Energy response of AlGaAs soft X-ray photon counting detectors

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Abstract: A variety of new types of detectors based on wide band gap materials have been developed for soft X-ray spectroscopy applications (e.g. GaAs, SiC, diamond). In this report we describe the spectroscopic performance of a simple p-i-n diode fabricated on AlGaAs. The energy response of the diode, operating in photon counting mode, at room temperature has been investigated using fluorescence from a number of high purity materials. X-ray spectra over the energy range 5 keV–25 keV show this type of diode can be used for spectroscopy with promising energy resolution (~1.3 keV) at 30°C and excellent linearity.

Keywords: Solid state detectors; X-ray detectors; Radiation-hard detectors

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1 Introduction

Radiation detectors that can operate in extremely harsh environments, such as in space and the automotive, aeronautic and nuclear industries, are increasingly in demand. An X-ray detector on a planetary exploration mission, for example, would need to satisfy the high demands on such instrumentation, including extreme thermal operating conditions, low mass, stringent power constraints and high radiation tolerance.

AlGaAs is one of a number of wide bandgap semiconductors such as SiC, GaN, and diamond which have the potential to operate in the harshest environments and overcome the temperature and radiation limitations of commercial silicon.

Although Al\textsubscript{x}Ga\textsubscript{1-x}As detectors have appeared in the literature [1]–[9], reports of photon counting X-ray detectors have been limited. Lees et al. [10] was the first to report Al\textsubscript{0.8}Ga\textsubscript{0.2}As p\textsuperscript{+}-p\textsuperscript{−}-n\textsuperscript{+} (or p\textsuperscript{+}in\textsuperscript{+}) photon counting spectroscopic Xray photodiodes in the literature. Since then a number of papers describing Al\textsubscript{0.8}Ga\textsubscript{0.2}As diodes as X-ray detectors, including their temperature dependence [11], avalanche photodiode (APD) operation [12] and modelling of their operating characteristics [13, 14] have followed.

We have characterized Al\textsubscript{0.8}Ga\textsubscript{0.2}As diodes as soft X-ray photon counting detectors at an operating temperature of 30°C, measuring the spectroscopic performance over the energy range \(\sim 5\)–26 keV. Results indicate that these detectors can be used for X-ray photon counting spectroscopy with a highly linear response over the full measured energy range.
Figure 1. Left: photograph of one of the 200 µm diameter diodes showing the quasi-circular gold contact with the bond pad at the top. Right: schematic of the diode showing an X-ray interacting within the depletion layer (see table 1 and section 3.4).

2 AlGaAs diode design and fabrication

2.1 Fabrication

Circular mesa Al$_{0.8}$Ga$_{0.2}$As diodes of radii 25, 50, 100 and 200 µm were fabricated by photolithography from wafers grown on GaAs n$^+$ substrates by molecular beam epitaxy at the National Centre for III-V Technologies, University of Sheffield, U.K. [10]. Each device had an Au/Zn/Au ohmic contact (annealed at 360°C) to the top p$^-$GaAs layer. In/Ge/Au alloy was deposited on the back n$^+$substrate and then annealed at 420°C to provide the ohmic n$^-$metal contact. The diode sets were mounted in TO-5 packages. Layer thicknesses and doping concentrations for one design of wafer grown and investigated are given in table 1. The capacitance of the 100 µm radius diodes was 5 pC for reverse bias voltages $>$ 5 V. Full depletion of the device was achieved for bias voltages $>$ 5 V. An operating bias voltage of 10 V was chosen to ensure full depletion but to keep the leakage current below 0.1 nA.

3 X-ray measurements

A common technique for generating X-rays at a range of energies is to illuminate pure materials with an X-ray source to generate characteristic fluorescence lines. We have used an X-ray tube with a Molybdenum (Mo, Z = 42) target to produce a bremsstrahlung X-ray flux and a variety of materials as targets. Table 2 lists the various materials, their thicknesses and purity along with the principal X-ray fluorescence line and energy.

3.1 Experiment and method

The Al$_{0.8}$Ga$_{0.2}$As detector (200 µm diameter) was mounted within the sample chamber of a commercial X-ray apparatus [16] which comprises an X-ray vacuum tube source, collimator and a
Table 1. Layer details for the $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ wafer.

| Layer | Material       | Thickness (µm) | Dopant Type | Doping Density ($\times 10^{18}$ cm$^{-3}$) |
|-------|----------------|----------------|-------------|------------------------------------------|
| 1     | GaAs           | 0.01           | Be          | p+                                       |
| 2     | $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ | 1              | Be          | p+                                       |
| 3     | $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ | 1              | Undoped     |                                         |
| 4     | $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ | 1              | Si          | n+                                       |
| 5     | GaAs           | 0.25           | Si          | n+                                       |
|       | Substrate      |                |             |                                         |

Table 2. Materials used as fluorescence sources. The thickness and purity are from the manufacturer’s data.\(^1\) Only the principal X-ray energy is listed for brevity, for other lines, fluorescence yield etc see Sanchez del Rio et al. [15].

| Material | Thickness (mm) | Purity (%) | X-ray line | Energy (keV) |
|----------|----------------|------------|------------|--------------|
| V        | 1.0            | 99.95      | K\(_\alpha\) | 4.95         |
| Cr       | 1.0            | 99.7       | K\(_\alpha\) | 5.41         |
| Mn       | 0.05           | 98.7       | K\(_\alpha\) | 5.90         |
| Cu       | 1.0            | 99.9       | K\(_\alpha\) | 8.05         |
| Au       | 0.25           | 99.95      | L\(_\alpha\) | 9.71         |
| Ge       | 1.0            | 99.99      | K\(_\alpha\) | 9.89         |
| Nb       | 1.0            | 99.9       | K\(_\alpha\) | 16.62        |
| Pd       | 0.5            | 99.95      | K\(_\alpha\) | 21.18        |

goniometer which includes a sample holder and a detector mount. Figure 2 is a schematic of the system which shows each component and defines the angular directions. The apparatus also includes control electronics and software for simple selection of X-ray source operating voltages and sample and detector angles. Each material was placed on the sample holder which was set at 45 degrees relative to the X-ray incident direction (\(\phi = 45^\circ\)) with the diode input face set at 90 degrees (\(\theta = 90^\circ\)). For all our measurements the X-ray tube was operated at a voltage of 35 keV and a current of 1 mA. The characteristic energy peaks of the Mo target within the X-ray tube are the K\(_\alpha\) line at 17.4 keV and the K\(_\beta\) line at 19.6 keV, both will be present in the X-ray source spectrum [16].

3.2 X-ray spectra

Each $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ diode was reverse biased at 10 V and connected to a novel, in-house designed, charge-sensitive preamplifier which operates without a feedback resistor [17] while utilising a Si JFET (Vishay Siliconix 2N4416, capacitance = 2 pF) input transistor [18] and housed in a small die cast box having a thin (4 µm) Al window. The preamplifier was connected to an EG&G Ortec 571 shaping amplifier operating with a 3 µs shaping time with the output connected to an Ortec multi-channel analyser (MCA). The input discriminator level of the MCA was adjusted to minimise the

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\(^1\)Goodfellow Cambridge Ltd., Ermine Business Park, Huntingdon, England PE29 6WR, U.K.
number of noise counts from the zero energy noise peak. During the measurement period, the bias voltage was continuously applied to the diode and the preamplifier constantly powered. The sample chamber was allowed to thermally stabilise prior to commencing the X-ray measurements with the detector operating at a nominal temperature of 30.0 ± 1.0°C as measured by a thermocouple.

A number of spectra were taken at each X-ray energy with accumulation times varying between 8 and 24 hours, depending on the fluorescence yield and detector efficiency, to obtain sufficient number of events in the principal photopeak to produce good statistics for analysis.

Comparison of two of the spectra brings out a number of interesting features related to the diode material and the energy of the illuminating X-rays.

**Niobium spectrum.** Figure 3 shows a spectrum obtained from X-ray emission from the niobium sample which has principal fluorescence line energies of 16.62 keV and 18.62 keV (K\(_\alpha\) and K\(_\beta\) respectively). The spectrum clearly shows the two Nb fluorescence lines along with escape peaks for Ga and As as would be expected. The characteristic K\(_\alpha\) fluorescence energies for Ga and As are 9.25 keV and 10.54 keV respectively. The As K\(_\alpha\) escape is the main peak at 6.04 keV whereas the other distinct peak at ~9.37 keV is the Ga K\(_\alpha\) escape peak. Neither of the K\(_\beta\) escape peaks are resolvable partly due to their lower fluorescence yield which, in the case of Ga, is compounded by its relatively low abundance in the diode material.

**Palladium spectrum.** Figure 4 shows a spectrum obtained from X-ray emission from the palladium sample which has principal fluorescence line energies of 21.17 keV and 23.82 keV (K\(_\alpha\) and K\(_\beta\) respectively). Both these fluorescence lines are clearly visible in the spectrum along with escape peaks for Ga and As. In this spectrum the As-K\(_\alpha\) escape peak related to the Pd-K\(_\alpha\) line occurs at 10.63 keV along with an additional lower energy peak (~9.5 keV) which is likely to be the As-K\(_\beta\) escape peak associated with the Pd-K\(_\alpha\) line. Another distinct peak at 13.28 keV is the As-K\(_\alpha\) escape peak from the Pd-K\(_\beta\) line. The Ga escape peaks and the As-K\(_\beta\) peak from the Pd-K\(_\beta\)
Figure 3. Nb spectrum accumulated over 17 hours. Peaks from the characteristic groups Nb K\(\alpha\) (red dashed line) and Nb K\(\beta\) are visible but the individual lines for K\(\alpha\) (\(\alpha_1\) and \(\alpha_2\)) and K\(\beta\) are not resolved. The As K\(\alpha\) escape from Nb K\(\alpha\) peak (blue dashed line) is also apparent along with the Ga fluorescence peak (9.25 keV). The line should also be present but their energies (\(\sim\) 13.4 keV and 11.9 keV respectively) mean they are likely combined in the shoulder of the larger As escape peaks. The peak with a nominal energy of 17.75 keV is attributable to Mo-K lines from the Molybdenum anode used in the X-ray source [16] scattering from the palladium sample. These lines are not obvious in the Nb spectrum as they are close to the energy to the Nb-K line and cannot be resolved by the limited energy resolution of the AlGaAs detector system.

3.3 FWHM

The Full Width at Half Maximum (FWHM) of the principle X-ray fluorescence photopeak was calculated for every each X-ray spectrum accumulated. Figure 5 shows the calculated FWHMs as a function of energy.

The FWHM energy resolution of a semiconductor X-ray detector is give by equation (3.1) [19] where \(E\) is the incident X-ray energy, \(F\) is the Fano factor and \(\omega\) is the electron hole creation energy.

\[
\Delta E = 2.35\omega \sqrt{\frac{FE}{\omega} + R^2 + A^2}
\]

(3.1)

The factor \(R\) is the equivalent noise charge (in r.m.s. e-) introduced by the detector during the movement of the charge to the contacts (e.g. by charge trapping), and \(A\) is the equivalent noise charge (ENC) introduced by the detector’s leakage current, capacitance and the properties of the preamplifier [12]. For optimal spectroscopic performance it is essential to minimise \(R\) and \(A\). In the ideal case, where both \(R\) and \(A\) are negligible, the spectral resolution is said to be Fano limited.

It has been observed that for compound semiconductors, effects such as charge trapping, charge transfer efficiency and polarization can lead to a non-Gaussian distribution with quasi-exponential tails appearing on the low energy side of the spectral lines [20]. Since we see little
Figure 4. Pd spectrum accumulated over 24 hours. Peaks from the characteristic groups Pd K$_\alpha$ (red dashed line) and Pd K$_\beta$ are visible but the individual lines for K$_\alpha$ ($\alpha_1$ and $\alpha_2$) and K$_\beta$ are not resolved. The As K$_\alpha$ escape from Pd K$_\alpha$ peak (blue dashed line) is also apparent.

Figure 5. Plot of FWHM of K$_\alpha$ peaks from an array of different sources against their peak energies in keV. The dashed black is the fitted noise function, equation (3.1).

evidence of this effect (the observed X-ray peaks are essentially Gaussian as demonstrated in figures 3 and 4), we can assume that peak broadening due to partial charge collection is negligible (i.e. $R^2 \ll A^2$) which may be related to the higher than desired electronic noise. For simplicity we have assumed that $R = 0$. 
Therefore the measured noise can be attributed solely to A which is a combination of the parallel white \(N_{PW}\), series white including induced gate current \(N_{SWC}\), \(1/f\) \(N_{1/f}\) and dielectric noise \(N_D\) contributions [12]. Using equation (3.1) and the assumption that \(R = 0\) the electronic noise was calculated for our system giving an ENC of 107 electrons rms. The dashed line in figure 5 indicates the calculated energy resolution and shows that this simple model gives a good fit to the experimental data.

Earlier papers [10, 12] have indicated that the electronic noise associated with the preamp and diode mounting used in our current detector design contributes significantly to the measured energy resolution. Although the \(N_{PW}\), \(N_{SWC}\) and \(N_{1/f}\) contributions can be calculated [12], \(N_D\) is not readily calculable because stray capacitances are not easily measured. However, by calculating the noise contributions \(N_{PW}\), \(N_{SWC}\) and \(N_{1/f}\) and, subtracting in quadrature from the total noise, \(N_I\), it is possible to obtain an estimate for the dielectric noise, \(N_D\).

The series white noise contribution was calculated following the method outlined by Lees et al. [12] assuming \(\gamma = 0.85\), a constant depending on the FET characteristics [21], transconductance of the FET \(g_m = 5\ \text{mS}\) [18], and that the total capacitance at the preamplifier input, \(C_I\), is dominated by the capacitances of the detector (5 pF) and FET (2 pF). The series white noise contribution was adjusted for induced gate current noise by assuming \(\sqrt{G_c} \approx 0.8\) [21]. The \(1/f\) noise contribution was calculated from

\[
N_{1/f} = \frac{1}{q} \sqrt{A_2 \pi A f C_I^2}
\]

with the above assumptions and also that \(A_2 = 1.2\) and \(A_f = 3 \times 10^{-15}\ \text{V}^2\) [22] where \(q\) is the electronic charge. The parallel white noise contribution for a shaping time of 3 \(\mu\)s and an operating temperature of 30° C was calculated [12] with a signal shaping function constant \(A_3 = 2\) [22].

The dielectric noise was then calculated from

\[
N_D = \sqrt{N_I^2 - N_{PW}^2 - N_{SW}^2 - N_{1/f}^2}
\]

Giving \(N_D = \sqrt{(107^2 - 61^2 - 30^2 - 0.43^2)} = 83\) electrons rms.

If the dielectric noise could be minimised through improvements to the diode and FET packaging we would expect the energy resolution at 30°C to improve from \(\sim 1.3\) keV (FWHM) to 835 eV at 5.9 keV (3 \(\mu\)s shaping time) [12]. Reducing the energy resolution further towards the Fano limited case would obviously require reducing the other noise sources of which the parallel white noise \(N_{PW}\) is the second most dominant in our current system. The expected energy resolution, if the system was Fano limited, would be 142 eV FWHM at 5.9 keV assuming a Fano factor of 0.12 and an electron-hole pair creation energy of 5.1 eV [23].

Figure 6 shows good agreement between the measured energy resolution, \(\Delta E/E\), of the Al-GaAs diode and the well-known form for semiconductor detectors (dashed line). The detector response is proportional to \(\sim 1/E\) whereas for a Fano limited system the response would be proportional to \(\sim 1/E^{0.5}\).

### 3.4 Linearity

An important characteristic of spectroscopic detectors is the degree of linearity as a function of energy. Ideally the detector would show no deviation from a one-to-one mapping over the entire operating energy range. However, there are a number of factors that can result in semiconductors not
meeting this goal such as charge trapping, charge transfer efficiency and polarization effects [24]. Figure 7 shows the linearity of the AlGaAs diode over the full energy range measured. The curve, fitted using the in-built routines in the commercial software Origin,\(^2\) indicates that the diode is extremely linear over the 5–25 keV range.

3.5 Efficiency

Although the diodes used in this work were not specifically designed for X-ray absorption, it is informative to consider the X-ray detection efficiency, \(Q_d\). The efficiency of the diodes is, in part, determined by the transmission and absorption in the various material layers (table 1). For simplicity, it is assumed that only the top three layers play a significant part in the diode’s efficiency for incident X-rays and that the charge collection efficiency from the \(i\) layer is 100% (figure 1 right). The transmission through the top two layers and the absorption in the third layer can be calculated to estimate the efficiency using

\[
Q_d = e^{-\mu_1t_1}e^{-\mu_2t_2} (1 - e^{-\mu_3t_3}),
\]

(3.4)

where \(\mu_i\) and \(t_i\) are the absorption coefficient and thickness for the \(i\)th layer. The calculated efficiency, figure 8, used the absorption coefficients (as a function of energy) of materials GaAs and \(\text{Al}_{0.8}\text{Ga}_{0.2}\)As and the effects of the various absorption edges for each of the elements Al, Ga, and As.

The energies for absorption edges of Ga-K, Ga-L\(_I\), Ga-L\(_II\), Ga-L\(_III\), As-K, As-L\(_I\), As-L\(_II\), As-L\(_III\), and Al-K are 10.367, 1.299, 1.143, 1.116, 11.867, 1.527, 1.359, 1.323, and 1.558 keV,

\(^2\)OriginLab Corporation, One Roundhouse Plaza, Suite 303, Northampton, MA 01060, U.S.A.
Figure 7. The graph demonstrates the linear behaviour between peak ADU measurements and energy. The elements used for each fluorescence source are indicated (their corresponding energies in keV are listed in table 2. The linear regression line fits very well with a Pearson’s $R^2$ value of 0.998. The gradient corresponds to 79.16 ADU/keV.

Figure 8. Calculated efficiency of the AlGaAs diode as a function of energy.

respectively. A density of $\sim 4.07\,\text{gcm}^{-3}$ was assumed for Al$_{0.8}$Ga$_{0.2}$As [25, 26]. Equation (3.4) may underestimate the efficiency because it ignores collection of carriers generated in layers 1, 2 and 4. Although these carriers are generated outside the depletion region, some of them can still diffuse to the depletion edges and hence contribute to the signal.
One would expect the higher density of Al$_{0.8}$Ga$_{0.2}$As to offer better efficiency for higher energy X-rays than a silicon detector of comparable thickness. Although the Ga and As L-edges (1.1–1.3 keV) will reduce the detection efficiency below 1 keV for Al$_{0.8}$Ga$_{0.2}$As diode when compared to the silicon diode, there will be improved detection for X-rays above 3 keV. When considering materials for X-ray detectors the position of the absorption edges within the energy range of interest, along with the fluorescence lines and their yields, needs to be to carefully considered e.g. a prominent Si-K edge may be undesirable in some X-ray analysis applications.

Overall the detection efficiency of AlGaAs diodes would be improved if the design (a) minimised absorption in the top two layers (thin Layers 1 and 2), and (b) maximised absorption in the i layer (thick Layer 3).

4 Conclusions

In a number of recent papers we have shown that AlGaAs detectors have many of the attributes, (high temperature operation, low leakage current and APD operation [11]–[14]) required to survive in relatively harsh environments while offering spectroscopic photon counting imaging.

Ideal X-ray detectors for spectroscopy should have high efficiency, low noise, good energy resolution and be linear over the energy range required by the application. In this report we have shown that the Al$_{0.8}$Ga$_{0.2}$As diodes we have tested have most of these attributes. The linearity of the diodes over such a wide energy range is remarkable given their relatively very thin active region. One parameter that needs obvious improvement is energy resolution. As discussed in section 3.3 a number of noise sources need to be reduced to move towards an energy resolution that would be competitive with other compound semiconductor devices. In our present system the main limiting factors are the preamp, the device packaging and the leakage current of the device. We are currently re-evaluating the device packaging and investigating other materials and mounting schemes rather than the existing T05 headers. Changes in device fabrication should lead to lower leakage currents (< 0.1 nA). Reducing these noise sources and the development of ultra-low noise electronics (≈ 10 electrons rms) should ultimately enable AlGaAs X-ray detectors to operate very close to the expected Fano limited resolution (142 eV).

Further developments of AlGaAs detectors will, in the future, lead to X-ray imaging spectroscopic arrays capable of operating in a wide variety of harsh environments. Combining AlGaAs detectors with the radiation hard electronics would lead to systems that could operate at elevated temperatures and in environments which would be unsuitable for most currently available spectroscopic detector systems.

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