GaAs arrays for X-ray spectroscopy

Alan Owens^{*1}, H. Andersson², M. Campbell³, D. Lumb¹, S. Nenonen², L. Tlustos³

¹Science Payload and Advanced Concepts Office, SCI-AT, ESA/ESTEC, Postbus 299, 2200AG, Noordwijk, The Netherlands

²Metorex International Oy, PO Box 85, FIN-02201 Espoo, Finland

³CERN, ETT division, 1211 Geneva 23, Switzerland

ABSTRACT

We present results from our compound semiconductor laboratory program and describe the development of a large area GaAs imaging array for planetary remote sensing applications. The device is fabricated from ~150 micron thick epitaxial material, patterned into a 64 × 64 pixel array, back-thinned and contacted. It will be flip-chip bump bonded onto a custom designed, fully spectroscopic, low noise (< 20 e- rms) active pixel sensor ASIC. At present, the ASIC is still under development and so in order to validate and qualify the various technological steps, we have produced a GaAs imager based on the MEDIPIX-1 format using a MEDIPIX-1 readout chip. In X-ray tests, the device was found to work well with a bump yield of 99.9%. After flat field corrections, the spatial uniformity of the array was commensurate with Poisson noise.

Keywords: Compound semiconductors, GaAs, X-ray arrays.

1. INTRODUCTION

X-ray imaging is an essential tool for a wide range of disciplines from astrophysics to material science. Whilst the majority of applications rely on analog integrating formats, the future development of this field lies in the exploitation of spatially resolved spectroscopy and in particular, using materials that can operate at room temperature with near Fano limited energy resolution. Although the bulk of research in direct X-ray imaging has concentrated on Si, GaAs is potentially far superior for the following reasons.

- 1) Its band-gap energy is sufficiently wide (1.43 eV) to allow room temperature operation, but narrow enough that its Fano limited energy resolution is close to that of Si.
- 2) Its density is twice that of Si ensuring excellent stopping power well into the hard X-ray region - a particularly attractive property for dental and medical applications.
- 3) It has a much larger bulk resistivity than Si allowing higher fields to be used for charge collection, which in turn allows thicker devices to be fabricated without compromising efficiency and spectral resolution.
- 4) Its electron mobilities are about a factor of 6 higher than Si, allowing faster operation.

Additionally, like Si, devices fabricated on semi insulating material can be self-isolating and are therefore ideally suited to integrated circuit fabrication and replication techniques.

*aowens@rssd.esa.int; phone 31-71-565-5326; fax 31-71-565-4690; <http://astro.esa.int/ST-general/index.html>

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A new generation of high resolution, direct detection GaAs X-ray imagers is being developed by the European Space Agency in cooperation with industry. The program is geared towards X-ray astronomy and remote planetary sensing, but has now been found to have wider applications [1]. In particular, the devices are ideally suited for the imaging of low density, low contrast media. Our research program initially concentrated on monolithic pad detectors and small format arrays. The aim of this work was to address the material, electronic and technological problems that needed to be solved in order to develop mega pixel, spectroscopic imagers with near Fano performances [2]. Building on this work, we have now produced a series of intermediate and large format arrays, intended for planetary remote sensing applications [3]. In addition to the technical effort required to produce spectroscopic grade material and subsequent processing into arrays, considerable effort has also been expended to produce a fully spectroscopic ASIC as well as develop the flip-chip bump bonding techniques to attach it to the sensor.

2. MATERIAL PRODUCTION

The imager program has relied heavily on extensive material science research and development. The sensors are fabricated on semi-insulating GaAs wafers using chemical vapour phase deposition (CVPD) techniques. During material processing and growth, the epi-layers and associated structures are subjected to a variety of analytical tests to characterize the material and the technique of producing ultra-pure GaAs layers. For example, Hall effect measurements indicate that impurity concentrations are $<10^{13} \text{ cm}^{-3}$ and the electron mobilities at 77 K are $2 \times 10^3 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$. These agree well with cyclotron resonance measurements of non-equilibrium electrons in n_0 -GaAs layers, which show that the mobilities at 1.8 K are $3 \times 10^3 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$ and the shallow impurity concentration does not exceed $5 \times 10^{12} \text{ cm}^{-3}$. Based on low temperature Photoluminescence (PL), the density of the As anti-site defect (EL2) is estimated to be of the order of 10^{12} cm^{-3} (the dominant levels are actually EB4 and EL5) and the room temperature carrier lifetimes of the order of 1 μs . This is confirmed by transient microwave absorption (MWA), which yields average carrier lifetimes of $(7.0 \pm 0.5) \mu\text{s}$. 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 $\sim 10^{18} \text{ cm}^{-3}$. Finally, high resolution Glow Discharge Mass Spectrometry (GDMS) measurements has shown that the concentrations of common impurities are typically of the order of a few ppB.

3. ARRAY DEVELOPMENT

The material science data was used (and still is) to probe material properties and to assess the electrical and isolation properties of individual pixels. The information gained was feedback into both our material science and theory programs to improve crystal growth, metrology, contacting procedures and detector design. Small format arrays were subsequently produced. In this case, the thrust of the research and development program was to improve processing at the foundry and develop low-noise front-end electronics. In fig. 1 we show the development from small format arrays through to an intermediate format array (1024 pixels). The corresponding improvement in the electronic readout is shown in the lower figures. The arrays are fabricated by growing a GaAs epi-layer on a 400 μm thick semi-insulating n^+ GaAs substrate. The thickness of the epi layer is chosen to be in the range 40 to 325 μm thick. A $\sim 5 \mu\text{m}$ thick p^+ layer is then deposited directly onto

Fig. 1. Top: - Nomarski photomicrographs of small and intermediate format arrays tested at the HASYLAB synchrotron research facility. Below: - the corresponding evolution of the packaging and the front-end electronics (left to right).

the epi-layer to form a p-i-n structure. This layer is then patterned by etching, to create a pixel structure surrounded by a guard ring (see fig. 1). The guard is 200 μm wide and is operated at ground potential. The pixels are metallized with alternate depositions of Au, Pt and Ti, forming a Schottky contact, whilst a full ohmic contact (Ni/Au/Ge/Au) is applied to the substrate. The pixel sizes are generally $250 \times 250 \mu\text{m}^2$ and the inter-pixel gap, 50 μm . From the pixel I/V characteristics, the typical current densities at 100 V are $< 0.06 \text{ nA/mm}^2$ at room temperature. The corresponding pixel leakage current is 0.0024 nA and the inter-pixel resistivities typically $> 10^{12} \Omega$.

In fig. 2, we show X-ray test data acquired at the HASYLAB synchrotron research facility for the 32×32 pixel array shown in the right hand image of fig. 1. Four pixels of the array were instrumented and subjected to rigorous testing on beamline X-1. Leakage currents for this device were typically pA at a bias of +50V.

Fig. 2. Composite pulse height spectra (left) and energy resolutions (centre) of monoenergetic lines measured by the 32×32 array shown in fig. 1 (right) under pencil beam illumination at the HASYLAB synchrotron research facility. The right hand image demonstrates that the device can operate at room temperature with little degradation in performance. The incident beam size was $20 \times 20 \mu\text{m}^2$. No difference in performance was found under full area illumination.

In fig. 2 (left), we show a composite of energy-loss spectra recorded by a single pixel over the energy range 10.5 keV to 100 keV. Plots for the other pixels are statistically consistent, both in terms of spectral distribution and energy resolution. The smaller peaks which appear at energies of 10.4 keV and 11.9 keV below the photopeaks are due to the Ga and As escape peaks. The energy resolution function for each pixel was determined from its pulse height data and is shown in fig. 2, (center). At room temperature, the resolutions range from ~ 290 eV FWHM at 5.9 keV to 780 eV FWHM at 100 keV. The electronic noise of the system was ~ 220 eV FWHM. As can be seen, the measured resolutions for all 4 pixels agree within 20% - the differences almost certainly arise from the difference in stray capacitance of the front-end components. The corresponding resolutions measured under full-area illumination were found to be the same as for pencil beam illumination within statistics, indicating uniform crystallinity and stoichiometry. Likewise, by raster scanning a 15 keV, $15 \times 15 \mu\text{m}^2$ beam across each of the pixels, the gain uniformity across the pixels (and by implication the entire array) was determined to be statistically flat. These data were verified using a 4×4 pixel array with all pixels instrumented using purpose designed hybrid electronics [4] (lower right figure in fig. 1). In this case, all pixels gave identical responses, within errors (to better than the 1% level), over the energy range 10 to 100 keV. Lastly, we note from the plotted energy resolutions at 5.9 keV shown in fig. 2 (right) that, unlike Si, cooling the array below $+10^\circ\text{C}$ does not improve its performance.

Fig. 3. Left: the process steps required to produce a flip-chip bump bonded array – a) back thinning, b) patterning, etching and contacting and c) flip-chip bump-bonding to the readout ASIC. Right: A 64×64 pixel GaAs array produced to qualify the bump bonding processes. The inset shows individual pixels in detail. Note, the center hole in the passivation is where the bump will be fixed; the upper hole is used to electrically probe the pixel prior to bumping.

The p-i-n structure was the key to producing near Fano limited performance in both monolithic and small format arrays by drastically reducing leakage currents. This in turn allowed us to test increasingly lower noise preamplifier designs, read-out through the p+ contact and positively biased *via* the n+ contact to ensure the efficient collection of holes. For array sizes $> 6 \times 6$, wire bonding is impractical and so the read-out is only realistically achieved using a custom built ASIC which is connected to the pixelated side of the array by flip-chip, bump bonding. However, this necessitates that the chip is now illuminated through the n+ electrode side, since the ASIC will cover and obscure the pixel side. To avoid excessive X-ray extinction in the n+

around 10 keV. Apart from a few dead pixels around the edges of the imager (due to dicing process), only 4 pixels were found to be non-functioning - thus the bump yield is 99.9%. After flat field corrections, the spatial uniformity of the array at 20 keV was commensurate with Poisson noise.

Fig. 5 Left: photomicrograph of some of 25μm diameter bumps attached to the MEDIPIX-1 readout ASIC. Right: the completed flip-chip bump bonded MEDIPIX-1 X-ray imager, as seen from the thinned GaAs side.

Finally, in fig. 6 (right) and fig. 7 we show a pair of images of a “Swatch” and a small sardine, illustrating the imaging quality of the GaAs chip. The data were taken with a conventional X-ray tube using a tungsten target. The objects were mounted on a sample holder and the detector on a precision x-y stage. The detector was then scanned past the object in steps of 0.8 of the detector width using the so-called move and tile method [8]. The resulting composite images have been flat-field corrected and a 3×3 median filter applied locally around defective pixels.

Fig. 6. X-ray image of a line pair rule taken using an un-collimated ^{109}Cd source located $\sim 5\text{cm}$ above the target. Right: image of a “Swatch”, taken with a conventional X-ray set operating at 55 kV with a W target and a 2.5 mm Al filter.

Fig. 7. Top: X-ray image of the sardine, shown in the lower image, taken using an X-ray tube with a tungsten target plus a 2.5 mm Al filter. The following tube settings were used 35 kV and 20 mAs. The target to object distance was 54 cm.

3. CONCLUSIONS

The present results are very encouraging and illustrate the quality of images that can be expected with spatially resolved spectroscopy, especially if coupled with contrast enhancement techniques such as differential X-ray absorptiometry. Lastly, the fact that GaAs sensors can operate at room temperature has important consequences for a number of applications where power, mass and volume are at a premium (*e.g.*, intraoral radiography), alleviating the need for complex and expensive cryogenic systems - as in the case of Ge or Si CCD-type sensors.

5. REFERENCES

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