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Characterization of room temperature AlGaAs soft X-ray mesa photodiodes

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Abstract

Results characterizing a set of nine prototype $Al_{0.8}Ga_{0.2}As$ p^+-i-n^+ mesa photodiodes (400 µm diameter, 1.7 µm i layer) are presented. The results show the performance of the devices as room temperature spectroscopic photon counting soft X-ray detectors. The responses of the photodiodes to illumination with an ^{55}Fe radioisotope X-ray source were measured using a low noise charge sensitive preamplifier; the energy resolutions measured with the devices were consistent with each other and had a mean FWHM at 5.9 keV of 1.27 keV. The devices are the thickest (highest quantum efficiency) AlGaAs X-ray spectroscopic mesa photodiodes reported in the literature to date. They also have better energy resolution than all previously reported non-avalanche AlGaAs X-ray detectors of the same area.

Keywords: AlGaAs; detector; X-ray; spectroscopy; photodiode

1. Introduction

Narrower bandgap materials such as silicon (the material most commonly used for semiconductor X-ray detectors) offer excellent energy resolutions when cooled to ≤ 20 °C [1], but this performance degrades at high temperatures due to increased thermal charge carrier generation [2]. In some extreme cases, the optimum operating temperatures for silicon X-ray detectors can be as low as -130 °C [3], although cooling to more modest temperatures is more common. Under certain circumstances, such as spaceflight, cooling detectors to low temperatures can be impractical or undesirable since it increases the mass, volume and power requirements of the instrument.

Spectroscopic photon counting X-ray photodiodes made from materials such as SiC [4,5], GaAs [6,7,8] and AlGaAs [9,10] offer the ability to operate uncooled in high temperature environments (>>20 °C) due to the low thermally induced leakage currents present in wide band gap materials giving rise to correspondingly small parallel white noises in the detector system [2]. Potential uses for high temperature spectroscopic photon counting detectors include X-ray fluorescence spectroscopy for geological applications on hot planetary surfaces (e.g. Mercury, Venus, parts of Earth) as well as for various terrestrial applications in industrial instrumentation and process control.

The first reported use of AlGaAs for X-ray detection was by Lauter et al. in 1995 [11] as part of an AlGaAs/GaAs X-ray APD. However, it is only in more recent years that AlGaAs has started to receive significant attention for X-ray applications with results reported showing the response of single pixel detectors to X-rays [9,10-13], beta particles and electrons [9,14] and alpha particles [12], with the subsequent measurement of key parameters relevant to high temperature AlGaAs detector physics such as the electron-hole pair creation energy [15,16] and the temperature dependence of the impact ionization coefficients [17]. Another challenge in the development of AlGaAs for X-ray detector applications has been the historically low good device yield (low leakage, acceptable and consistent spectral performance) from growth and fabrication runs. The effect of this has been that until now researchers have presented results from only single or very few AlGaAs X-ray devices rather than reporting characterisation of multiple devices on the same die as would be required if monolithic AlGaAs pixel arrays are to become a reality.

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In this paper, results are presented from a new nine diode set of $Al_{0.8}Ga_{0.2}As$ X-ray mesa photodiodes (400 µm diameters, 1.7 µm i layers) operated at room temperature and coupled to a charge sensitive preamplifier of custom design. The devices were randomly selected from a ~5 mm by ~5 mm die from a wafer grown by Molecular Beam Epitaxy. Unlike previous work, every diode tested showed a low leakage current and a spectroscopic photon counting response with consistent energy resolution. This is a significant step towards the realisation of AlGaAs mesa X-ray photodiode pixel arrays since the device yield is now demonstrably high enough for the production of small arrays (e.g. 3 by 3 pixels) to be a reality. The devices also have the highest quantum efficiency for spectroscopic photon counting AlGaAs X-ray mesa photodiodes reported in the literature to date, the best spectral resolution for non-avalanche AlGaAs devices of this size reported in the literature to date, and for the first time, a quantitative estimate of charge trapping noise in AlGaAs X-ray detectors is calculated.

2. The photodiode design

$Al_{0.8}Ga_{0.2}As$ p^+-i-n^+ epilayers (**Table 1**) were grown by Molecular Beam Epitaxy on GaAs n^+ substrates at the EPSRC National Centre for III-V Technologies, Sheffield, UK. Mesa diodes with diameters of 400 µm were photolithographically etched from the wafer by researchers at University of Sheffield, UK. The p^+-side Ohmic contact covered 45 % of each diode's face and was formed from Au, Zn, Au layers with thicknesses of 5 nm, 10 nm and 200 nm, respectively. The capacitance of the devices was measured at University of Sheffield using an HP 4275 LCR meter (AC test voltage signal magnitude of 50 mV rms, frequency of 1 MHz). At reverse biases ≥ 5 V, the capacitance of each diode was 7 pF and there was no reduction in capacitance at higher applied fields. This indicted that the i layer was fully depleted at biases of 5 V and higher. This assumption was subsequently confirmed by X-ray measurements. Nine randomly selected diodes on a single die were subsequently gold ball bonded to a standard TO package for I-V and X-ray characterisation.

Figure 1 shows the calculated quantum efficiency of the devices assuming that the i layer is the only active region of the detector. For comparison, the quantum efficiencies of two other previously reported AlGaAs devices [9,17] are also plotted in **Figure 1** with the same assumption. It should be noted that whilst the detectors reported here are the thickest spectroscopic photon counting AlGaAs X-ray mesa photodiodes reported to date, the detectors are still thin and intended for device research, rather than as 'user-ready' detectors which would normally require thicker active layers and thinner dead layers to give higher quantum efficiencies.

[TABLE 1]

[FIGURE 1]

3. Experimental method and results

3.1 Leakage current

After packaging, each diode's leakage current was measured as a function of applied reverse bias up to 10 V using a Keithley picoammeter. The measurements were carried out in a dry N_2 environment at a temperature of 20 °C. Plots of the measured leakage currents as a function of applied reverse bias are presented in **Figure 2**. At 5 V, the normal operating reverse bias of the detectors, the mean leakage current of the nine detectors was 5.4 pA ± 2.1 pA (rms deviance) corresponding to a leakage current density of 4.72 nA cm^{-2} ± 1.67 nA cm^{-2} (rms deviance). These leakage current densities are smaller than some that have been reported for AlGaAs X-ray devices at full depletion (e.g. 17.5 nA cm^{-2} and 13.7 nA cm^{-2} [10]), but larger than the best reported in the literature (2.2 nA cm^{-2} [9]). Ensuring low leakage currents is important in order to minimise the contribution from white parallel noise (§3.3.2) to the achievable energy resolution; we highlight that the leakage current densities so far reported for AlGaAs mesa devices are much greater than those reported for high quality 4H-SiC Schottky devices (e.g. 1 pA cm^{-2} [18]).

[FIGURE 2]

3.2 X-ray measurements

3.2.1 Measurements at 5 V reverse bias

To obtain X-ray spectra, the diodes were each reverse biased at 5 V and connected to a single channel low noise charge sensitive preamplifier in turn. The preamplifier used a silicon JFET (NJ26, capacitance ~2 pF) as the input transistor. The preamplifier was of a feedback resistorless design similar to ref. [19]. The preamplifier was connected to an Ortec 571 shaping amplifier (shaping time constant = 3 µs) and multi-channel analyser (MCA). The MCA lower input discriminator was set at 1.8 keV to limit counts from the zero energy noise peak of the preamplifier. An ^{55}Fe radioisotope X-ray source, giving characteristic Mn Kα (5.9 keV) and Mn Kβ (6.49 keV) lines, was positioned above the diodes. As was the case for the leakage current measurements, the diodes and preamplifier were operated in a dry N_2 environment at a temperature of 20 °C. Spectra with live time limits of 300 seconds were accumulated for the devices.

Figure 3 shows the ^{55}Fe spectrum accumulated at 5 V reverse bias with one of the devices, Diode 3. Double Gaussians (dashed lines in **Figure 3**) have been fitted to the observed peak representing the Mn Kα (5.9 keV) and Kβ (6.5 keV) peaks from the radioisotope source in their accepted ratios [20]. The Mn Kα and Kβ lines were too close together to be resolved given the energy resolution of the detector. The MCA low energy cut off (1.8 keV) was set as a compromise between minimising the number of noise counts from the tail of zero energy noise peak and maintaining the low energy response of the detector system. The upwards curve on the low energy tail at low energies is from the right hand side of the zero energy noise peak (which has not been completely eliminated by the 1.8 keV low energy cut off) extending under the low energy tail of the combined Mn Kα, Mn Kβ peak. The spectra were calibrated in energy terms by using the position of the zero energy noise peak and the position of the fitted Mn Kα peak at 5.9 keV for each spectrum as points of known energy on the MCA's charge scale and assuming a linear variation of detected charge with energy.

[Figure 3]

The energy resolution of the system (as measured by the FWHM at 5.9 keV) for each diode when reverse biased at 5 V is shown in **Figure 4**. Also shown in the figure are FWHM for a subset of the devices operated at 10 V reverse bias (see §3.2.2). Every diode functioned as a spectroscopic photon counting detector and all diodes had remarkably similar FWHM suggesting uniform quality of the wafer material across the die. At 5 V, the mean energy resolution was 1.27 keV ± 0.04 keV (rms deviance) at 5.9 keV. The majority of the variability of the FWHM comes from the different leakage currents of the devices giving rise to differently sized parallel white noises (see §3.3.1). The FWHM are significantly better than that previously reported with a 400 µm diameter AlGaAs X-ray photodiode (FWHM at 5.9 keV of 1.95 keV [9]), but the energy resolutions are not as good as the best currently reported for 200 µm AlGaAs devices (1.07 keV at 5.9 keV) [10]. The 200 µm devices in ref. [10] had an area four times smaller than the presently reported devices and consequently benefitted from a reduced capacitance and correspondingly lower series white noise giving improved energy resolution.

[Figure 4]

Low energy tailing on the combined Mn Kα, Mn Kβ peak due to partial charge collection can also be seen in the spectrum presented in **Figure 3**. This is hypothesized to be from charge created by X-ray photon interactions in the non-active layers of the device diffusing towards the active region of the device and consequently having some limited collection. The valley-to-peak (V/P) ratio is one method of quantifying of the amount of low energy tailing, and the V/P ratio for the detectors we report (mean = 0.08) is better than that of previous AlGaAs devices even of smaller area (0.13 [10]), but is not as good as has been reported for thicker room temperature and cooled GaAs detectors (V/P = 0.04, [8,21]) or cooled silicon DEPFETs (V/P ~ 0.0001) [22]. If the low energy tailing in the AlGaAs detectors reported here is primarily a consequence of partial charge collection from photons absorbed in the non-active regions of the devices, then the V/P ratio is likely to improve when thicker (higher quantum efficiency) AlGaAs detectors are produced.

The number of counts per second in the combined Mn Kα Mn Kβ fitted peaks for each of the nine diodes when operated at 5 V was 139 s^{-1} ± 12 s^{-1} (rms deviance); this will be commented on further in §3.2.2.

3.2.2 Measurements at 10 V reverse bias

To investigate the performance of the detectors when operated at increased reverse bias, X-ray measurements were repeated at 10 V for a random selection of two-thirds (six) of the diodes, for convenience these diodes were numbered 1–6 for this manuscript. At this elevated reverse bias, the mean of the leakage currents for the subset of detectors had increased to 14.1 pA ± 5.3 pA (rms deviance) from 5.1 pA ± 1.3 pA (rms deviance) at 5 V. The FWHM measured with the devices when they were reversed biased at 10 V are shown in **Figure 4**; the FWHM were increased compared with those measured at 5 V, indicating that the larger parallel white noise at 10 V outweighs any positive aspects which may be brought from operation higher reverse bias, such as reduced charge trapping (see Section 3.3.1). The V/P ratios for spectra accumulated with the detectors reverse biased at 10 V were the same as when the detectors were biased at 5 V.

To assess whether there was any difference in the quantum efficiency of the devices when operated at 10 V compared to 5 V, the count rate in the combined Mn Kα, Mn Kβ fitted peaks for each detector measured at 10 V was calculated. Had the quantum efficiency or width of the depletion region been significantly increased at 10 V compared with at 5 V, a higher count rate would have been correspondingly expected. No such increase was observed. For the subset of diodes characterised at 10 V the mean count rate was 137 s^{-1} ± 12 s^{-1} (rms deviance); at 5 V the mean count rate for the same subset of devices was 136 s^{-1} ± 14 s^{-1} (rms deviance). Consequently it can be concluded there was no additional extension of the depletion region or increase in quantum efficiency at 10 V. This corroborates the assumption made from the C-V measurements that the devices were fully depleted at 5 V and that there was no extension of the depletion region into the p^+ or n^+ layers at biases up to 10 V.

3.3 Noise analysis

The fundamental 'Fano-limited' energy resolution (FWHM) of a non-avalanche photodiode is given by

$$\Delta E = 2.355\omega\sqrt{\frac{FE}{\omega}} \qquad \text{(Eq. 1)}$$

where ω is the average energy consumed in the generation of an electron-hole pair (recently measured to be 5.1 eV for X-rays in $Al_{0.8}Ga_{0.2}As$ at room temperature [15][16]), F is the Fano factor (still to be experimentally measured for AlGaAs), and E is the energy of the photon. In practice, this resolution is degraded by electronics noise from the connection of the preamplifier to the detector and the preamplifier itself, and noise arising from imperfect charge transport processes in the semiconductor detector, such that

$$\Delta E = 2.355\omega\sqrt{\frac{FE}{\omega} + a^2 + r^2} \qquad \text{(Eq. 2)}$$

where a is the equivalent noise charge contributed by electronics noise (comprised of many constituent noise sources) and r is the equivalent noise charge contributed by charge trapping and collection inefficiencies (both in units of e^- rms). Even though the energy resolutions of the detectors reported here are better than comparable AlGaAs detectors previously reported, the detectors have energy resolutions far poorer than if they were Fano limited (FWHM = 142 eV at 5.9 keV, assuming F = 0.12). As such, it is informative to consider the relative contributions of the noise components that are broadening the energy resolution beyond the Fano limit.

3.3.1 Charge trapping noise

Very large amounts of charge trapping can manifest itself in X-ray spectra obtained with semiconductor devices as significant deviations in peak shape from the expected Gaussian forms [23]. The peaks in the spectra accumulated with the detectors are Gaussian and do not show morphology suggestive of trapping being the dominant noise source. Another common ‘quick test’ for the presence of changes in the charge collection efficiency as a function of reverse bias was also performed: the positions on the MCA’s charge scale (in units of MCA channel number) of the 5.9 keV peaks in the 10 V spectra were compared to the positions of the 5.9 keV peaks in the 5 V spectra. A significant change in the amount of charge collected from the absorption of a 5.9 keV photon in the active region would have revealed itself as a change in peak position. No such shift was present.

However, a more quantitative assessment of trapping noise was also made, which showed that significant levels of trapping were present. Other than charge trapping noise, the only noise source which varies with detector reverse bias is the parallel white noise (Section 3.3.2). By subtracting the parallel white noise from the equivalent noise charge of the measured FWHM at each respective reverse bias, in quadrature, and then subtracting the remaining value for 10 V reverse bias from that for 5 V, in quadrature, the additional charge trapping noise that is present in the 5 V spectra compared with the 10 V spectra can be estimated.

$$\Delta r^2 = \left(\frac{\Delta E_{5V}}{2.355\omega}\right)^2 - N_{5Vpw}{}^2 - \left(\left(\frac{\Delta E_{10V}}{2.355\omega}\right)^2 - N_{10Vpw}{}^2\right) \quad \text{(Eq. 3)}$$

Computing Eq. 3 suggests a mean additional charge trapping noise of 26 e^- rms at 5.9 keV when operating at 5 V compared to 10 V. Consequently it can be said that there is at least 26 e^- rms equivalent noise charge attributable to charge trapping at 5 V.

The measured amount of trapping noise is significant, but small compared to the noise from the electronics currently used. If the electronics noise remained the same but the trapping noise was eliminated, the FWHM at 5.9 keV would improve from 1.27 keV to 1.23 keV. However, the significance of the trapping would be more readily apparent if the electronics noise was negligible and the detector system was Fano limited apart from trapping noise; from Eq. 1, a Fano limited resolution (FWHM) of 142 eV at 5.9 keV was predicted, however the energy resolution achievable in the presence of 26 e^- rms of trapping noise would be 343 eV.

The presence of significant levels of charge trapping in compound semiconductors is well known, with much having been published on trapping and polarisation in many compound semiconductor materials, including GaAs [24] and CdZnTe [25]. That an emerging and relatively young material (for X-ray spectroscopy use) such as AlGaAs suffers trapping is not a surprise, however, to the authors’ knowledge this is the first reported measurement and quantification of trapping in AlGaAs.

3.3.2 Electronics noise

The electronics noise was the most significant contributor to the measured energy resolution in the system we report. It is comprised of parallel white noise, series white noise (including induced gate current noise), 1/f series noise, and dielectric noises. An introduction to these noise components in X-ray photodiodes coupled to charge sensitive preamplifiers can be found in Ref. [26]. The calculated contributions of these noise sources for each diode when reverse biased at 5 V are shown in **Figure 5**.

With the exception of the parallel white noise, the electronics noise components are the same for each diode characterized. The values in **Figure 5** assume that any remaining charge trapping noise beyond the 26e$^-$ rms ENC calculated in Section 3.3.1 was small compared to the other noise sources contributing to the total energy resolution (Eq. 1). Only a minimum bound for the value of the series white noise could be readily calculated since it depends on the total capacitance load on the input transistor of the preamplifier. Due to the prototype nature of the preamplifier used, there were significant stray capacitances with unknown values in addition to the capacitances that were known or readily estimable. The same is true for the dielectric noises; dielectric noise contributions from the detector, JFET and feedback capacitor were readily estimable, but other lossy dielectrics in proximity to the preamplifier may have also added to the noise.

[**Figure 5**]

By subtracting the predicted Fano noise contribution, the calculated charge trapping noise and electronics noise contributions from the measured energy resolution in quadrature, the remainder can be attributed to the total noise from the stray capacitances and dielectrics that were not included previously; however, their separate contributions cannot easily be detangled. The results shown in **Figure 5** are consistent with previous findings for comparable detectors using similar preamplifiers [27] in that they suggest that the noises from these sources (likely to be dominated by contributions from the packages of the input JFET and detector) are the most significant source of noise in systems of such design. Using an unpackaged (die form) input JFET is known to significantly reduce the noise [19]. If the noises from the stray capacitances and the additional dielectrics could be eliminated, it is predicted that a mean energy resolution of 1.0 keV FWHM at 5.9 keV would be achieved with detectors and system.

4. Discussions, conclusions and further work

A set of nine 400 µm diameter $Al_{0.8}Ga_{0.2}As$ mesa p^+-i-n^+ photodiodes with 1.7 µm i layers have been characterised as room temperature soft X-ray detectors. The devices were found to be fully depleted at low reverse bias (5 V) and they showed low leakage currents (mean = 5.4 pA at 5 V). The X-ray performance of the detectors was investigated by coupling them to a low noise charge sensitive preamplifier; the devices functioned as photon counting spectroscopic X-ray detectors with moderate energy resolution (FWHM = 1.27 keV at 5.9 keV). Whilst the energy resolutions are modest compared to those achievable at colder temperatures and with more mature technologies such as silicon DEPFETs (e.g. 135 eV at 5.9 keV at -10 °C [22]) and the best GaAs devices (e.g. 266 eV at 5.9 keV at -31 °C [28]), the resolutions now reported are the best so far recorded for AlGaAs devices of this size at room temperature, surpassing the previous best of 1.95 keV [9]; in both cases the AlGaAs devices were investigated using preamplifiers of similar design. The improved performance reported here is likely attributable to lower white series noise in the present detectors due to their lower capacitance and improvements in device fabrication and wafer quality.

Operation at increased reverse bias was investigated for a randomly selected sub-set of two-thirds of the devices. The count rates of the devices were consistent and the same at 10 V as they were at 5 V, indicating that there was no increase in quantum efficiency at the higher reverse bias. This supported the assumption from the C-V measurements that the devices were fully depleted at 5 V. Interestingly, the FWHM of the devices at 10 V had broadened less than would have been expected from the measured increase in leakage current at 10 V. Since the electric fields developed in the devices at reverse biases of 5 V and 10 V are too small to have produced avalanche multiplication, and since the electronic noise sources other than the leakage current driven parallel white noise are unchanging with increased reverse bias, the reduction in noise at higher reverse bias may be attributed to reductions in charge trapping noise. The measurements suggested there was 26e$^-$ rms equivalent noise charge more charge trapping noise at 5 V than 10 V. However, the FWHM were still larger at 10 V than at 5 V because the increase in parallel white noise from the leakage current was greater than the reduction in suspected charge trapping noise. This is the first time there has been sufficient data to be able to quantitatively estimate the trapping noise in AlGaAs X-ray detectors.

If the preamplifier had had a pulse generator test signal input (as per ref. [27]), it would have been possible to measure the total electronics noise directly since it would have been given by the width of the peak from the test signal. This could then have been subtracted in quadrature, along with the expected Fano noise, from the experimentally measured FWHM of the 5.9 keV peak from the ^{55}Fe radioisotope X-ray source to produce an absolute measurement of the trapping noise in the detectors rather than a lower bound. Unfortunately the preamplifier did not have a test signal input so this was not possible. We plan to build a preamplifier with a test input to enable such a measurement in future.

The results reported here are the first investigation that characterises multiple randomly selected AlGaAs X-ray diodes from the same semiconductor die, rather than simply reporting characterisation of single 'known good' devices selected by pre-screening. By characterising nine randomly selected devices across a die size of ~5 mm by ~5 mm, and finding that every diode is functional, with consistent C-V, I-V and X-ray performances, it has been shown that AlGaAs X-ray detector technology is now at a stage suitable for research to move to the production of small pixel arrays (e.g. 3 by 3 pixels). This is an important advance for AlGaAs X-ray detectors and we anticipate reporting on the wafer growth, device fabrication and characterisation of such arrays in the near future as part of the ongoing semiconductor research at University of Sussex. Further investigations of charge trapping in AlGaAs as well as the growth of wafers using metal organic chemical vapor deposition (rather than MBE) in order achieve thicker i layers are also anticipated.

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