Epitaxial GaAs X-ray detectors for X-ray astrophysics

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ABSTRACT

In recent years, considerable effort has been expended in producing semiconductor based X-ray detectors for X-ray astrophysics with high spectral and high spatial resolution. In practical terms, this means producing pixelated detectors, comprising over 10^3 pixels each less than 100 microns in size, with spectral resolving powers, $E/\Delta E > 20$ at 10 keV. While progress at soft X-rays wavelengths has been spectacular, largely due to the introduction of X-ray sensitive CCD's, progress at higher energies has been slow. This is because traditional high resolution detectors either suffer from poor detection efficiencies above 10 keV, as in the case of Si based technology, or are very constrained by cryogenic and fabrication problems as in the case of Ge based detectors. Recent developments in the material science of wide-gap semiconductors, and in particular GaAs and CdZnTe, have shown that it may now be possible to construct efficient hard X-ray detectors with near Fano limited energy resolution. In this paper we report on hard X-ray measurements with two prototype deep depletion epitaxial GaAs detectors of active areas 2.22 mm^2 and thicknesses 40 and 400 microns at the ESRF and HASYLAB synchrotron research facilities. The results show that charge collection efficiencies must be in excess of 98% and that the material used to produce them is of extremely high purity, with impurity concentrations $< 10^{13} \text{ cm}^{-3}$.

1. Introduction

GaAs is one of the high group (III/V) compound semi-conductors with a bandgap sufficiently wide (1.42 eV) to permit room temperature operation but small enough so that its Fano limited spectroscopic resolution is reasonably close to that of Si. In addition, the atomic numbers of its constituents bracket that of germanium, thus potentially offering the advantages of a Ge detector, such as high detection efficiency and robustness, without the inherent disadvantage of cryogenic cooling. However, in spite of two decades of intensive research, the potential of GaAs has not yet been fully realised. Early bulk devices suffered from poor charge collection and intermittent burst noise, and while later devices fabricated by liquid vapour or chemical vapour phase epitaxial deposition techniques proved to be better detectors, they suffered from poor detection efficiencies, due to the difficulties in producing thick layers with low-doping concentrations. In addition, high leakage currents and charge trapping (particularly for holes) limit the attainable energy resolution.

The Space Science Department of ESA has worked for a number of years to produce Fano limited large area compound semiconductor detectors and arrays for future astrophysics and planetary missions. Several materials are under study including; GaAs, CdZnTe, TlBr and HgI₂. For GaAs, the research program has focused on two areas: 1) how to produce hyper-pure material, and 2) how to produce thick epitaxial layers. In this paper, we report measurements on two prototype deep depletion epitaxial detectors which are the product of this program. Both detectors are identical, being fabricated from the same wafer stock and differ only in the thickness of the epi-layer. This was made 10 times thicker in one detector in order to try and isolate the effects of trapping and charge collection. Preliminary results have been presented elsewhere [1,2].

2. Detector fabrication

The detectors were grown epitaxially onto semi-insulating GaAs wafers using chemical vapour phase deposition (CVPD) techniques. During material processing and growth, the epi-layers and associated structures were subjected to a

variety of analytical tests to characterise the material and the technique of producing ultra-pure GaAs layers. Hall effect measurements show that the epi-material used to produce the detectors had impurity concentrations $<10^{13} \text{ cm}^{-3}$ and electron mobilities of $2 \times 10^6 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$ at 77 K. These values agree well with cyclotron resonance measurements of non-equilibrium electrons in n_0 -GaAs layers, which yield mobilities of $3 \times 10^6 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$ at 1.8 K and shallow impurity concentration levels $\leq 5 \times 10^{12} \text{ cm}^{-3}$. Based on low temperature Photo-luminescence (PL), the density of the As anti-site defect (EL2) is estimated to be of the order of 10^{12} cm^{-3} and the room temperature carrier lifetimes of the order of $1 \mu\text{s}$. The corresponding density of EL2 traps in the substrate material is estimated to be about $3 \times 10^{15} \text{ cm}^{-3}$ (which is about one tenth of the values normally obtained for semi-insulating bulk material) and the total impurity concentration $\sim 10^{18} \text{ cm}^{-3}$. Monte-Carlo modelling supports these values.

Figure 1. Schematic view of the detectors

The detector design is shown schematically in Fig. 1. Both detectors are 1.5 mm in diameter (physical area = 1.77 mm^2) and consist of a 40 or 400 μm thick epitaxial layer grown onto a 100 μm thick n+ substrate. A pin structure is then formed by depositing a 5 μm thick p+ layer directly onto the epitaxial layer and then depositing a full ohmic contact (Ni/Au/Ge/Au) on the n+ side. The p+ side is patterned by etching to define the detector (mesa) and guard ring structure. Both the mesa and the guard ring are metalized with alternate depositions of Au/Pt/Ti to form a Schottky contact. The devices are housed in ceramic holders and operated as reverse biased diodes with the p+ contact at negative potential. At nominal biases of -40 V for the 40 μm device and -300 V for the 400 μm device, the leakage currents are 40 pA and 100 pA, respectively at room temperature. The detectors are cooled by a water cooled two stage peltier cooler, capable of cooling the devices to $\sim -45^\circ\text{C}$.

3. Experimental

The hard X-ray characterisation of the detectors was carried out on the open bending magnet (BM5) high energy beam line at the European Synchrotron Research Facility (ESRF) and the X1 beamline at the Hamburg Synchrotron Laboratory (HASYLAB). Both beamlines use double crystal monochromators to produce highly monochromatic X-ray beams. The energy range covered at the ESRF was 7-35 keV using a Si[111] reflection and at HASYLAB, 6-60 keV (X1) using both Si[311] and Si[511] reflections. The intrinsic energy resolution was typically 1 eV at 10 keV and ~ 20 eV at 35 keV. The detectors were mounted on a 2-axis X-Y table capable of positioning each device with respect to the beam to a precision of ~ 1 micron. For the majority of measurements, the beam was normally incident on the centre of the detectors and had a typical spot size of 25×25 microns². Both detectors were operated at a temperature of -45°C.

Figure 2. The measured energy resolution of the both detectors. For comparison the fwhm electronic noise was measured to be 690 eV and 1100 eV in the 40 micron and 400 micron detector, respectively

Although there is an order of magnitude difference in the thickness of the epi-layers of the two detectors, there is relatively little difference in performance. For example, at 10 keV the fwhm energy resolutions are 700 eV in the 40 micron detector and 1.2 keV in the 400 micron detector. At 60 keV, the corresponding resolutions are 1.0 and 1.3 keV (see Figure 2). These should be compared to the calculated Fano resolutions of ~220 eV and 525 eV at the same energies. At the lower energies, the resolution is dominated by leakage current, whereas at medium and high energies, Fano noise becomes an appreciable fraction of the resolution function.

Both detectors are remarkably linear, with average rms non-linearities of 0.2% over the energy range 10-60 keV. This indicates that charge collection efficiency must be > 98% - a figure confirmed by Monte-Carlo simulations of the measurements. Additionally, it is found that the shape of the full energy photopeaks were very nearly Gaussian for both detectors. Only the 40 micron device showed evidence of low energy tailing at energies above 35 keV which we attribute to increasing penetration of incident X-rays into the substrate. This is substantiated by the response of the 400 micron device

which was found to have Gaussian profiles independent of both bias and incident energy. Again this illustrates that charge collection efficiencies must be close to unity and that trapping effects must be negligible.

Figure 3. Composite pulse height spectra taken at HASYLAB with the 40 μm and 400 μm detectors. The smaller peaks which appear at an energy of ~ 11 keV below the photopeaks are due to the Ga and As escape peaks. Due to its better energy resolution, these are just resolved in the 40 μm device.

3.1 Spectral response

In Figure 3 we show two energy spectra recorded by the detectors in response to monoenergetic radiation at 30 keV to 60 keV. The peak at ~ 10 keV is due to a combination of Ga and As fluorescent lines from the p+ layer. Likewise, the peaks located ~ 11 keV below the photopeaks are due to the Ga and As escape peaks, which due to its better energy resolution, are just resolved in the 40 μm device. From the figure we see that the level of the continuum is extremely low in both devices, being at worse $\sim 1\%$ of the photopeak amplitude for 30 keV incident X-rays. At 60 keV the continuum level in the 400 micron device is at the 0.3% level, whereas it is considerably worse in the 40 micron device. Since the level of the low energy continuum in the 400 micron device is the same for both input energies and it is also comparable continuum measured in the 40 micron device for 30 keV incident X-rays, we attribute high level of continuum level for 60 keV incident X-rays in the 40 micron device to charge loss caused by X-ray penetration into the substrate (the penetration depth of 60 keV photons is several hundred microns).

3.2 Spatial response

Both detectors were raster scanned in the plane perpendicular to the beam axis, to map the spatial uniformity of their count rate response. The incident beam size used in these measurements was adjusted to $20 \times 20 \text{ micron}^2$ using a pair of slits located 10 cm in front of the detector. For both detectors, the uniformity in response within the central 1 mm of the active area is in excess of 99% level and independent of energy. In Figure 4 we show an X-Y scan across of the 400 device at an incident energy of 10 keV. The response of the 40 micron detector looks similar. The spatial resolution is 25 microns. The two depressions near the right hand edge are due to absorption in the wire bond pads (two wires were bonded for redundancy). The enhancement near the edges was later found to be due to a p+ etching error when the mesa and guard ring were defined. SEM showed that the etch profiles near the edge were stepped rather than vertical, becoming increasing thin towards the edge. Thus the rise in count rate can be simply attributed to the increased X-ray transmission of the p+ layer near the edge. Beyond the edge, the response falls off linearly due to vignetting of the incident beam. Lastly, from Figure 4, it is clear that the p+ layer in the negative Y direction has not been completely etched away at the detector boundary, effectively increasing the active area from 1.77 mm^2 to 2.22 mm^2 . More detailed microscopy of the etch profiles of the 400 micron detector also revealed that some of the mesa metalization had also been etched and allowed to "wash" onto the intrinsic region. Since both detectors were produced from the same material and are packaged identically, the residual of this metalization is probably the cause of the relatively high leakage current in the 400 micron device.

Figure 4. The spatial variation in the count rate response measured by the 400 micron detector. The incident X-ray energy is 10 keV. The count rate profile of the 40 micron detector looks similar.

4. Conclusions

The present results are very encouraging and show that the material used to produce these detectors is very pure. Despite an order of magnitude difference in the depletion depth, we see little evidence for charge collection problems or trapping. Based on the SEM data, we have reviewed and changed the etching process and are currently producing new detectors and arrays.

References

1. M. Bavdaz, et al., Mat. Res. Soc. Symp., Material Research Society, Vol. **487** (1997) 477.
2. A. Owens, M. Bavdaz, S. Kraft, A. Peacock, S. Nenonen, H. Anderson, M. Gagliardi, T. Gagliardi, F. Scholtze, G. Ulm, J. App. Phys., in press.