GROWTH AND CHARACTERISATION OF INAS PHOTODETECTORS FOR MWIR APPLICATIONS

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Abstract: This paper reports on the development of InAs photodiodes by the Department of Physics at Nelson Mandela Metropolitan University. The device structures have been grown by metal-organic vapour phase epitaxy and processed using conventional photolithography techniques. Due to the narrow band gap of these materials, the detectivity of the devices are often limited by the junction leakage currents associated with avalanche multiplication and trap assisted tunnelling and generation effects, as well as surface related conduction channels. The various contributions to the leakage current and photo-response have been analysed, and correlated to the material and electrical characteristics of the device structures grown.

Keywords: InAs, photodiode, photoresponse, MOVPE

1. INTRODUCTION

The $InAs_{1-x}Sb_x$ material system is suitable for detection in the highly strategic 3 μm to 5 μm range of the infrared spectrum. As a prelude to the development of the InAsSb photodiodes, the electrical and structural characteristics of epitaxial InAs films have been characterised in detail. In particular, the accurate determination of the p-type and background doping of InAs offers various challenges due to the large contribution by the surface of the material to the measured conductivity [1]. Various electrical characterisation techniques have consequently been developed at Nelson Mandela Metropolitan University (NMMU) in order to optimise the device structure [2-4]. The basic material characterisation work leading up to device processing has consequently greatly contributed to development of InAs photodetectors with response characteristics comparable to commercial devices.

2. EXPERIMENTAL DETAILS

The homoepitaxial InAs diode structure was grown by metalorganic vapour phase epitaxy using a laboratory scale, horizontal Thomas Swan reactor operating at atmospheric pressure. The layers were grown on p^+ InAs substrate misoriented by 2 degrees from (001) towards (111)B. Liquid TMIn and TBAs were used as indium and arsenic precursors, respectively. The layers were grown at 600°C using a group V to group III vapour ratio of 10. The diode structure used is depicted in Fig. 1. A p^+ buffer layer was grown directly on the InAs substrate, followed by a 2 μm thick undoped layer. The p-type doping was achieved using trimethylcadmium due to the relatively low diffusion coefficient of cadmium [5]. Horikoshi *et al.* estimated the effective diffusion coefficient D_{eff} of Cd by measuring the junction depth following various anneals, with $D_{eff} \approx 6\times10^{-12}$ cm^2/s at 600°C [5].

The hole density was determined by a thermoelectric characterisation technique developed at NMMU [2]. A maximum doping density of 7×10^{17} cm^{-3} could be achieved. The undoped InAs is characteristically n-type, with a highly compensated carrier density in the medium to low-10^{15} cm^{-3} range [4]. The background carrier density was shown to decrease with increasing growth temperatures [4]. The growth temperature was however limited by the Cd diffusion profile required. The emitter was formed by a Sn-doped layer with a carrier density of 5×10^{17} cm^{-3}. The n^+-n-p doping sequence was used to avoid the strong residual doping effect that persists after Sn doping. Using Sn prior to the growth of the undoped layer would consequently have raised the electron carrier density significantly above the background doping level. The Ohmic contacts were formed by depositing Au/Ti contacts through a photoresist mask, with the photodiode isolated by a two-step mesa etch. The diameter of the circular photodiodes and metal contracts were 500 μm and 200 μm, respectively. No anti-reflective coating or surface passivation treatment was used.

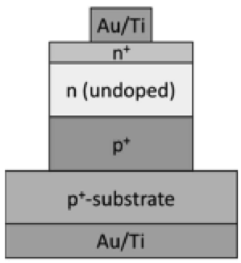

Figure 1: Schematic of the n^+-n-p photodiode structure grown by MOVPE.

The photo-response of the diode was obtained using a 100 W tungsten-halogen light source passed through a ¼-m monochromator and appropriate high pass filters. The photocurrent was measured using a Keithley preamplifier and a phase sensitive lock-in amplifier. The incident flux density was calibrated using a commercial InGaAs photodiode and a pyroelectric sensor.

3. RESULTS AND DISCUSSION

The diode structure depicted in Fig.1 has the junction placed between the undoped layer and the p^+ buffer layer. This type of buried junction differs from the more conventional p^+-n structure, which is typically formed by diffusion/implantation of a p-type dopant into undoped InAs substrate. The characteristic inversion layer that is observed at the surface of p-type InAs [2] is, however, expected to impede minority carrier (hole) collection in a p^+-n photodiode, with the hole current relying on tunnelling between the surface layer and the p^+ emitter. Due to the high doping and defect density of bulk material, however, hole extraction from the back-contact is expected to be more efficient. Since the surface layer is also expected to result in a higher surface recombination velocity for a p-type front layer, the photodiode structure proposed in Fig. 1 is thought to be more suitable for InAs.

Considering the relatively high growth temperature used, the diffusion of cadmium from the heavily doped p-type buffer layer into the undoped layer has been considered. Since the diffusion front remains below the growth surface, the role of vacancies on the diffusion profile was neglected [6]. The Cd profile was therefore assumed to be described by a single complementary error-function. Depending on the growth rate and the thickness of the undoped layer, the position of the Cd diffusion edge/junction could therefore be well controlled [5]. Figure 2 depicts the calculated concentration profiles for the Cd doped base layer and the tin doped emitter. In the case of the device described in this paper, the junction is expected to lie at approximately 200 nm below the n^+ emitter, thereby ensuring that the undoped region is fully depleted.

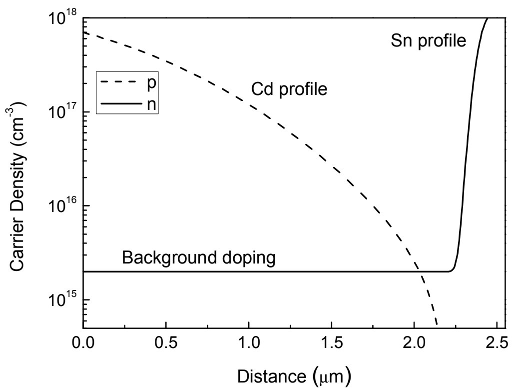

Figure 2: Simulated diffusion profiles for cadmium and tin. The abscissa denotes the distance from the intended p-doped layer interface. The background doping density has been estimated from variable temperature Hall Effect measurements [4].

The room temperature current-voltage characteristic of the photodiode, in the dark, is shown in Fig. 3. The diode exhibits rectifying behaviour with a rectifying ratio of two orders of magnitude. The reverse current follows a cube-root voltage dependence, indicative of space-charge generation within a graded junction [7]. The capacitance-voltage measurements performed on the diode at 77 K (Fig. 3 inset), also revealed a $1/C^3$ voltage dependence, indicative of a graded junction [7].

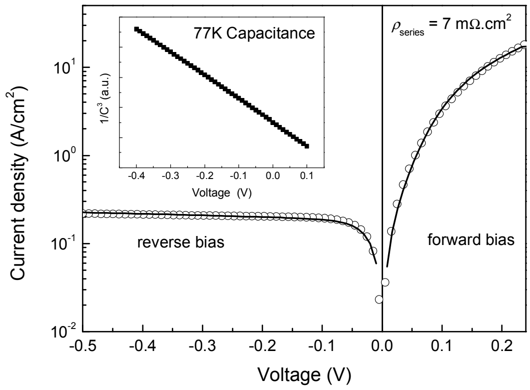

Figure 3: Room temperature dark current-voltage characteristic of the InAs photodiode manufactured at NMMU. The solid line represents the simulated behaviour. The forward bias current is dominated by band-to-band recombination, with the reverse bias current attributed to generation within the space-charge region of the diode. The inset shows the $1/C^3$ voltage dependence of the 77 K capacitance-voltage characteristics.

The forward bias characteristics appear to be ideal, which suggests that the recombination current within the diode is dominated by radiative band-to-band recombination, with a negligible contribution from Shockley-Read-Hall recombination centres. The series resistance of ρ_{series} = 7 mΩ.cm^2 was estimated from the high injection region of the forward bias measurements.

In the case of generation-recombination processes dominating diode characteristics, the differential resistance-area product is described by:

$$R_0A = \frac{2kT\tau_0}{e^2 n_i W}, \tag{1}$$

where W is the depletion width, τ_0 the effective generation lifetime, and the other parameters have their usual meaning. Equation (1) is derived by differentiating the well know relation describing the generation-recombination process in a p-n junction [7]. The measured resistance-area product of R_0A = 0.16 Ω.cm^2 therefore relates to an effective lifetime of τ_0 = 8 ns. The resistance-area product is an important performance parameter, with the measured room temperature value comparable to commercial devices [6].

The photo-response of the InAs photodiode is depicted in Fig.4. The photodiode has a maximum sensitivity of 0.75 A/W at 2800 nm, decreasing sharply at the InAs absorption edge. The various contributions to the photocurrent have been determined by simulating the spectral response associated with the emitter (n^+-region), the depletion region and the p-type base [8]. It is evident that a significant contribution is attributed to generation within the emitter, with the depletion region representing a smaller component to the overall response. The photo-response of the diode was also independent of the applied reverse bias, thus validating the proposed doping profile described in Fig. 2.

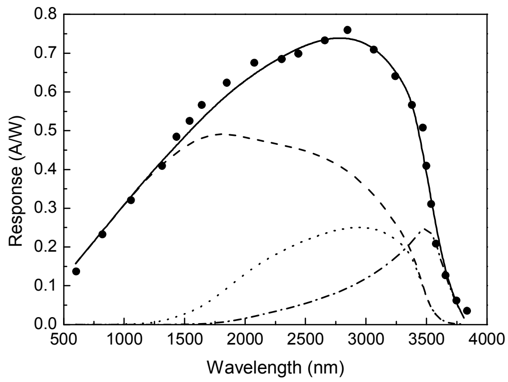

Figure 4: Room temperature spectral response of the InAs photodiode. The simulated response (—) has contributions from the emitter (- - -), base (-.-.-) and space-charge (····) region of the diode.

Figure 5 depicts the internal quantum efficiency (QE) calculated from the total response simulated in Fig. 4. Due to the Cd diffusion profile, the space-charge region of the photodiode is positioned near the surface, with the shallow n^+ emitter acting as a front-surface field (FSF) for holes. As a result, the FSF reduces the surface recombination velocity, thereby increasing the short-wavelength QE of the photodiode. The surface recombination could be estimated from the measured photo-response, with the increased short-wavelength response associated with a maximum surface recombination velocity of 10^5 cm/s.

The Cd doping profile is also expected to produce a back-surface field for electrons, enhancing the photo-response associated with the base of the diode. The buried diode structure, however, exhibits a reduced QE at the peak response wavelength. The negative slope of the QE below the peak response wavelength is indicative of collection from the base of the photodiode. The relatively narrow space-charge region of 200 nm obtained from 77 K capacitance measurements is likely to be the main contributing factor. Carrier recombination within the p-type region of the diode is also a likely contributor to the overall decrease in the peak response. A recent paper [4] presented deep level transient spectroscopy (DLTS) measurements performed on InAs diodes fabricated at NMMU. The measurements revealed a band of *electron* traps within InAs. These levels were found to be situated near mid-gap and related to extended defects. These electron traps are likely to impact device performance, with the trapping behaviour determined by the charge nature of the defects. Based on the DLTS results, the extended defects are expected to be completely filled within the n-type region of the diode, whilst trapping minority carriers in the p-type region. Since no *minority* carrier (hole) deep level transients were observed, it is likely that extended defects are more detrimental within p-type regions of the device. As a result, the peak response of n^+-n-p diode structures is expected to be more sensitive to the crystalline quality.

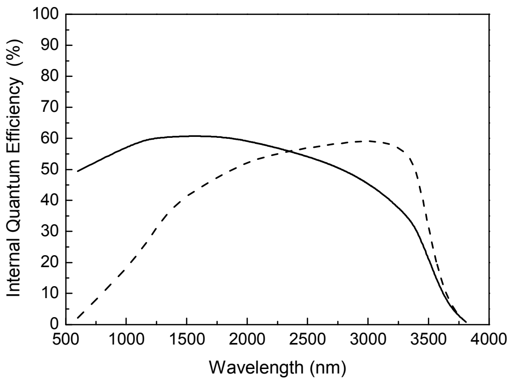

Figure 5: Comparison of the room temperature internal quantum efficiency of an InAs n^+-n-p photodiode fabricated at NMMU (—) and a Hamamatsu (part number: P10090) p-n photodiode (- - -).

In conclusion, the good rectifying and photo-response characteristics of an n^+-n-p photodiode have been demonstrated. The front-surface field associated with the n^+-n emitter also significantly enhanced the short-wavelength response of the photodiode. The more conventional p^+-n diode structure would therefore be more appropriate for applications requiring a narrow spectral band-width. A relatively low peak response was however observed and attributed to non-optimum junction characteristics. It is anticipated that the optimisation of the Cd diffusion profile, in particular the depletion width, would further improve the photodiode response.

4. ACKNOWLEDGEMENTS

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