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PROPOSAL TO DEVELOP GaAs DETECTORS FOR PHYSICS AT THE LHC

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This proposal could not have reached the present stage without the development work done in the LAA Project. Before the present proposal could be worked out, basic problems have been studied and solved within the LAA Project. The continuation of our work is of great relevance for LHC physics experiments and should therefore be supported.

SUMMARY

Over the last two years the Glasgow and CERN-based LAA groups have successfully constructed GaAs detectors for minimum ionising particles with radiation hardness and potential speed which is more than competitive with silicon detectors. The timely development of this new technology, in particular for high radiation regions of LHC detectors near the beam pipe and in the forward region, now requires the investment of more resources and more intensive effort, including industrial collaboration in detector fabrication. In addition, there is an urgent need for the development of appropriate read-out electronics with radiation tolerance and speed characteristics to match the detectors, and with the lowest possible power consumption, needed for the large number of channels required in a vertex detector, for example. The present proposal first describes the results obtained using GaAs Schottky diode detectors which we have constructed, and the initial steps which we have taken towards the design of a GaAs preamplifier to match the detectors. We then propose a continuation of the programme of work towards a demonstration detector module for an LHC pre-shower tracker detector based on GaAs, within a time-scale of two years. The module will be compatible with the design of the proposed pre-shower tracker using silicon detectors [1], and should allow direct substitution for comparison purposes. The authors of the silicon-based proposal, (DRDC/P3) have expressed their support for our GaAs counter developments, and their willingness to collaborate with us in the testing of such counters.

Introduction

We first discuss the choice of semi-insulating GaAs as a detector material, the manufacture of our Schottky diodes [2], and details of the response of the diodes to alpha, beta and gamma radiation and to high energy test beam pions. Results are presented of the effect of gamma - and neutron - irradiation on GaAs diodes and of measurements of the speed of response of the diodes, using picosecond laser pulse excitation. This status report concludes with a summary of our current understanding of GaAs diode detectors fabricated in semi-insulating material, and a discussion of the programme of work still to be done to improve our understanding of the charge transport mechanism in this material. The requirements of appropriate read-out electronics are very briefly discussed.

The advantages of GaAs

That the time is ripe for development of GaAs detectors is supported by evidence of the radiation tolerance of integrated circuits in this material and by the improved understanding of the processes of crystal growth and wafer preparation achieved recently [3].

GaAs is a direct band-gap semiconductor, with a band-gap of 1.43 eV. The larger band-gap reduces the bulk generation current by almost four orders of magnitude compared to silicon, (with a band-gap of 1.11 eV). The radiation length is 2.3 cm, (four times shorter than silicon), but this is partly compensated by the higher specific ionisation loss of 5.6 MeV/cm, which means that for a given signal, a GaAs detector can be thinner than silicon. GaAs wafers are generally prepared by the LEC (Liquid-encapsulated Czochralski) method. Higher purity may be achieved by Molecular Beam Epitaxy, (MBE), but this is limited to layers of at most a few tens of microns in thickness by the slow rate of deposition. Vapour Phase Epitaxy (VPE) may overcome the latter limitation in the future [4]. Liquid Phase Epitaxial growth, (LPE), formerly employed for preparation of pure and doped GaAs wafers, has been almost completely superseded by MBE and VPE for most applications. Typical characteristics of a semi-insulating (undoped) GaAs wafer prepared by LEC growth are given in Table 1, together with some physical properties of the basic semiconductor material.

Several studies were made of LPE GaAs diodes as particle detectors in the early 1970's [5]. The best results at that time were rather difficult to reproduce but established that good energy resolution for X- and gamma-rays was indeed possible with small diameter, n-doped diodes. Figure 1 shows a spectrum obtained with a more recent LPE diode [6]. While development in LPE detectors has been inhibited by the variability of the wafer material available, recent improvements in LEC commercial crystal growth techniques, including better stoichiometric control, magnetic field melt stabilisation, post-growth annealing and stress-relieving In doping [3] have resulted in more uniform wafers of higher purity and mechanical strength, and with a greatly improved surface quality. The prospects for further improvements and for larger wafer diameters also seem bright.

GaAs devices are also of great interest because of the high electron mobility in this material, (almost six times that of silicon at best), offering the prospect of high speed particle detection and signal processing. Modern digital technologies based on GaAs have smaller gate delays and power consumption per gate than even the best silicon technologies available, as shown in Figure 2.

Diode Manufacture and Electrical Tests

Diodes of 500, 300 and 125 microns thickness and 1 and 3mm contact diameter were manufactured in the University of Glasgow Department of Electrical and Electronic Engineering by evaporating a Ti - Au Schottky barrier onto one side of a semi-insulating GaAs chip and an ohmic contact of Ni - Ge - Au onto the other. The sequence of evaporations for both contacts, described in Table 2, constitutes a rather reliable recipe for good contacts. No attempt was made to deposit a passivating layer on the surface of the diodes, so that the processing is relatively straightforward. The thinnest diodes are relatively fragile mechanically.

A typical diode characteristic, shown in Figure 3, reveals a reverse bias leakage current which is significantly higher than that for typical silicon detectors. Figure 4 shows the uniformity in diode leakage current achieved with an array of diodes on one chip. Measurements on diodes with a guard ring electrode surrounding the Schottky contact suggest that the leakage is not predominantly due to surface effects, but probably more to bulk generation. Capacitance measurements are compatible with total depletion of the semi-insulating sample with almost zero bias voltage.

Tests with Radioactive Sources and in a Test Beam

Each diode was tested with alpha-, beta- and gamma ray radioactive sources. Typical spectra obtained with Am^{241}, Ru^{106} (in coincidence with pulses detected in a scintillator behind the GaAs detector), and Co^{57} are shown in Figure 5. The charge released by each particle was known from the energy required to generate an electron-hole pair in GaAs, namely 4.2 eV. The measured charge collection efficiency increased with bias voltage as shown in Figure 6, up to a maximum of around 50% for alphas, with lower values for betas and gammas. The inefficiency is interpreted as due to very rapid trapping of the holes released by the ionising particles, the observed signal being due to the residual electrons migrating to the collecting electrode. This interpretation is supported by a comparison of the pulse height spectrum obtained from an alpha source next to the ohmic contact with that obtained with the source at the Schottky electrode. Since the alpha particle range in GaAs is only about 20 microns, the hole trapping and very short transit distance of the electrons released gave a very small signal in the former case compared with that seen in Figure 5. Simulation of the charge trapping mechanism by a simple model gave the predicted charge collection efficiency variation also shown in Figure 6, (cf. [2], [7]). The variation in charge collection efficiency among the diodes of the array illustrated in Figure 4 is given in Figure 7.

Figure 8 shows the pulse height spectrum obtained in a 6 GeV/c pion test beam, with a conventional scintillator telescope trigger, [2]. The efficiency for recording the passage of minimum ionising beam particles, shown in Figure 9 as a function of detector bias, indicates that the GaAs diode is essentially 100% efficient for minimum ionising particles.

Speed of Reponse

The picosecond laser facility at the Lens Laboratory of the University of Florence was used to excite a GaAs diode with a 1.5 picosecond pulse. The output signal from the diode, observed using a high speed (8 GHz) oscilloscope, is shown in Figure 10. The very fast initial pulse is followed by a tail of around 4 nanoseconds in length, thought to be due to trapping effects in the charge tranport mechanism. A simulation of the effects of trapping, using a trap cross-section of 10^{-13} cm^2 and a de-trapping time of 245 psec gave the pulse shape, shown in Figure 11. More detailed studies of the trapping and de-trapping process may lead to better understanding of the charge collection inefficiency discussed above.

Radiation Hardness

Several diodes, subjected to gamma irradiation up to a total dose of 17 MRad, showed only a very small change in leakage current, and the response to radioactive sources was almost completely unaffected. A set of diodes was also subjected to neutron irradiation at the R.A.L. test facility in the ISIS accelerator. The neutron energy spectrum is shown in Figure 12 [8]. Figures 13, 14 and 15 show the changes in leakage current, charge collection efficiency and signal to noise ratio in a number of diodes, after a total neutron fluence of 7.10^{14} n/cm^2. This exceeds the total fluence expected at a radial distance of 5 cm from the intersection point of the proposed LHC collider operating at nominal luminosity for one year. (The assumed integrated luminosity for this period was taken as 10^{41} cm^{-2} s^{-1})[9]. A comparison is given in Figure 16 of the pulse height spectrum obtained with a collimated Ru-106 source, (equivalent to minimum ionising particles), before and after the neutron irradiation. The GaAs diode has clearly deteriorated, but the signals are still easily resolved, and the detector continues to be usable.

Alternatives to Semi-insulating material

We have concentrated on diodes made from semi-insulating GaAs because this is the cheapest available material, (used as a substrate in GaAs electronic device construction). Previously, LPE GaAs diodes have been used successfully for gamma ray spectroscopy. More recently, high purity V.P.E. GaAs wafers have been produced at growth rates exceeding 100 microns per hour [4]. The density of trapping centres in these LPE and VPE materials is reported to be significantly less than in semi-insulating wafers, so that the charge collection efficiency may be higher in epitaxial diodes. We hope to test samples of both these alternative materials within the next few months.

GaAs Read-out Electronics

Up to the present, very little use has been made of GaAs front-end electronics in High Energy Physics experiments. GaAs FET pre-amplifiers operating at low temperatures have recently been used in a liquid argon calorimeter read-out system, [10]. In addition, a SPICE analysis of a bipolar pre-amplifier design in GaAs predicts noise and power consumption figures which are significantly lower than corresponding values for silicon, [11]. The expected higher radiation resistance of the GaAs circuits make this a worthwhile area of study. In the longer term, the possibility exists of integrating optical read-out onto the semi-insulating wafer. This is a rapidly evolving commercial activity and could offer useful advantages in particle physics, which we shall attempt to monitor closely. It is our intention to submit a further proposal for developments of this kind at an appropriate time.

Summary of Results Obtained to Date

In summary, GaAs Schottky diodes have been shown to work satisfactorily as charged particle detectors, with essentially 100% detection efficiency for minimum ionising particles. We have established their ability to tolerate radiation loads at the level expected in more than one year of running at a radial distance of only a few cm. from the intersection point of the LHC at nominal luminosity. The diode output signal of only a few nanoseconds is very satisfactory for the new colliders. While these results are already extremely encouraging, a more comprehensive study of the charge trapping mechanisms which we have observed in semi-insulating GaAs may enable substantial improvements in the performance of diodes manufactured in this material. It is our aim to pursue this study and also to proceed to a more systematic study of the use of GaAs read-out electronics. Our plan is to design and construct, within a time scale of two years, a GaAs detector module which can be installed in a working experiment and serve as a demonstration of the viability of GaAs detectors in a real, high radiation environment.

R. & D. Programme

We now present our proposal for support of a two year programme of development in detector technology and read-out electronics, based on GaAs. This work is already receiving support from our local funding agencies, (the SERC in the U.K. and the INFN in Italy), and we have interested industrial concerns in participating in further developments.

The electronics will be developed primarily by RAL, in collaboration with the university groups. Our primary aim is to develop, in collaboration with industry, a simple front-end chip in GaAs which will provide the necessary gain, noise performance and radiation hardness within an existing processing technology. We wish to request assistance from CERN in the design and evaluation of a suitable preamplifier, at the level of one man year of engineering effort.

Detector fabrication will continue to be carried out in the Departments of Electronic Engineering and Physics at the University of Glasgow and at the University of Sheffield, as part of a programme funded by the Universities and the SERC at the level of around 200 kSwfr over the next two years. Device testing will be carried out in both Physics Departments and at CERN, using the facilities established by the LAA group. The Bologna and Florence groups who have been actively involved in the LAA project, are now supported by INFN at the level of 100 kSwfr. We believe, however, that to achieve in two years a complete GaAs detector module of the appropriate size for the pre-shower tracker proposed in Ref [1] will require industrial involvement, implying costs beyond the present level of our support. We have already had preliminary discussions with two industrial concerns who have expressed interest in fabricating GaAs devices. The wisdom of going to two separate manufacturers has already been established in the case of silicon detectors, and given the relatively unknown nature of the production difficulties with GaAs, one production run is unlikely to be sufficient to ensure a successful production process technology. The present proposal therefore includes a bid for two commercial production runs in each year of the two year period.

The Bologna group will take charge of directing the tests to be carried out at CERN, and for the study of charge transport mechanisms in GaAs, together with the group from Florence. We wish to request from CERN the provision of the usual test beam support, and we would hope to combine our beam tests with those of the liquid argon calorimetry group and the pre-shower tracker group. A total of three periods, each of five days, in each of the two years, is our present estimate of test beam requirements.

The Florence group will take responsibility for mechanical design of the support structures required for precision location of large area arrays of detectors, taking advantage of existing engineering strength in their Institute. We request additional support from CERN in the form of mechanical engineering effort to ensure compatibility with the silicon pre-tracker shower detector.

Radiation hardness tests of detectors and electronics will be carried out both at CERN and at the ISIS neutron irradiation facility at RAL, with the involvement of all the university groups.

The following table defines a series of milestones to be reached in the proposed programme of work, which will include studies of microstrip detectors of various geometries, the relative merits of semi-insulating, LPE and VPE wafers and different wafer thicknesses and of course the radiation hardness of our devices, and of the front-end electronics which we shall design and build.

Milestones

Item	Date of Completion
1. LPE, VPE Tests	March 31st, 1991
2. First Commercial Production	September 30th, 1991
3. Second Commercial Production	March 31st, 1992
4. Mechanical Support Design	June 30th, 1991
5. Mechanical Support Build	September 30th, 1991
6. Preamplifier Design	June 30th, 1991
7. Preamp. Prototype Build	December 31st, 1991
8. Beam tests (microstrips)	September 30th, 1991
9. Beam tests (pads)	September 30th, 1991
10.Radiation Tests (microstrips)	September 30th, 1991
11.Radiation Tests (pads)	September 30th, 1991
12.Assemble Prototype Module	March 31st, 1992
13.Beam test Prototype Module	September 30th, 1992
14.Radiation tests (Proto.Mod.)	December 31st, 1992

Summary of Requests

In summary, our requests to CERN for the two year period of the proposal are for

(a) one electronic engineer for one year,

(b) one mechanical engineer for one year,

(c) six periods of test beam running, each of five days, in conjunction with tests of a calorimeter and pre-shower tracker, and with normal technical support, and

(d) the costs of four commercial production runs of GaAs detector fabrication. In view of the greater uncertainties involved with this new technology than with silicon, the cost per process run is likely to be higher than for silicon initially. We have been given an estimated price of around 60 kSwfr per run, and would expect to get from such a run a total of 18 modules, each 3cm square, of pad detectors, (with 3mm square pads), and 36 microstrip modules, also 3cm square, (with 360 micron strips of 24 mm length).

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Diameter (mm)	50.9
Orientation	(100)
Dopant	Nil
Wafer flatness (microns)	< 3
Wafer thickness (microns)	500 ± 25
Weight (g)	5.37
Resistivity (ohm-cm)	$7.5.10^7 - 1.2.10^8$
Mobility ($cm^2 V^{-1} s^{-1}$)	$6.8.10^3 - 6.6.10^3$
Carrier Concentration (cm^{-3})	$1.2.10^7 - 8.2.10^6$
Etch Pit Density (cm^{-2})	$2.1.10^4 - 3.0.10^4$

Table 1: GaAs wafer characteristics, as supplied by the manufacturer.

Contact	Metal	Thickness
ohmic	Ni	5 nm
	Ge	25 nm
	Au	43 nm
	Ni	30 nm
	Au	50 nm
Schottky	Ti	30 nm
	Au	80 nm

Table 2: Diode electrode composition. The ohmic contact metals are evaporated at a base pressure of $< 8.10^{-6}$mbar and the final annealing step at 360° lasts 50 - 60 seconds. The Schottky contact requires evaporation at the lowest possible pressure, typically $< 5.10^{-6}$ mbar.

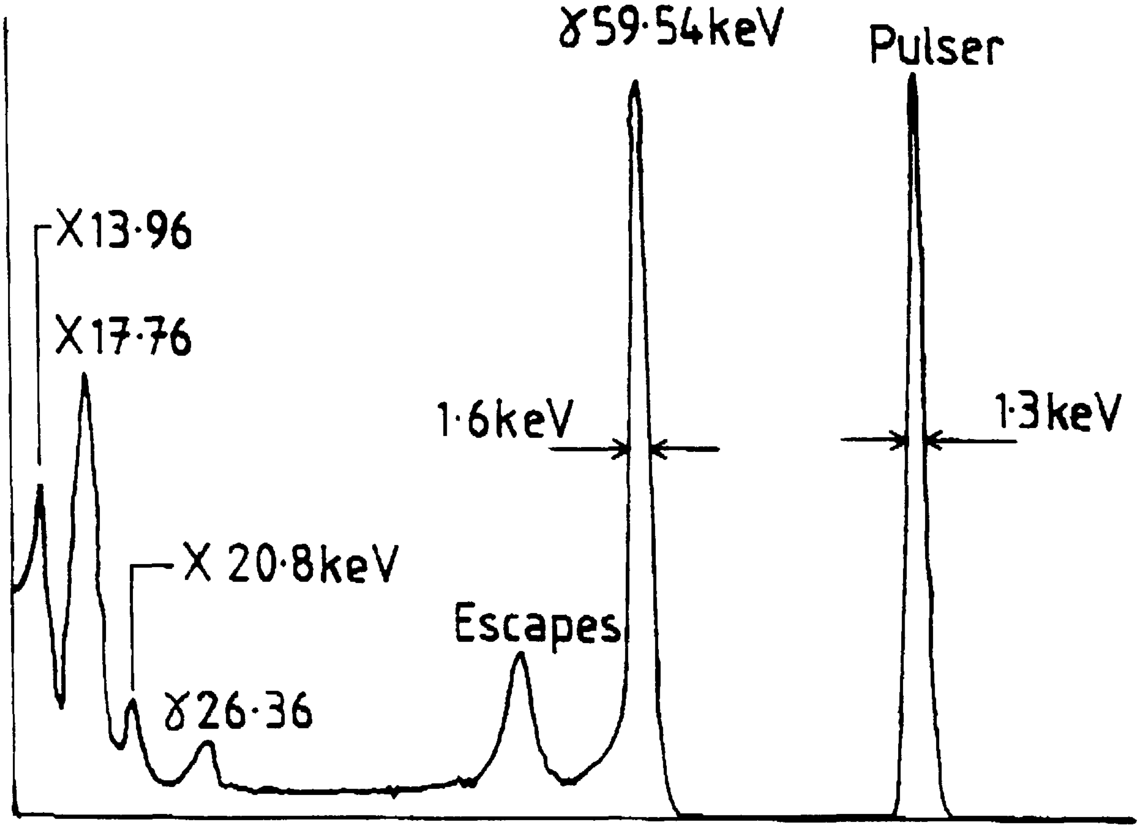

Figure 1: Gamma and X-ray spectrum obtained with an L.P.E. diode, cooled to liquid nitrogen temperatures then allowed to warm up to the optimum signal/noise temperature ([6]).

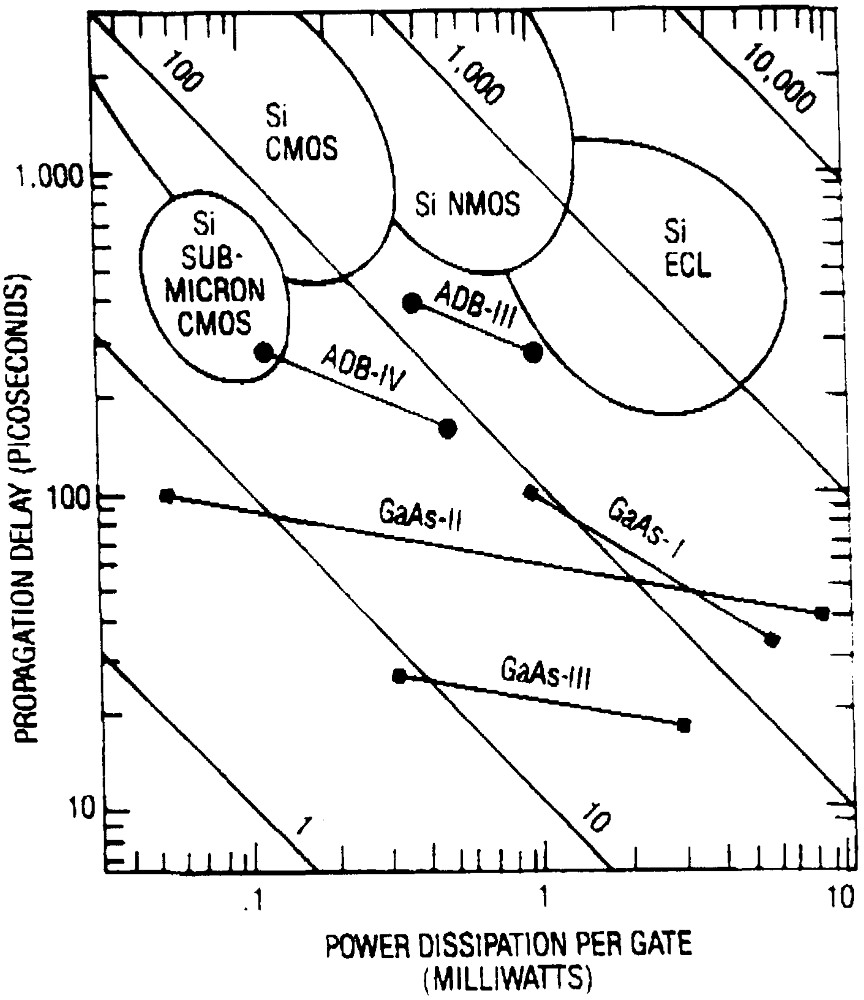

Figure 2: Speed - power requirements for different semiconductor technologies.

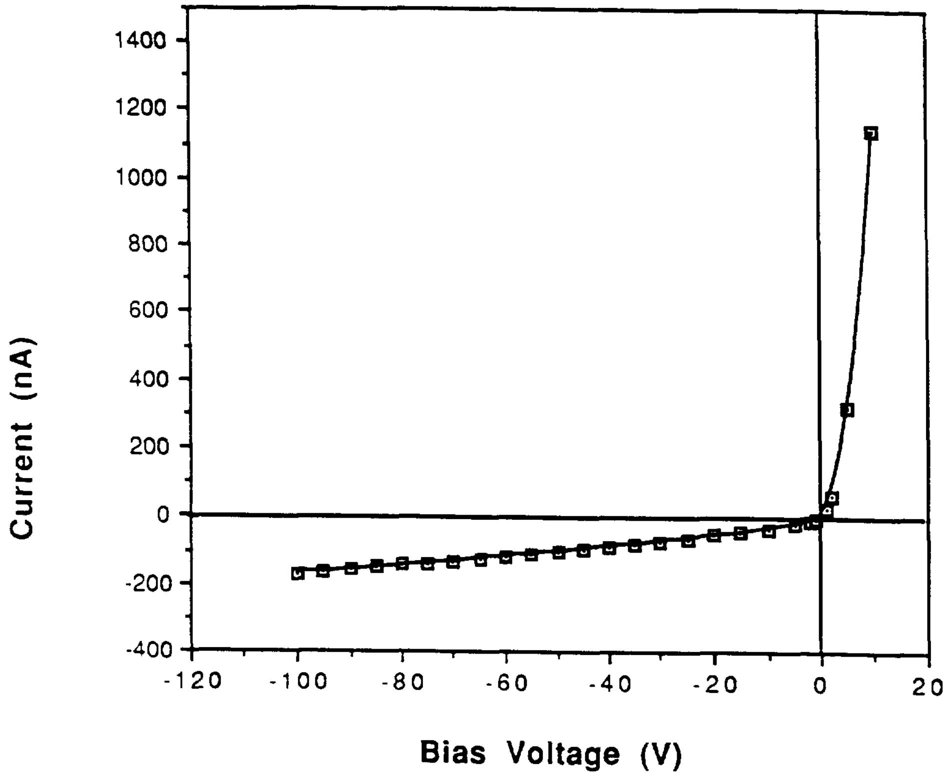

Figure 3: I-V characteristic of a typical semi-insulating substrate GaAs Schottky diode.

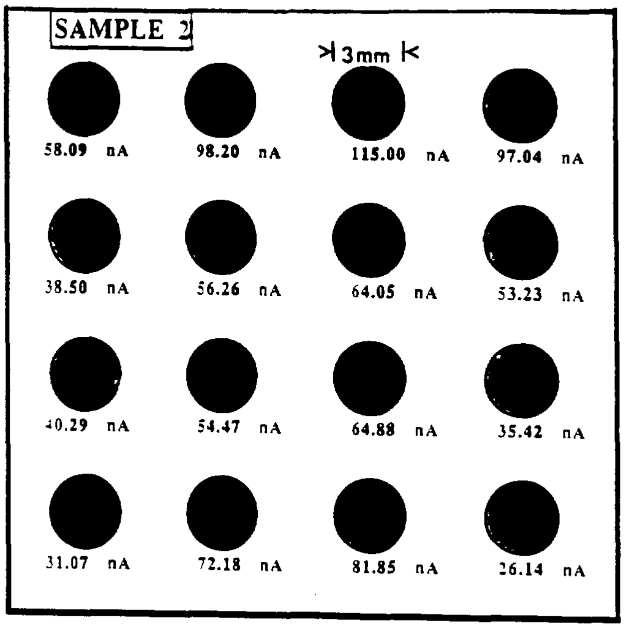

Figure 4: Diode array on a single chip, with measured leakage current at 36 V reverse bias.

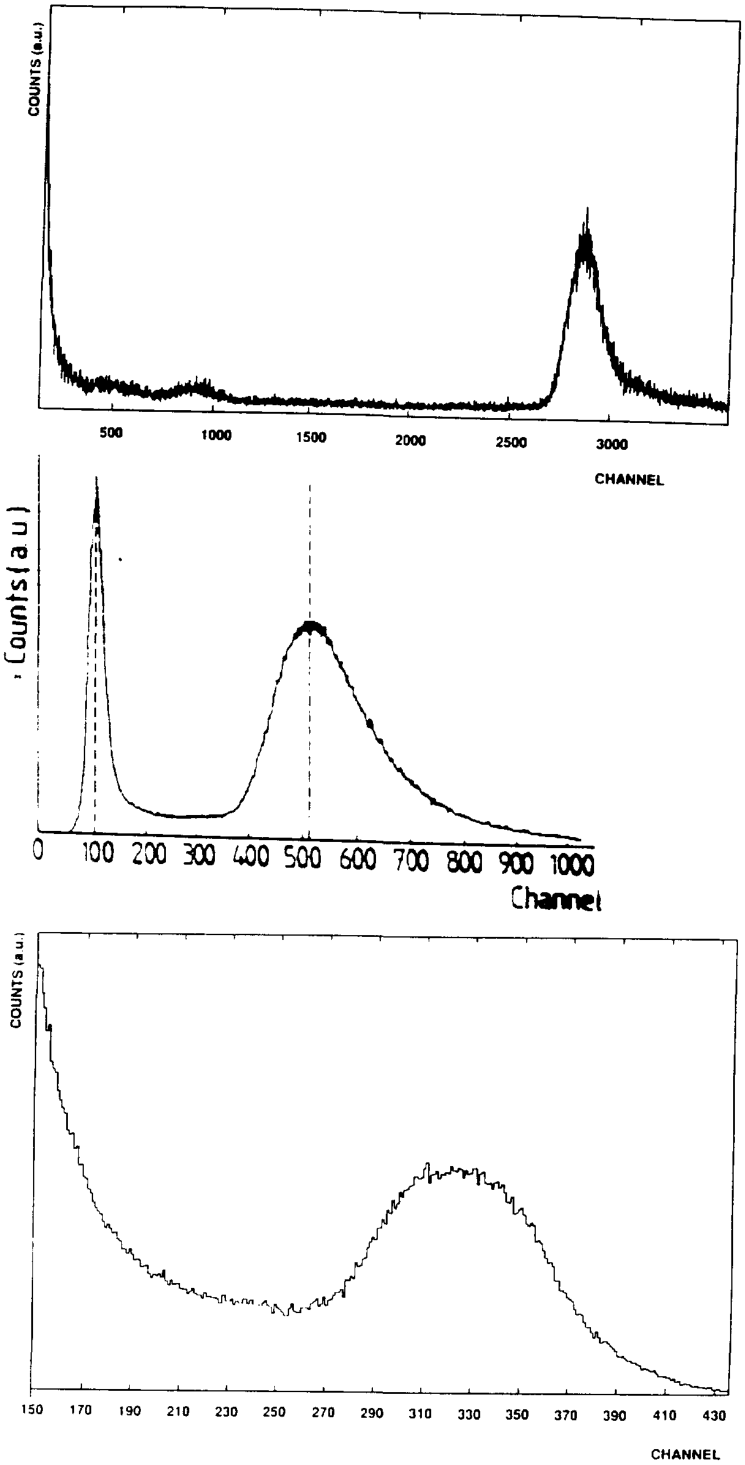

Figure 5: Pulse height spectra obtained with alpha-, beta- and gamma-ray sources in a GaAs detector.

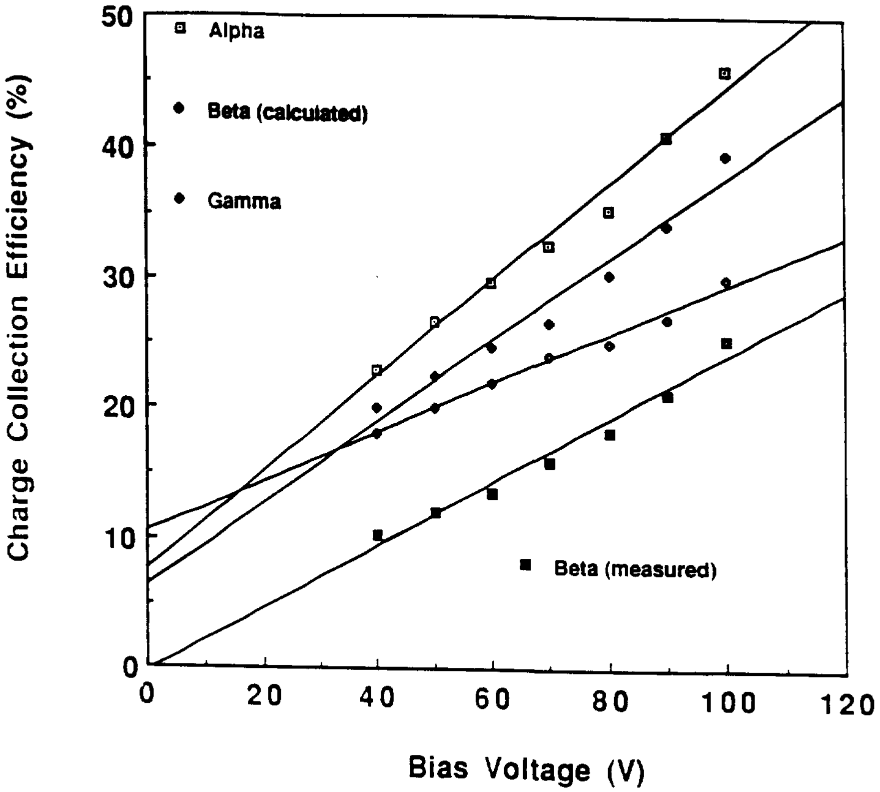

Figure 6: Charge collection efficiency variation with bias voltage, for alphas, betas and gamma rays.

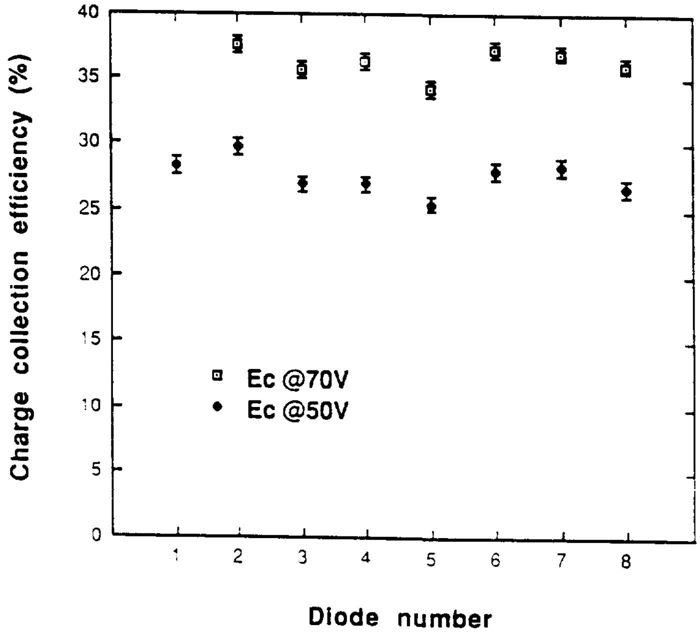

Figure 7: Charge collection efficiency variation for the diode array.

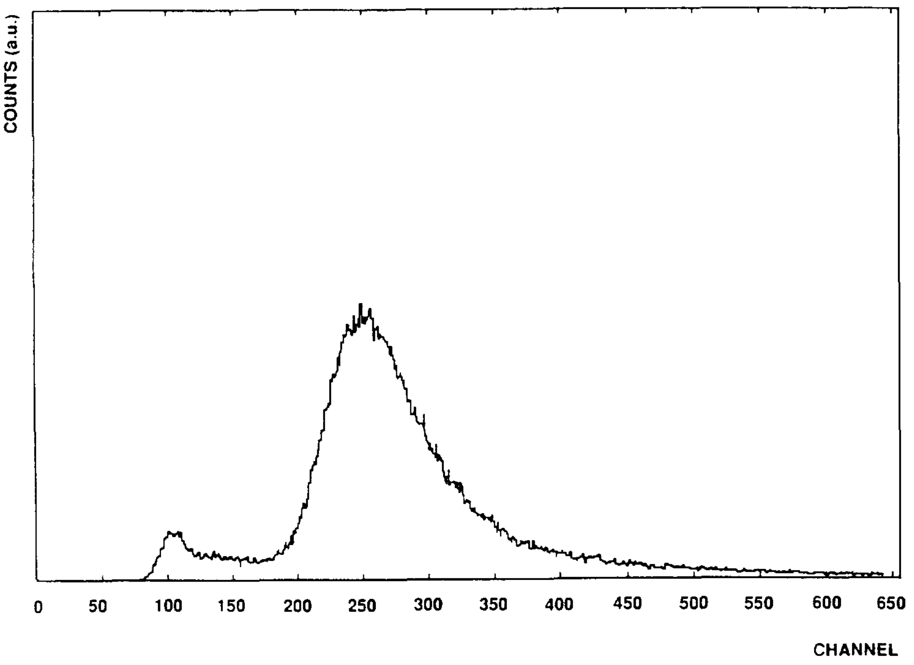

Figure 8: Pulse height spectrum obtained in a GaAs detector with 6GeV/c pions.

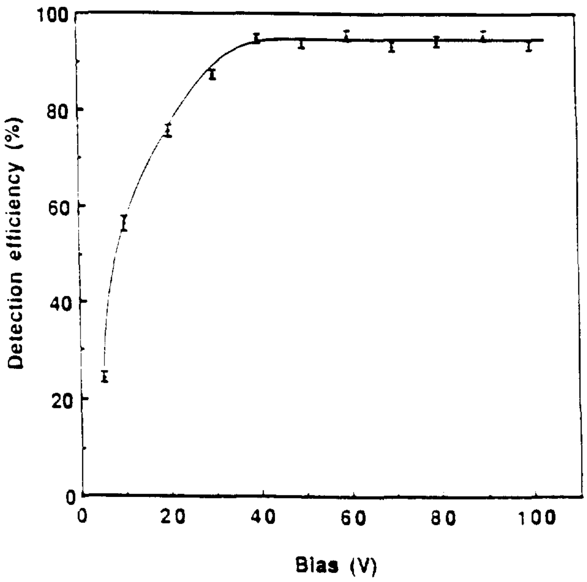

Figure 9: Detection efficiency variation with bias for 6 GeV/c pions.

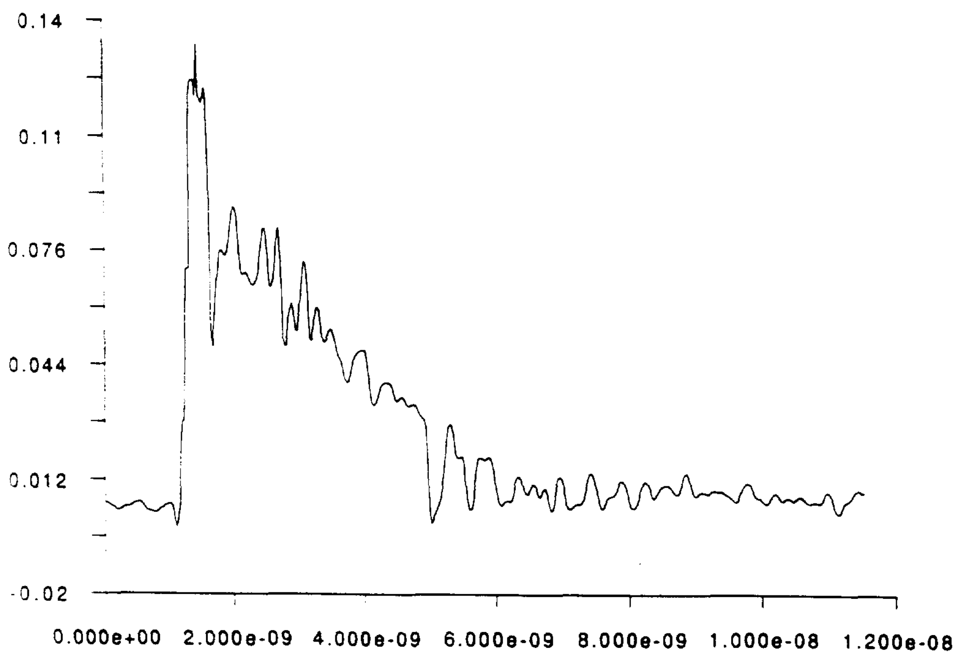

Figure 10: Oscilloscope trace of GaAs detector response to a 1.5 picosecond laser excitation pulse.

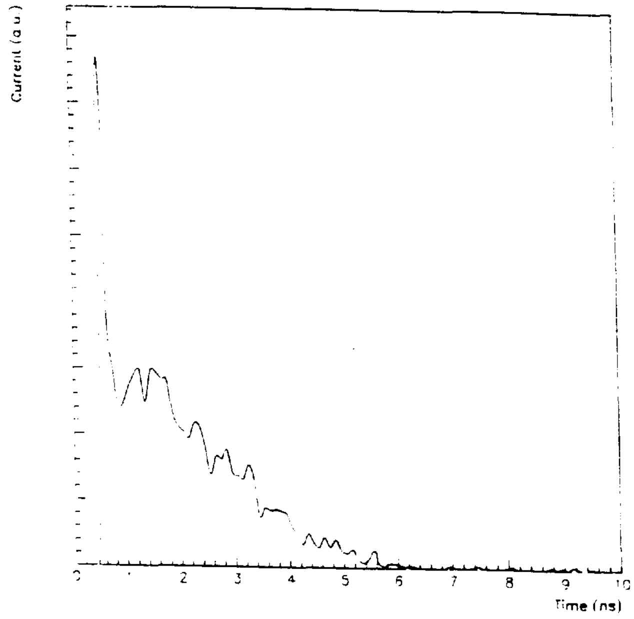

Figure 11: Simulation of GaAs reponse to the picosecond excitation, using a charge transport model which incorporates a hopping mechanism between traps.

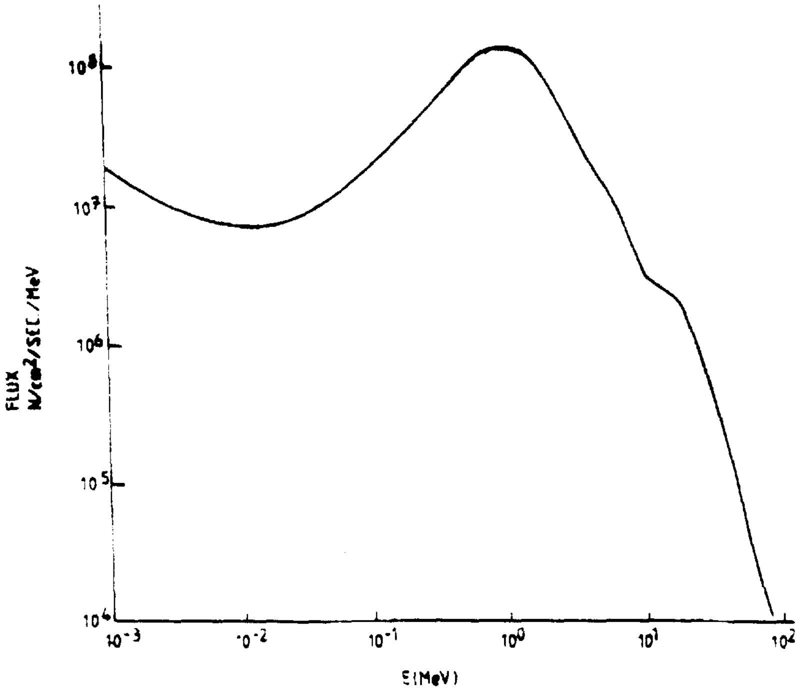

Figure 12: The spectrum of neutrons from the ISIS irradiation facility at the R.A.L..

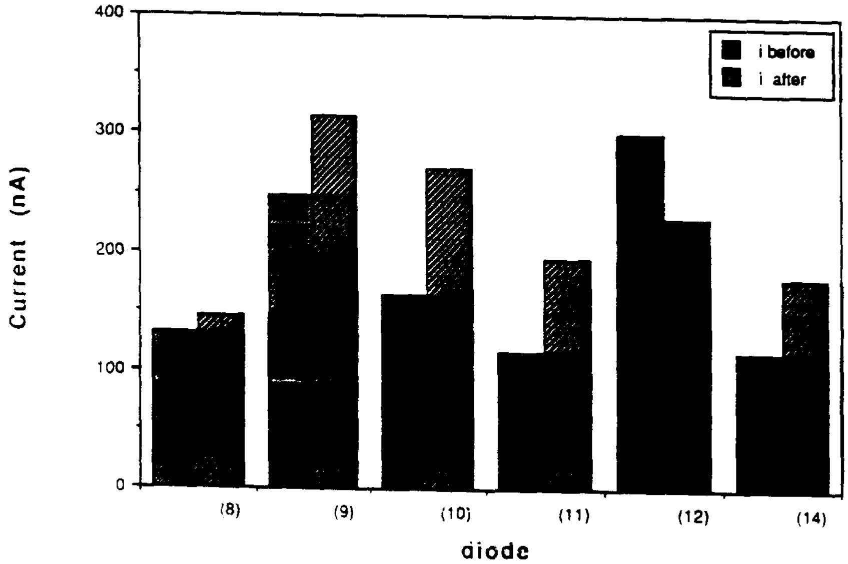

Figure 13: Comparison of reverse bias leakage current in several GaAs diodes before and after neutron irradiation by a neutron fluence of 7.10^{14}n/cm^2.

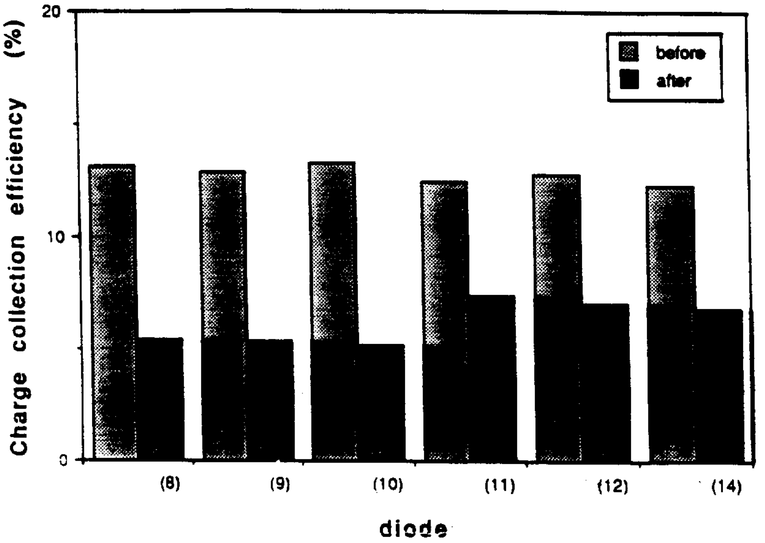

Figure 14: Charge collection efficiency of several GaAs diodes before and after irradiation by a neutron fluence of 7.10^{14}n/cm^2.

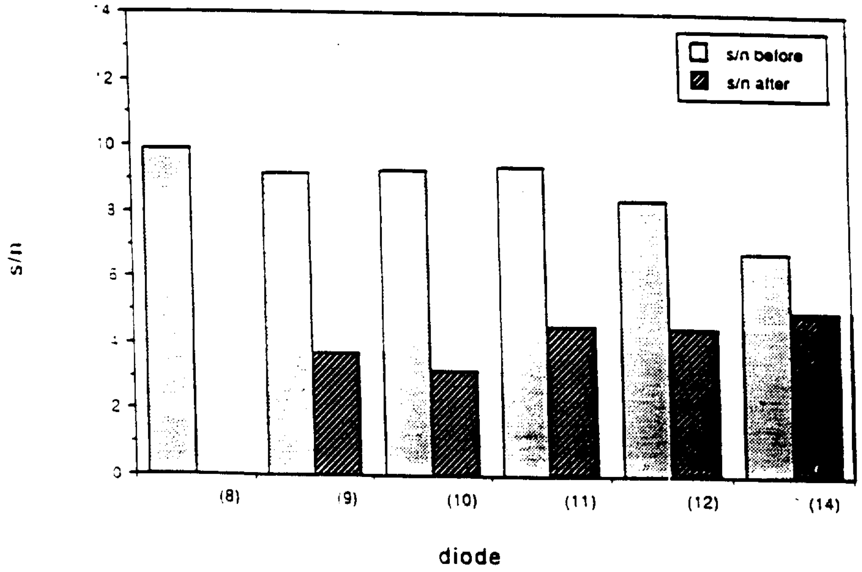

Figure 15: Signal to noise ratio in several GaAs diodes before and after irradiation by a neutron fluence of 7.10^{14}n/cm^2.

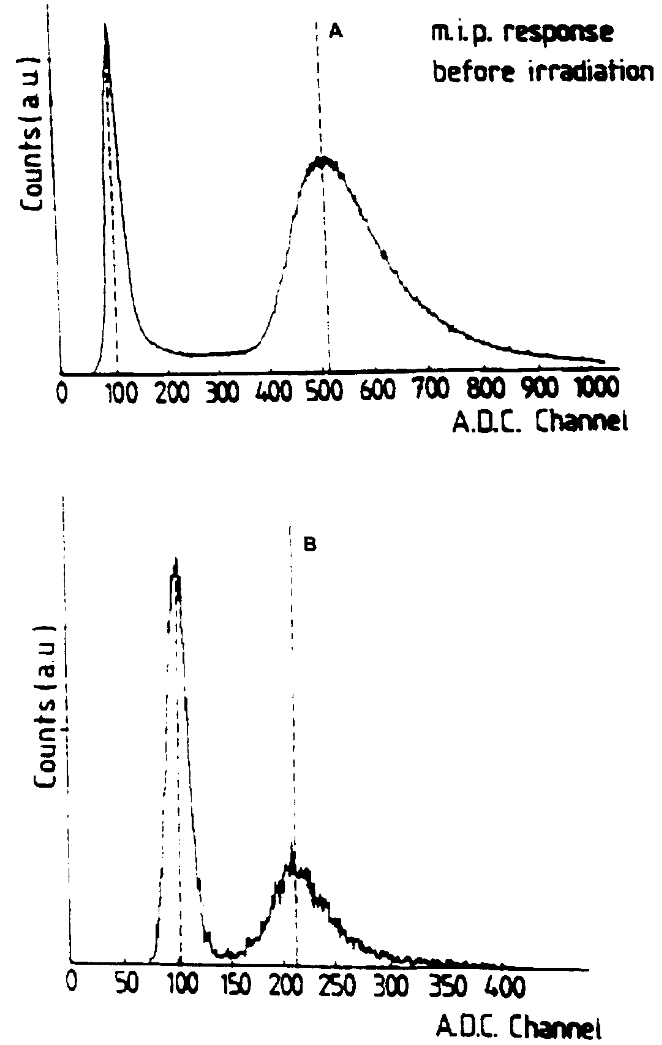

Figure 16: Pulse height spectrum from Ru-106 source, corresponding to minimum ionising particles, before (a) and after (b) irradiation of the GaAs detector.