Measurements of the quantum efficiency and depletion depth in gallium-arsenide detectors

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ABSTRACT

Measurements of quantum efficiencies are presented for three epitaxial gallium arsenide detectors with nominal depletion depths of 40, 325, and 400 μm . Attempts to measure the depletion as a function of bias indicated that the apparent depletion depth was much less than the intrinsic layer thickness. Expectation that the of the detection efficiency could be increased using a larger intrinsic layer could not be met. The largest value of a depletion depth measured by X-rays was determined at about 100 μm for the 400 μm device.

Keywords: GaAs, X-ray detectors, hard X-rays, gallium arsenide, quantum efficiency, depletion depth

1. INTRODUCTION

For several years ESA's Science Payloads and Technology Division has developed detectors based on compound semiconductor materials.^{1,2} Starting with simple pad devices, these developments have also evolved into the production of small and large format arrays with varying pixel sizes.² A number of materials are under active development, the most promising being epitaxial gallium arsenide. While our earlier studies in gallium arsenide concentrated on optimization and improvements of the energy resolution, the current work focuses on the study of the quantum efficiency of wafers so as to further optimize the wafer fabrication process.

The wafers from which all detectors presented are fabricated, were grown as epitaxial GaAs intrinsic layers on n^+ type substrates. The substrates were in the early phases of the program about 400 μm thick, and were later reduced to about 100 μm . The top surfaces were doped to form typically a 5-10 μm thick p^+ -layer, after which a Schottky contact was applied. An Ohmic contact was applied at the n^+ surface. A cross-section of the pad detectors is shown in Fig. 1. The detectors were negatively biased at the substrate contact and read out at the Schottky-contact.

The detectors studies had the following basic properties:

Detector 1 a circular pad detector with an active area of 2.22 mm², and a nominal thickness of the intrinsic layer of 40 μm ;

Detector 2 a pad detector, similar to detector 1, with a nominal thickness of the intrinsic layer of 400 μm ; and

Detector 3 a 4 $\times$ 4 array with a pixel size of 350 $\times$ 350 μm^2 , and a nominal thickness of the intrinsic layer of 325 μm .

Detector 1 originates from a more recent wafer, and its X-ray performance results are reported in Ref. 1. Detector 2 was taken from one of the first wafers of the development. Its X-ray performance was previously reported in Refs. 3, 4. Results from detector 3 were reported previously in Ref. 2. It was made from one of the most recent wafers, from which also another large pixelated array^{5,6} (32 $\times$ 32 pixels) was made.

The pixelated array (detector 3) had the same internal cross-section as the pad detectors, but the p^+ -layer was etched in the form of square pixels with a pitch of 400 μm and an inter-pixel gap of 50 μm . A guard ring around the pixels of width of 200 μm was also formed.

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Figure 1. The layout of the pad detectors is shown, and typical dimensions are also indicated. The detectors are negatively biased at the n^- layer, and the readout at the p^+ -layer. The guard ring was kept at ground potential. The lithographic layout of detectors 1 and 2 are identical, but the thicknesses of their intrinsic layers and their p^+ -layers are different.

2. MEASUREMENTS

Measurements on detectors 1 & 2 were carried out at the *Hamburger Synchrotronstrahlungslabor* (HASYLAB)⁷ using X-ray beams ranging in energy from 10.5 to 95 keV. Detector 3 was measured at the wavelength shifted beam line (WLS) of the German Physikalisch Technische Bundesanstalt⁸ at BESSY II.⁹ The energy range of this beamline was from 10 to 57 keV. All three detectors were mounted such that the p^+ side was exposed to the X-ray beam.

2.1. Detector 1, a 40 μ m Pad Device

The quantum efficiency was determined relative to an “off the shelf” CZT counter (Amptek XR-100T-CZT), which consisted of a square crystal of $3 \times 3 \text{ mm}^2$ and thickness of 2 mm inside a housing with a $25 \mu\text{m}$ beryllium entrance window. The efficiency of this detector was cross-calibrated with a calibrated Ge planar detector. The quantum efficiency of this detector is identical to the theoretical value expected for a 2 mm CZT crystal. The thickness of the beryllium entrance window was the same as that of the GaAs devices under test. The CZT reference counter and the test GaAs detector were placed into the X-ray beam sequentially. The beam intensity was monitored during each measurement by using the beam current monitor of the synchrotron.

The number of counts measured by the GaAs detector and by the CZT reference counter were corrected for any drift of the synchrotron current during the period of the measurement. The number of counts of the CZT counter was then corrected by the theoretical absorption probability in a 2 mm CZT crystal.¹⁰ The number of counts measured by the GaAs detector was divided by the corrected number of counts measured by the CZT reference, and the result is shown with full circles in Fig. 2.

The measured efficiency was fit with a simple, two-layer absorption model, with the depleted thickness of the detector, and the thickness of the absorbing p^+ -layer (acting as a dead layer) as free parameters. The best fit parameters are for a depleted thickness of $46.7 \pm 3.2 \mu\text{m}$, and for the p^+ -layer thickness $2.0 \pm 0.75 \mu\text{m}$. It should be noted that the fit estimate for the thickness of the p^+ -layer is only constrained by the results at the lowest energy measured (15 keV). The total error of the thickness determination, including systematic errors, was estimated to be about $\pm 5 \mu\text{m}$ and $\pm 1 \mu\text{m}$ for the depleted layer and for the p^+ -layer, respectively.

Figure 2. Measured detection efficiency as a function of energy for the 40 μm thick pad detector (detector 1; full circles). The continuous line is a fit to the measured data. The intrinsic layer fit is found to be 47 μm in agreement with the wafer growth estimates.

These results are within expectations and confirm past conclusions that the detector is fully depleted, which were based on interpretations of the X-ray performance data with respect to linearity of the response and close to Fano limited energy resolution.

2.2. Detector 2, a 400 μm Pad Device

The efficiency of detector 2 was measured in a similar manner. With the addition to measuring the efficiency at the best operating point with respect to detector temperature and bias, measurements were also carried out at different biases. The aim was to study the dependence of the quantum efficiency on a possible partial depletion of the detector. The results of the measured quantum efficiency are shown in Fig. 3. It is remarkable that the measured quantum efficiency is independent of the bias over the range measured.

All data were again fitted with the same simple two-layer absorption model, that was previously used for detector 1. The best fit parameters corresponding to the thickness of the layers are $97.5 \pm 4.5 \mu\text{m}$ for the depletion layer, and $22.5 \pm 0.7 \mu\text{m}$ for the p^+ -layer. The errors quoted are statistical only. The systematic uncertainty per energy can however be estimated from the spread of the measured efficiency values, and is also indicated in Fig. 3. Due to the choice of energies at which the efficiencies were measured, the systematic uncertainties of the two fitted parameters are uncorrelated: the parameter of the thickness of the p^+ -layer is only constrained at low energies, and in particular by the measurements at either side of the arsenic K-edge, whereas the parameter of the thickness of the depleted layer is constrained by data at energies $\geq 30 \text{ keV}$. We estimate the systematic uncertainties from the spread of the measurements of ± 3 and $\pm 1 \mu\text{m}$ for the depleted layer and for the p^+ -layer, respectively.

The value of the effective thickness of the p^+ -layer is in agreement with an estimate performed previously by a different measurement technique.³ This detector was manufactured from a wafer, which was produced rather early in the program, before optimization of the p^+ doping parameters. This is probably the reason why this detector has a significantly thicker p^+ -layer than more recent detectors. Furthermore, an scanning electron microscopy (SEM) image (Fig. 4) taken from a separate sector of the wafer, indicated that the thickness of this layer is about $30 \pm 5 \mu\text{m}$.

The thickness determined from these efficiency measurements for the depleted layer however appears to be significantly thinner than expected, although the nominal thickness of 400 μm was confirmed by the SEM

Figure 3. The measured detection efficiency of a 400 μm pad detector (detector 2) is plotted as a function of energy for bias values ranging from 50 V to 500 V. The symbols show the results of the measurements for a specific value of bias and energy. The solid curve is the result of a fit of all data to a simple two-layer absorption model. The best fit values for the intrinsic layer and for the p^+ -layer were 97. μm and 22 μm , respectively. The dotted curve shows changes of the quantum efficiency by a variation of the thickness of the depleted layer by $\pm 6 \mu\text{m}$ ($\sim 2\sigma$ total uncertainty). The dashed line indicates the effect of a variation of the p^+ -layer by $\pm 1.5 \mu\text{m}$ ($\sim 2\sigma$ total uncertainty). The inset shows the results of the measurements and of the fit around the arsenic K-edge (11.867 keV) with the same indication of changes of the model by variations of the parameter of the thickness of the p^+ -layer.

images, from which a thickness of $390 \pm 5 \mu\text{m}$ was measured. Given the independence of efficiency with bias and the confirmation of the geometrical thickness it would appear that the first 100 μm a barrier acting as a charge trap exists between this region and the remainder of the intrinsic layer.

The linearity and resolution of the response of the detector is plotted in Figs. 5 and 6. This shows that the detector performs according to expectations: the linearity is very good and independent of bias, with the exception of at one measurement (at 40 keV energy and 50 V bias), which is attributed difficulties during the analysis in isolating the center of the peak, due to the rather broad resolution of the detector at this low bias values. As expected, the energy resolution improves asymptotically up to a bias value of 200 V, after which it remains roughly constant as a function of bias.

2.3. Detector 3, a 325 μm thick small Array

The quantum efficiency of detector 3 was measured at the WLS beamline of the German Physikalisch Technische Bundesanstalt⁸ (PTB) at the synchrotron installation BESSY⁹ in Berlin, over an energy range from 10 to 57 keV. A calibrated germanium detector was used as the reference counter. This counter was mounted at a distance of 350 mm further downstream from the GaAs detector. This was corrected by assuming the X-ray absorption equivalent absorption coefficients of dry air as provided in Ref. 10. Furthermore the data of the Ge counter had to be corrected for the difference in thickness of the beryllium entrance window of 100 μm . And finally a correction of the efficiency of the Ge counter, as calibrated by PTB, was applied. This was compatible with a fully depleted 1.5 mm thick Ge detector. As with the setup at HASYLAB, the luminosity of the beam was monitored by measurement of the beam current.

The measured efficiencies are plotted in Fig. 7 as a function of energy. The systematic uncertainties can be estimated from the spread of those measurements, which were repeated. As before, a two-layer absorption model was fit to the measured data. The best fit values are $65.2 \pm 3.0 \mu\text{m}$ for the thickness of the depletion layer, and $2.1 \pm 0.4 \mu\text{m}$ for the thickness of the p^+ layer. Due to the narrow sampling in energy at the lower energies,

Figure 4. SEM image showing a cross section from a separate area of the same wafer as detector 2. The bright feature at the left is the p^+ -layer. The grey shaded band at the right is the n^+ substrate, which apparently contains different densities of doping.

Figure 5. The center of the photo-peak of a $400\text{ }\mu\text{m}$ pad detector (detector 2) plotted as a function of energy for detector bias values ranging from 50 to 500 V. The symbols show the results of the charge output for a specific value of bias and energy. The lines are only connecting the symbols and are used to guide the eye but are indistinguishable of a perfectly linear device.

Figure 6. The full width at half maximum resolution of the response of the photo-peak of a $400\text{ }\mu\text{m}$ pad detector (detector 2) is plotted as a function of bias for different incident energies. The symbols indicate the measurements for a given energy. The lines connect the results for the same energy as a function of bias and are drawn to guide the eye.

Figure 7. Measured detection efficiency as a function of energy for the $325\text{ }\mu\text{m}$ thick array (detector 3; full circles). The continuous line is a fit to the measured data.

the thickness of the p^+ -layer layer is well constrained by several measurements, and is also within expectation for this wafer. The effective thickness of the effective depleted layer, however is again significantly less than is expected.

3. DISCUSSION

The p^+ -layer is fully conducting. Therefore the quantum efficiency for absorptions in this layer is close to zero. Only for very low X-ray energies ($\sim 6\text{ keV}$) a statistically significant probability of charge collection due to partial interactions in this p^+ -layer was observed.^{6,11} The thickness of the p^+ -layers of all devices are therefore in good agreement with the wafer growth specification and its experience with growth over time.

The quantum efficiency of the intrinsic layer, however, is of concern and is only partly understood at this point in time. The quantum efficiency of the 40 μm device is within expectations indicating that the device is fully depleted and performs very well in terms of energy resolution and quantum efficiency. The thicker devices (detectors 2 & 3), however, do not show the expected increase in high energy quantum efficiency. Both detectors do on the other hand, perform excellently in terms of energy resolution,^{2-4,6} which previously leads to the conclusion that they must be fully depleted. Since these detectors were illuminated from the side of the readout connection (at the Schottky-contact of the p^+ -layer), the quantum efficiency measurements seem to indicate that charge is only collected from 70–100 μm of the intrinsic layer, closest to this contact. As clearly shown for the 400 μm device (detector 2), this volume is already depleted at bias values as low as 50 V. The thickness of the intrinsic layer was independently confirmed by simple mechanical measurements (deduced from the total thickness of the device), and by SEM. The various layers of the wafer could well be identified by the SEM, but no structure could be seen, which would explain the inconsistency of the measured quantum efficiency. This implies that during growth a charge barrier appears to be introduced into the intrinsic layer after 70–100 μm . The reason for such a barrier is not at all clear although further diagnostic measurements of these wafer are currently planned.

4. CONCLUSION

The effective thickness for X-ray absorption of two layers of a set of epitaxial GaAs has been determined. While a device with an intrinsic layer of 40 μm confirmed full depletion, thicker devices did not. It should be noted, however, that all measured thickness values effective for X-ray absorption are $> 40 \mu\text{m}$, a value which is essential for X-ray remote sensing, e.g. as is proposed in Ref. 12. The effective intrinsic layer has been established to be 70–100 μm compared to the geometric thickness of 400 μm . Possibly a charge trap or barrier has been introduced during the growth, which needs further investigation.

The improvements of the reduction of the p^+ -layer over the course of the development was confirmed with a thickness as low as 2 μm being derived. The importance of the thickness of the contact layer was highlighted once more by these measurements.

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