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Article (Published Version)

Whitaker, M D C, Lioliou, G, Krysa, A B and Barnett, A M (2020) InGaAs x-ray photodiode for spectroscopy. Materials Research Express, 7 (10). a105901 1-5. ISSN 2053-1591

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To cite this article: M D C Whitaker et al 2020 Mater. Res. Express 7 105901

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InGaAs x-ray photodiode for spectroscopy

M D C Whitaker¹, G Lioliou¹, A B Krysa² and A M Barnett¹

¹ Space Research Group, Sch. of Mathematical and Physical Sciences, University of Sussex, Falmer, Brighton, BN1 9QT, United Kingdom
² EPSRC National Epitaxy Facility, Dept of Electrical and Electronic Engineering, University of Sheffield, Mappin Street, Sheffield, S1 3JD, United Kingdom

Abstract
A prototype In$_{0.53}$Ga$_{0.47}$As p$^+$-i-n$^+$ x-ray photodiode, fabricated from material grown by metalorganic vapour phase epitaxy, was investigated as a novel detector of x-rays. The detector was connected to a custom low-noise charge sensitive preamplifier and standard readout electronics to produce an x-ray spectrometer. The detector and preamplifier were operated at a temperature of 233 K (−40 °C). An energy resolution of 1.18 keV ± 0.06 keV Full Width at Half Maximum at 5.9 keV was achieved. This is the first time InGaAs (GaInAs) has been shown to be capable of spectroscopic photon counting x-ray detection.

The compound semiconductor In$_x$Ga$_{1-x}$As has found utility across a wide number of applications; including, but not limited to, laser diodes [1–3], single photon avalanche detectors [4, 5], eye-safe 3D laser scanning (Lidar) [6–8], and transistors [9, 10]. However, to date, there has been no report of the suitability of In$_x$Ga$_{1-x}$As photodiodes as detectors for x-ray (or γ-ray) photon counting spectroscopy.

At present, in environments where low temperature (< 300 K) operation is possible, Ge (bandgap, $E_g$ = 0.66 eV at 300 K [11]) and Si ($E_g$ = 1.12 at 300 K [12]) x-ray detectors are commonplace [13]. Detectors of both materials can provide good Fano-limited energy resolutions (101 eV [14] and 120 eV [15] full width at half maximum, FWHM, at 5.9 keV), but Ge has better (larger) linear x-ray absorption coefficients (841 cm$^{-1}$ at 5.9 keV [16]). Consideration of alternative detector materials, with possibly even better properties, is also interesting. In this letter, an In$_{0.53}$Ga$_{0.47}$As ($E_g$ = 0.75 eV at 300 K [17]) photodiode is demonstrated to be capable of spectroscopic x-ray detection for the first time. The immediate attraction of the material is that its linear x-ray absorption coefficients are better than those of both Ge and Si (e.g. 1530 cm$^{-1}$ for In$_{0.53}$Ga$_{0.47}$As at 5.9 keV [16]). Another favourable indication for In$_{0.53}$Ga$_{0.47}$As is that devices made from the material have been reported with very small leakage currents ($≈$ 10$^{-14}$ A) [18]; this is important because leakage currents in part control the parallel white noise of x-ray spectrometers and therefore play a key role in setting the energy resolution achievable in such spectrometers [19].

An In$_{0.53}$Ga$_{0.47}$As p$^+$-i-n$^+$ structure (see table 1) was grown by metalorganic vapour phase epitaxy on an (100) InP n$^+$ substrate. Circular mesa photodiodes (200 μm diameter) were fabricated by a two-step wet etching in 1:1:1 HBr:K$_2$Cr$_2$O$_7$:CH$_3$CO$_2$H and 1:8:80 H$_2$SO$_4$:H$_2$O$_2$:H$_2$O solutions. A quasi-annular top metal contact (200 nm Au, 20 nm Ti; covering 45% of the diode’s face) was evaporated onto the p$^+$ side of each mesa structure. A rear planar metal contact (200 nm Au, 20 nm InGe) was evaporated onto the rear of the substrate. A randomly selected photodiode was packaged in a TO-5 can and gold ball-wedge wirebonded.

The packaged detector was connected to a custom-made feedback resistorless charge-sensitive preamplifier (similar to [20]) and standard onwards readout electronics as per [21]. The detector and preamplifier were installed within a TAS Micro MT environmental chamber, which was continually purged with dry N$_2$ [22]. An $^{55}$Fe radioisotope x-ray (Mn Kα = 5.9 keV; Mn Kβ = 6.49 keV) source (activity $≈$ 164 MBq) was placed atop the In$_{0.53}$Ga$_{0.47}$As x-ray photodiode with $≈$ 4 mm between the source and photodiode. A thermocouple was placed atop the In$_{0.53}$Ga$_{0.47}$As x-ray photodiode in order to monitor the temperature of the detector and preamplifier. The internal temperature of the environmental chamber was reduced to 233 K (−40 °C). The remaining electronics chain...
was kept at room temperature. Once the detector, preamplifier, and chamber atmosphere had reached thermal equilibrium at 233 K, measurements were started. 55Fe x-ray spectra were acquired with the In0.53Ga0.47As x-ray photodiode operated at applied reverse biases, \( V_{ARB} \), of: (a) 0 V; (b) 0.1 V; (c) 1 V; and (d) 5 V (black lines). The fitted peaks of Mn K\( \alpha \) (5.9 keV, blue dashed lines) and Mn K\( \beta \) (6.49 keV, red dashed lines), together with the combination of those peaks (purple solid lines), are also shown. The Mn K\( \alpha \) and Mn K\( \beta \) peaks were not resolved individually and so form a combined peak in the detected spectra. The spectra were normalised into counts per keV in order to account for the differing multi-channel analyser channel widths of each spectrum.

Table 1. Layer details of the In0.53Ga0.47As p\(^{+}\)-i-n\(^{+}\) structure from which the device was fabricated.

| Material         | Dopant | Dopant type | Thickness (nm) | Doping density (cm\(^{-3}\)) |
|------------------|--------|-------------|----------------|-------------------------------|
| InP              | Zn     | p\(^{+}\)    | 10             | \(1 \times 10^{19}\)          |
| In0.53Ga0.47As   | Zn     | p\(^{+}\)    | 200            | \(2 \times 10^{18}\)          |
| In0.53Ga0.47As   | Si     | n\(^{+}\)    | 5000           | Undoped                       |
| In0.53Ga0.47As   | Si     | n\(^{+}\)    | 100            | \(2 \times 10^{18}\)          |
| InP              |        |             | 200            | \(2 \times 10^{18}\)          |
| InP n\(^{+}\) substrate | | | | |

Figure 1. 55Fe x-ray spectra accumulated with the In0.53Ga0.47As p\(^{+}\)-i-n\(^{+}\) x-ray photodiode based spectrometer operated at a temperature of 233 K (−40 °C) and a shaping time of 0.5 \(\mu\)s with the detector at applied reverse biases, \( V_{ARB} \), of: (a) 0 V; (b) 0.1 V; (c) 1 V; and (d) 5 V (black lines). The fitted peaks of Mn K\( \alpha \) (5.9 keV, blue dashed lines) and Mn K\( \beta \) (6.49 keV, red dashed lines), together with the combination of those peaks (purple solid lines), are also shown. The Mn K\( \alpha \) and Mn K\( \beta \) peaks were not resolved individually and so form a combined peak in the detected spectra. The spectra were normalised into counts per keV in order to account for the differing multi-channel analyser channel widths of each spectrum.
1.49 keV ± 0.06 keV at 5 V. Detector self-fluorescence of the In L shell (L\(\alpha_1\) = 3.29 keV, L\(\alpha_2\) = 3.28 keV, L\(\beta_1\) = 3.49 keV, L\(\beta_2\) = 3.71 keV, L\(\gamma_1\) = 3.92 keV) caused the increased number of counts apparent in the spectra around those energies. Partial collection of charge created in the non-active regions of the detector gave rise to the portion of it can still be seen in each spectrum.

The energy resolution (FWHM) of a non-avalanche semiconductor photodiode x-ray spectrometer is given by

\[
FWHM \ [eV] = \omega \left( \frac{8 \ln (2) FE}{\omega} + R^2 + A^2 \right)^{0.5},
\]

where \(\omega\) is the electron-hole pair creation energy, \(F\) is the Fano factor of the material, \(E\) is the incident photon energy, \(R\) is the total electronic noise of the spectrometer (the quadratic sum of all series white, parallel white, 1/f, dielectric, and induced gate drain current noises), and \(A\) is any incomplete charge collection noise arising from the detector. When \(R\) and \(A\) are zero, equation (1) reduces to the Fano limit of the energy resolution for a given material. Whilst \(F\) and \(\omega\) have yet to be measured and reported for In\(_{0.53}\)Ga\(_{0.47}\)As, it is informative to make cautious estimations of these parameters in the context of considering the noise sources contributing to the overall achieved energy resolutions reported in figure 1.

Considering the ternary nature of the detector material and the high atomic numbers of its constituent elements, the Fano factor of In\(_{0.53}\)Ga\(_{0.47}\)As is likely to be larger than those of Si and Ge; thus a highly cautious value of 0.14 is assumed for the purposes of the estimation. The relationship between \(E_g\) and \(\omega\) is still a topic of investigation [27], but for present purposes, an estimate of \(\omega = 3.05 \text{ eV} \pm 0.13 \text{ eV}\) may be made for In\(_{0.53}\)Ga\(_{0.47}\)As at 300 K, given \(E_g = 0.75 \text{ eV}\) at 300 K [17] and use of the Bertuccio-Maiocchi-Barnett (BMB) relationship [27]. Thus a Fano limit of 118 eV ± 6 eV FWHM at 5.9 keV may be estimated for In\(_{0.53}\)Ga\(_{0.47}\)As at 300 K which is comparable to those of Ge and Si.

Given the leakage current and capacitance of the detector and its packaging, and a priori knowledge of the custom preamplifier, approximations of at least some of the white parallel, white series (including induced gate drain current noise), 1/f, and dielectric noise contributions from the preamplifier and the detector itself, could be calculated as per [28–30]. The calculated white parallel noise included the leakage current associated with the detector, the detector packaging, and the gate leakage current of the input JFET which was estimated to be 1 pA [31]. The calculated white series noise included the capacitance associated with the detector, the detector packaging, and the input JFET capacitance which was estimated to be 2 pF [31]. The calculated dielectric noise included the detector dielectric contribution (assuming a dielectric dissipation factor of 0.001 for In\(_{0.53}\)Ga\(_{0.47}\)As), the detector packaging dielectric contribution (assuming a dielectric dissipation factor of 0.01), and the input JFET dielectric contribution (assuming a dielectric dissipation factor of 0.0008 [32]).

### Table 2. Measured leakage current, capacitance, and depletion width of the In\(_{0.53}\)Ga\(_{0.47}\)As p+–n– x-ray photodiode at 233 K (−40 °C).

| Applied reverse bias (V) | Detector current (pA) | Detector capacitance (pF) | Depletion width (μm) |
|--------------------------|-----------------------|--------------------------|----------------------|
| 0                        | 4.9 ± 0.4             | 1.77 ± 0.02              | 2.19 ± 0.04          |
| 1                        | 255 ± 1               | 1.43 ± 0.02              | 2.70 ± 0.04          |
| 2                        | 344 ± 1               | 1.38 ± 0.02              | 2.81 ± 0.04          |
| 3                        | 391 ± 2               | 1.32 ± 0.02              | 2.88 ± 0.04          |
| 4                        | 420 ± 2               | 1.26 ± 0.02              | 2.95 ± 0.04          |
| 5                        | 441 ± 2               | 1.09 ± 0.02              | 3.07 ± 0.04          |
difference in the Fano-limited energy resolution between 300 K and 233 K is unlikely to be significant compared with the large non-Fano noises present in the reported system.

The degradation in energy resolution (FWHM at 5.9 keV) of the spectrometer as a function of increased applied detector reverse bias (1.18 keV ± 0.06 keV at 0 V cf 1.49 keV ± 0.06 keV at 3 V) was explained, in part, by the increase in calculated parallel white noise (contributing 41 eV ± 3 eV at 0 V cf 360 eV ± 2 eV at 5 V). However, it should be noted that the values calculated for the various noise components when combined in quadrature with the likely Fano noise did not amount to the entirety of the noise observed to be present in the system; the remaining noise contribution, calculated by subtracting in quadrature the calculated noise contributions (including the estimated Fano limit) from the measured energy resolution, remained significant, increasing from a contribution of 1.06 keV ± 0.07 keV at 0 V to 1.36 keV ± 0.07 keV at 5 V. This remaining noise contribution included additional stray electronic noises, which remained unaccounted in the approximation employed to estimate the electronic noise contributions, likely originating from lossy dielectrics in proximity to the gate of the input JFET, as well as parasitic components of white parallel and stray white series noise arising within the system; incomplete charge collection noise may also have played a part.

Since the depletion width of the In0.53Ga0.47As x-ray photodiode did not extend across the 5 μm i layer (see table 2) within the investigated applied reverse bias range, incomplete charge collection noise may have been present, particularly from the non-depleted region of the i layer, but this cannot be quantified from the present results. In addition, the large leakage current of the In0.53Ga0.47As detector (e.g. 441 pA ± 5 pA at 5 V applied reverse bias) may have adjusted the operating bias condition of the preamplifier input JFET, which is in part set by the leakage current of the detector in feedback resistorless designs such as the one used here [20]; this may have increased the leakage current and consequently the parallel white noise contribution of the JFET. Although the JFET leakage current was estimated to be 1 pA at the optimal operating bias condition (equivalent to 17 eV parallel white noise), this can increase to >10 nA when it is operated in suboptimal bias conditions (equivalent to >1.71 keV parallel white noise) [31]. The increase in noise brought by modification of the bias point of the JFET was included in the quantity of noise classified as stray, and likely explains, in part, the variation of the stray noise contribution with detector bias.

In summary, InGaAs has been shown to be capable of photon counting x-ray spectroscopy for the first time. An energy resolution of 1.18 keV ± 0.06 keV FWHM at 5.9 keV at a temperature of 233 K (−40 °C) was achieved using a prototype In0.53Ga0.47As p−−i−n+ photodiode coupled to a charge-sensitive preamplifier and standard onwards readout electronics. Although the energy resolution achieved was modest compared to current gold-standard cooled spectrometers using Ge or Si detectors, as well as other uncooled prototype detectors such as AlGaAs (630 eV FWHM at 5.9 keV at 20 °C [27]), CdZnTe (270 eV FWHM at 5.9 keV at room temperature [33]), GaAs (250 eV FWHM at 5.9 keV at −5 °C [34]), and InGaP (770 eV FWHM at 5.9 keV at 20 °C [35]), further development of InGaAs x-ray detectors is likely to improve the performance attainable. In addition, recent work on superlattice structures [36–38] may help to improve the FWHM of future InGaAs x-ray detector designs. This promise, together with the results already obtained, as well as the large x-ray absorption coefficients of InGaAs and the possibility of developing spectroscopic In0.53Ga0.47As-InP heterojunction x-ray avalanche photodiodes, provides motivation for further work on x-ray detectors made from the material in
future. In order to inform future development of InGaAs x-ray spectrometers, investigation of their performance as a function of temperature and in response to illumination with different energy x-rays and γ-rays (e.g. those from $^{241}$Am and $^{109}$Cd radioisotope x-ray/γ-ray sources) would be valuable.

Acknowledgments

This work was supported, in part, by the Science and Technology Facilities Council, UK; Grants ST/P001815/1 and ST/R001804/1. A M B acknowledges funding from the Leverhulme Trust, UK, in the form of a 2016 Philip Leverhulme Prize. The authors are grateful to R J Airey and S. Kumar at University of Sheffield for device fabrication.

Authors’ data statement

All data that support the findings of this study are included within the article (and any supplementary information files).

ORCID iDs

M D C Whitaker https://orcid.org/0000-0001-6109-5793
G Lioliou https://orcid.org/0000-0002-6989-7106
A B Krysa https://orcid.org/0000-0001-8320-7354

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