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LETTER TO THE EDITOR

Impact ionisation coefficients in $In_{0.53}Ga_{0.47}As$

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Abstract. There is a surprising sparsity of experimental information on electron and hole impact ionisation coefficients in $In_{0.53}Ga_{0.47}As$, and the only available results are in wide disagreement. In this letter, results for electron and hole ionisation coefficients, α and β, are presented for $In_{0.53}Ga_{0.47}As$. α and β have been calculated from photocurrent gain measurements (using both mixed and pure electron injection) made on $In_{0.53}Ga_{0.47}As$/InP p–i–n structures fabricated from three separate wafers. The values for α and β are in good agreement with those found by Osaka *et al*, whereas Pearsall's results are an order of magnitude higher.

Optical communication systems require high-speed, low-noise detectors. Avalanche photodiodes, in which the ratio of electron and hole ionisation coefficients is large ($\alpha/\beta > 10$ [1]) would be ideal candidates for such detectors. However, unlike Si APDs [2], most III–V semiconductors have α/β values in the range ~ 0.5–3.0. It has been proposed that an enhancement of α/β can occur by introducing a superlattice, or staircase, into the APD structure [3, 4], and some experimental confirmation has been reported for GaAlAs/GaAs and InGaAs/InAlAs multilayer heterostructures [4, 5]. In $In_{0.53}Ga_{0.47}As$/InP multiple quantum well structures, Osaka *et al* [6] have reported an enhancement in the value of the hole ionisation coefficient as a result of the larger valence band offset and consequently find α/β values of ~ 0.5. This is clearly an interesting materials system to study, although it is not expected to yield sufficiently high values of α/β for practical applications. However, as part of that study it is necessary to know the electric field dependence of α and β in both bulk $In_{0.53}Ga_{0.47}As$ and InP, so that any enhancement in α/β over and above the expected alloy trend [7] can be determined. The ionisation coefficients in InP are well established (see for example [8], and references therein). For $In_{0.53}Ga_{0.47}As$, however, experimental information is sparse, and in wide disagreement [6, 7, 9]. Pearsall [9] has reported values in $In_{0.53}Ga_{0.47}As$ that are an order of magnitude higher than those reported by Osaka *et al* [6, 7].

In this letter, we report results for the ionisation coefficients in $In_{0.53}Ga_{0.47}As$ obtained from gain measurements made on InGaAs/InP p–i–n structures, using both mixed and pure electron injection. This work forms part of a larger study on ionisation coefficients in multiple quantum well InGaAs/InP which will be reported in a separate paper.

The p–i–n device structures used in these measurements were grown by LP MOVPE, on (100)-oriented n^+ InP substrates. The first structure, grown specifically for ionisation coefficient measurements, consisted of a 0.5 μm n^+ InP buffer layer, 1 μm n^- $In_{0.53}Ga_{0.47}As$, followed by 1 μm Zn-doped p^+ ($\sim 10^{18}$ cm^{-3}) InP, with a thin Zn-doped p^+ InGaAs cap to provide an ohmic contact (this is identified as wafer #1). Measurements were also carried out on double heterostructure planar p–i–n photodiodes taken from two separate wafers (#2 and #3). These had thicker InGaAs absorbing layers ~ 3 μm, with ~ 0.5 μm upper InP layer and an InGaAs cap layer. The ohmic p-contact in these devices was formed by a Zn diffusion through the InGaAs cap and upper InP layer, penetrating ~ 0.1–0.2 μm into the n^- InGaAs absorption region.

Mesa devices were fabricated using a 1:17:34, Br:HBr:H_2O etch with device area $\sim 7.7 \times 10^5$ cm^2. Reverse leakage currents of these devices were typically of the order of 5 nA at $0.5V_b$ (where V_b is the breakdown voltage, defined as the voltage at 1 μA). The InGaAs cap was removed in the region to be illuminated. Capacitance–voltage measurements were used to determine the carrier concentration and depletion width of the n^- InGaAs region. A high degree of uniformity of breakdown voltage, depletion depth and gain characteristics were obtained across the wafer. Details of breakdown voltages, depletion depths (at breakdown) and background doping levels (as estimated from C–V measurements) are given in table 1.

The photocurrent gain was measured as a function of

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Table 1. Wafer characteristics.

Wafer	Doping (cm^{-3})	Depletion depth (μm)	Breakdown voltage (V)
#1	4×10^{15}	1.0	24
#2	5×10^{14}	2.8	67
#3	10^{15}	2.8	68

reverse bias using a computer-controlled measurement system. The gain for both mixed electron and hole injection, and pure electron injection, was measured with top illumination, using a 1.3 μm semiconductor laser and a 0.6 μm helium neon laser as optical injection sources. The chopped light was focused down centrally within the active region of the device through an optical microscope system. Pure electron injection was obtained by absorption of the 0.6 μm HeNe light in the top p^+ InP layer, in which some 95% of the incident light will be absorbed. The residual mixed injection due to 0.6 μm light in the InGaAs region was neglected in the subsequent analysis. Finally, mixed injection was obtained by absorption of light at 1.3 μm in the undoped InGaAs layer.

The derived ionisation coefficient results were calculated from averaged gain data for typically 5–10 devices, and a typical pure electron gain curve for wafer #2 is shown in figure 1. The non-zero gradient observed experimentally at low voltages was removed by fitting a sloping baseline to the low voltage data points, and the corrected data are also shown in figure 1 for comparison. This sloping baseline is attributed to a voltage-dependent collection efficiency due to incomplete depletion at low bias, and the numerical correction applied leads to a reduction in the calculated value of α by 5–10% in the high-field region. The gain curves for devices from wafer #1, for both pure electron and mixed injection, were analysed by standard methods [10] to yield the results for α and β which are plotted as a function of inverse field in figure 2. Reliable analysis of the gain data under mixed injection was not possible for wafers #2 and #3 because of the penetration of the Zn diffusion into the InGaAs absorption region of the planar p–i–n diodes; therefore, analysis of the pure electron gain curve only was used to corroborate the data obtained from wafer #1. Since a single gain curve cannot be used to calculate α and β independently, it is necessary to assume a value for the ratio α/β, and in figure 2 a value of 2 has been used, consistent with the data from wafer #1. The resulting values for α are only very weakly dependent upon the assumed value of α/β, and are in good agreement across devices from all three wafers.

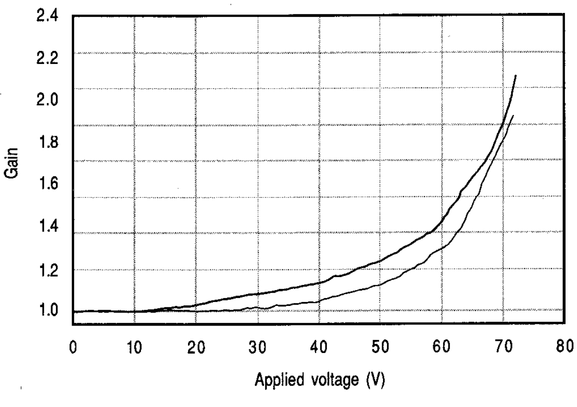

Figure 1. A typical pure electron gain curve obtained from a device from wafer #2, (upper curve) as measured and (lower curve) after correction for the sloping baseline has been taken into account.

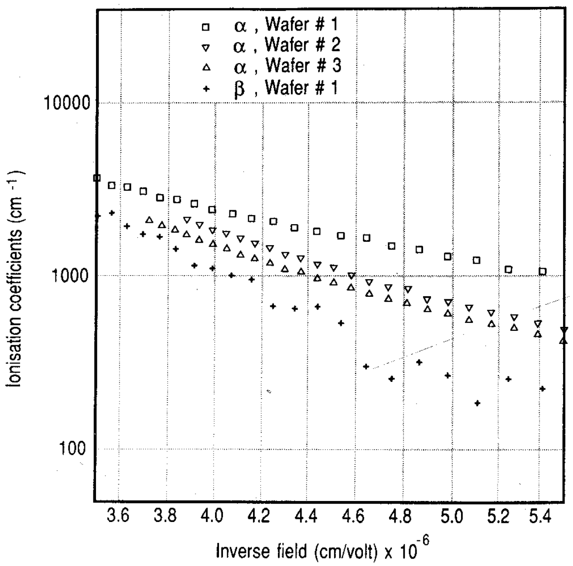

Figure 2. A graph of ionisation coefficient (cm^{-1}) against inverse field ($cm\ V^{-1}$) for wafers #1, #2 and #3. Values of α have been obtained for each wafer, but the value of β could only be obtained from wafer #1, for the reasons explained in the text.

The best-fit ionisation coefficients, over the inverse field range $3.5\text{–}5.5 \times 10^{-6}$ cm V^{-1}, are given by

$$\alpha(E) = 6.90 \times 10^4 \exp(-0.9 \times 10^6/E)$$

$$\beta(E) = 1.15 \times 10^6 \exp(-1.7 \times 10^6/E)$$

where the ionisation coefficients are in units of cm^{-1}, and the electric field, E, is in units of V cm^{-1}. In figure 3, the results reported in this letter are compared with the previously published results of Osaka *et al* [7] and Pearsall [9]. Care has been taken to plot the data only over the field ranges given in the original papers [7, 9], so that no extrapolation of Osaka *et al*'s and Pearsall's data has been carried out. Clearly, the consistent results obtained from all three wafers are in excellent agreement with those of Osaka *et al*, and more than an order of magnitude smaller than the values given by Pearsall. In addition to the close agreement with Osaka *et al* [7] for the absolute values of α and β, the gradients of α and β with respect to the inverse field, $d\alpha/d(1/E)$ and $d\beta/d(1/E)$, also agree well with the results of Osaka *et al* [7],

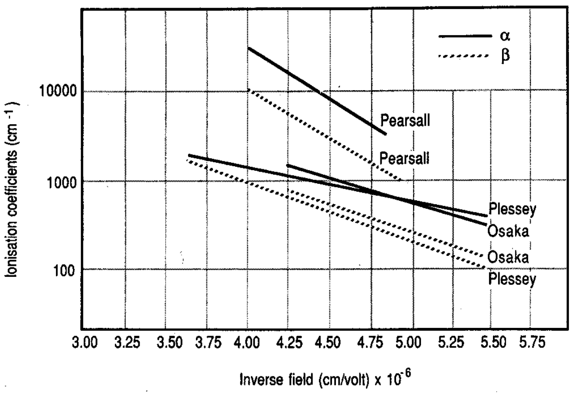

Figure 3. A graph of ionisation coefficient (cm^{-1}) against inverse field (cm V^{-1}), comparing the results reported here with those of Pearsall [9] and Osaka *et al* [6, 7].

although the gradient of α with respect to inverse field differs slightly, so that if Osaka *et al*'s data were extrapolated to higher electric fields, the value of α obtained would be higher than the values we find.

In summary, the electron and hole ionisation coefficients of $In_{0.53}Ga_{0.47}As$ have been estimated from photocurrent gain measurements and our results tend to confirm the values and field dependences of α and β given by Osaka *et al* [7] rather than the values given by Pearsall [9].

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