [3]. There are however some issues associated with the use of HgCdTe, in particular compositional uniformity and intolerance to temperatures in excess of

70°C. Recent reports of InAs APDs [4]-[6] matching the performance of these excellent HgCdTe APD, presents an alternative in the III-V material system. Such InAs APDs offer greatly improved tolerance to high temperatures and commercially available growth with high uniformity. Further development of InAs APDs is required to obtain higher gains at ROIC compatible voltages, and very high gains at higher biases for detection at levels approaching single photon.

Electric Field Dependence of Gain and Tunnelling Current

One crucial aspect of avalanche multiplication in InAs which has not been full explored until now is the interrelationship between tunnelling current and gain. It is important for all APDs that they are capable of generating sufficient gain before any tunnelling current in the diode builds up to an unacceptable level. Tunnelling like impact ionisation is strongly electric field dependent. Unfortunately to reduce the operating voltage of established APDs it is necessary to increase the electric field at which they operate. This leads to a trade-off, for a desired gain, between reducing operating voltage and increasing tunnelling current. This has ultimately made practical APDs operating with gain greater than 10 at below 10V unavailable until now.

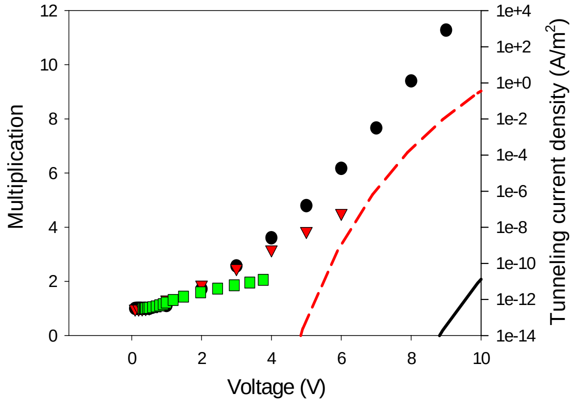

Figure 1: Measured multiplication M_e from InAs APDs with intrinsic region widths of 3.5 µm (●), 1.9 µm (▼) and 0.9 µm (■). Lines show modeled tunneling current densities (right hand axis) for ideal pin approximations of the 3.5µm (solid) and 1.9µm (dashed) diodes.

Through the measurement of gain in InAs APDs with different multiplication region widths an atypical trend has been observed. InAs APDs with wide multiplication regions show higher gain at a given bias than ones with thinner multiplication regions. This trend can be seen in figure 1 and is attributed to the relatively high electron ionisation coefficient at low electric fields in InAs. As a result of this it is clear that high gain InAs APDs operating below 10V are best realised with wide multiplication regions of 4µm or more.

With its relatively narrow band gap tunnelling currents in InAs APDs are of particular concern. Characterisation of InAs APDs at room temperature and 77K has made it possible to fit the tunnelling current to the common expression used by Forest et al. [7]

$$I_{tun} = \frac{(2m^*)^{1/2} q^3 FVA}{4\pi^2 \hbar E_g^{1/2}} \exp\left(- \frac{\alpha_T (m^*)^{1/2} E^{3/2}}{q\hbar F} \right)$$

where m* is the electron effective mass, q is the electron charge, F is the electric field at the junction, V is the applied voltage, A is the cross-sectional area of the junction, ħ is the reduced Plank's constant, E_g is the band gap energy and α_T is a parameter dependant on the detailed shape of the barrier and of the order of unity. It was found that an α_T of 1.16 provided a good fit in all cases. This can be used to model the tunnelling current in diodes where it cannot easily be measured and hence facilitate the comparison of gain and tunnelling current. The un-multiplied tunnelling current in the two thicker APDs reported in figure 1 has been modelled and is shown for comparison. It is clear that the APD with a 1.9µm wide multiplication region can only offer low gain before the tunnelling current starts to become unacceptably high. However the tunnelling current in the thicker APD is modelled to be low below 10V, while the gain rises to usable levels.

MOVPE Growth with Low Background Doping Concentrations

In order to achieve the clearly desirable wide multiplication regions it is necessary to grow thick p-i-n diode type structures, while also maintaining a low-enough background doping concentration for the intrinsic region to deplete even at operating voltages below 10V. Early diode structures used in this work were grown by molecular beam epitaxy (MBE), which proved capable of producing background doping concentrations less than 1×10^{15} cm^{-3}. However MBE growth is relatively slow with a rate in the region of 1µm/hour. Hence the growth of epitaxial structures 10µm thick or more takes a full day. Metal organic vapour phase epitaxy (MOVPE) offers higher growth rates making it preferable for growing the thicker diodes needed for the development of higher gain InAs APDs, so long as the required low background doping concentration can be achieved.

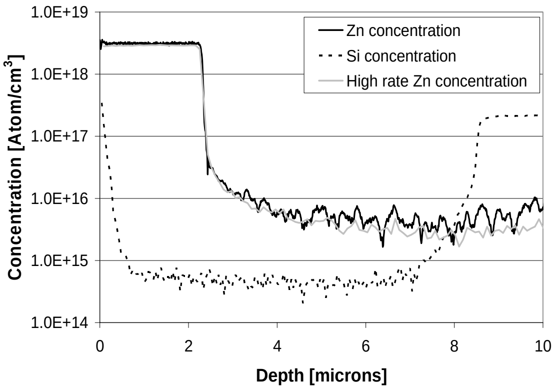

Figure 2: SIMS doping profile for a MOVPE grown p-i-n diode.

Secondary ion mass spectroscopy (SIMS) measurements can be used to determine the doping concentration of selected atoms following growth. Figure 2 shows a doping profile for an MOVPE grown p-i-n diode as measured by SIMS. Unfortunately SIMS has limitations in terms of its lower detection limit and its measurement of physical atoms rather than electrically active dopant. In the results shown it can be seen that the zinc trace is already approaching a noise floor and a high erosion rate is needed to minimise the noise and confirm the zinc concentration. This result also implies that the background doping in the intrinsic region would be p-type, however electrical characterisation of fabricated test structures shows the background to be n-type. Hence SIMS is not capable of accurately determining the background doping or being used alone to guide the development of thick InAs APDs.

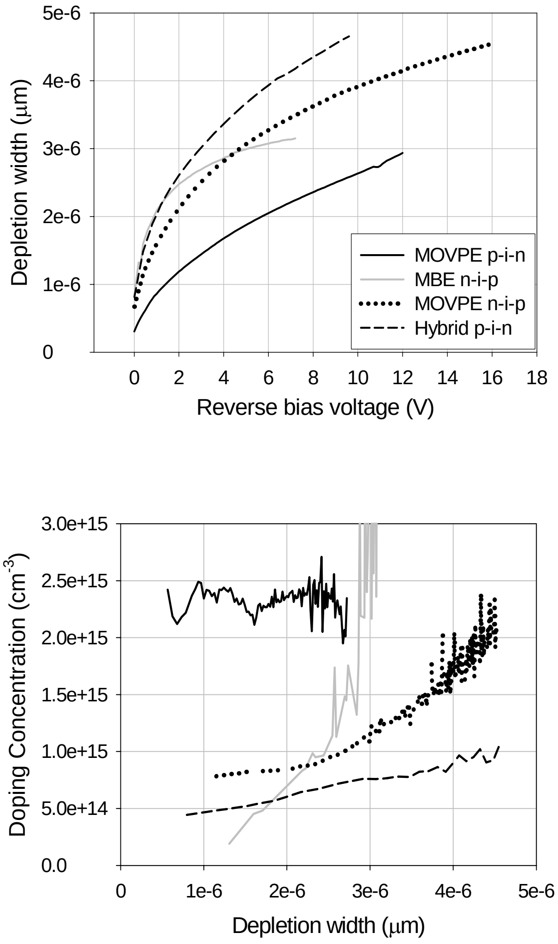

Figure 3: Depletion width vs. voltage (top) and inferred doping concentration vs. depletion width (bottom graph with key as for top) for 4 diode structures.

It is necessary to make and analyse capacitance-voltages (CV) measurements, which show the electrically active doping concentration, in conjunction with SIMS measurements to develop reduced background doping. Figure 3 shows depletion width and inferred active doping concentration as a function of reverse bias for 3 diodes grown during the development of MOVPE growth. A fourth data set shows the corresponding results for a diode grown by MBE. It can be seen that the background doping in this MBE diode is well below $1x10^{15}$, resulting in the depletion reaching the doped cladding layers below 10V. The first MOVPE p-i-n diode in contrast, also shown in figure 2, shows background doping greater than $2x10^{15}$, limiting the depletion width achievable below 10V. Comparison with SIMS and CV data from a further layer indicated a link between background doping concentration and the p-type cladding doping concentration. This link was confirmed by further growths in which measures were taken to reduce the p-type doping and its expected diffusion. These culminated in the MOVPE n-i-p diode growth, shown in figure 3, in which a depletion width approaching 4µm is achieved at 10V. The greatest depletion width demonstrated to date however was achieved using a hybrid MBE/MOVPE sequential growth routine. In this layer a diode structure was grown by MOVPE on top of a MBE grown etch stop structure, itself grown on an InAs substrate. Following the complete removal of the substrate the diode was characterised and found to have a background doping concentration below $1x10^{15}$, which in combination with its thick intrinsic region allowed a depletion width of more than 4.5µm by 10V. By extending such techniques it is expected that even greater depletion widths can be achieved, supporting the development of higher gain InAs APDs.

The InAs APDs grown by MOVPE have a further advantage over those grown by MBE, in that they demonstrate greater robustness at the reverse biases necessary for gain. The reasons for this are believed to be twofold. Firstly greater depletion widths lead to reduced electric fields, and hence less stress on the material. The peak electric field for a depletion width of 4µm or greater will be less than 50kV/cm for example, well below the electric field typical in established APDs. Secondly the higher growth temperature achievable by MOVPE yields a higher crystal quality less susceptible to failure.

High Gain InAs APDs

Early MOVPE grown p-i-n diodes proved capable of tolerating relatively high reverse biases and this made it possible to demonstrate gains as high as 100 at room temperature. This result, shown in figure 4, is the highest gain demonstrated to date in an InAs APD and was measured on the same structure as those reported in figure 2 and 3.

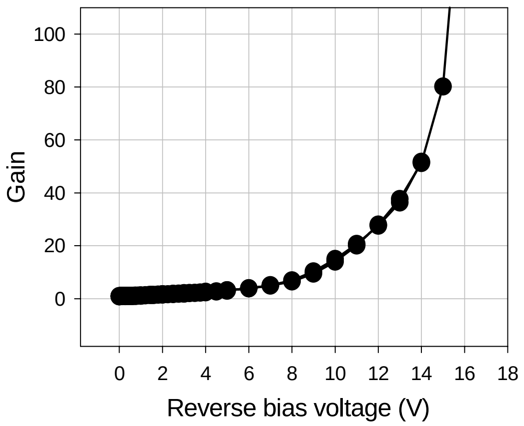

Figure 4: Avalanche gain measured on an InAs p-i-n diode grown by MOVPE.

Following growth improvements to reduce the background doping concentration, the highest gain at less than 10V was measured on the hybrid MBE/MOVPE structure introduced previously. The greater depletion width yielded a gain of 19 by 8V as shown in figure 5, again at room temperature. This is a desirable level of gain to be achieved at this low bias and indicates that much higher gain could also be achieved while still maintaining low electric fields in the region of 50kV/cm. Hence InAs APDs hold promise not only for FPA applications with moderate gain but also for very high gain applications facilitating the detection of low intensities approaching single photon levels. Also shown in figure 5 for comparison are the highest low bias gains measured to date in entirely MOVPE and MBE grown diodes. The MOVPE diode is the same one as reported in figures 2 to 4, while the MBE diode has been previously reported elsewhere [4], [5]. It should be noted that early observations show that reducing the APD operating temperature will reduce the gain achieved at a given bias voltage. With cooling realistically required for most applications somewhat reduced gain must be expected. Quantifying this requires further work.

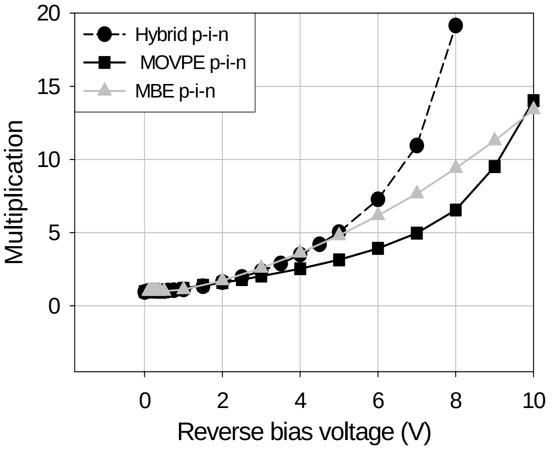

Figure 5: Avalanche gain measured on InAs diodes grown by MBE, MOVPE and the sequential MBE/MOVPE technique.

Conclusions

It has been shown that InAs APDs can be made with negligible tunnelling current by employing a thick intrinsic region in a p-i-n type structure. Crucially it is shown that increasing the intrinsic region in an InAs APD in this way can also lead to increased avalanche gain at low reverse biases. This relationship, converse to that demonstrated in other APDs makes InAs APDs operating at less than 10V achievable. The requirement to maintain a low background doping concentration has been noted and success in developing MOVPE growth to achieve this has been reported. The latest APDs reported would be well suited to FPA applications in emerging active imaging systems, currently supported by the less widely available HgCdTe. Indeed InAs exhibits highly desirable low noise gain, comparable to the excellent HgCdTe electron APDs recently reported and unlike other III-V APDs. Potential exploitations however also extend to high gain applications where the electron APD type characteristics would also be advantageous in the detection of low intensities approaching single photon levels.

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