CERN -LHCC-97-37

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CERN/LHCC 97-37
Status Report/RD8
July 10th, 1997

STATUS REPORT OF THE RD-8 COLLABORATION

Presented by K.M.Smith,
(University of Glasgow),
for

The GaAs Collaboration

I.Phys.Inst.,R.W.T.H. Aachen, Germany
ANSTO and University of Sydney, Sydney, Australia
University of Bologna and INFN, Italy
University of Florence and INFN, Italy
Albert-Ludwigs Universitat, Freiburg i.B., Germany
University of Glasgow, U.K.
University of Lancaster, U.K.
University of Melbourne, Australia
University of Modena, Italy
Czech Technical and Charles Universities and
Institute of Physics, Academy of Sciences, Praha, Czech Republic
I.H.E.P., Protvino, Russia
Rutherford-Appleton Laboratory, Chilton, Didcot, Oxon., U.K.
University of Sheffield, U.K.
S.P.T.I., Tomsk, Russia
University of Udine, Italy
ICSC World Lab., Vilnius, Lithuania

Present members of the RD8 collaboration are listed below.

D.Alexiev[2],M.Alietti[10],S.Arbabi[1],S.P.Beaumont[6],C.N.Booth[14], W.Braunschweig[1],
J.Breibach[1],D.L.Budnitsky[16],K.S.A.Butcher[2],C.Buttar[14], C.Canali[10],L.Carraresi[5],
A.Cavallini[3],A.Chilingarov[8],C.Chiossi[10],V.Chmill[12], Z.Chu[1],A.Chuntonov[12],F.Cindolo[3],
M.Colocci[5],F.H.Combley[14],S.D'Auria[7],C.DaVia[7], C.delPapa[17],M.Dogru[14],Z.Doležal[11b],
I.Donnelly[2],M.Edwards[13],F.Fares[9],F.Fiori[3],F.Foster[8], A.Francescato[5],
R.Geppert[4],S.Gowdy[7],R.Gray[15],G.Hill[15],Y.Hou[14], P.Houston[15],
J.Jakůbek[11a],B.Jones[8],W.Karpinski[1],R.Krais[1], S.Khludkov[16],J.Kubašta[11a],
Th.Kubicki[1],K.Lübelsmeyer[1],J.Ludwig[4],M.Macpherson[8], J.J.Mareš[11c],
O.Mang[1],S.Manolopoulos[14],A.Matulionis[18],G.Moorhead[9], F.Nava[10],M.Nuti[5],V.O'Shea[7],
D.Pandoulas[1],P.Pavan[10],L.Peak[2],P.G.Pelfer[5], S.Pospíšil[11a],J.Pozela[18],C.Raine[7],
P.Ratoff[8],C.Rente[1],K.Runge[4],J.Santana[8],A.Savedra[2], M.Schöntag[1],M.Schweizer[4],P.H.Seller[13],
P.J.Sellin[14],R.Siedling[1],I.O.Skillicorn[7],T.Sloan[8], K.M.Smith[7],V.E.Stepanov[16],O.Syben[1],
N.Tartoni[5],G.Taylor[9],F.Tenbusch[1],O.Tolbanov[16], Z.Tomiak[11a],M.Toporowsky[1],Yu.Tsyupa[12],
U.Vanni[5],K.Varvell[2],A.Vinattieri[5],A.Vorobiev[12], W.Wallraff[1],S.Walsh[14],
M.Webel[4],I.Wilhelm[11b],M.L.Williams[2],B.Wittmer[1], M.Williams[2],W.J.Xiao[1] and K.Zdansky[8]

1 - Physikalisches Institut, RWTH Aachen, Germany
2 - ANSTO and University of Sydney, Sydney, Australia
3 - Dipartimento di Fisica dell'Universita' and INFN Bologna, Italy
4 - Physikalisches Institut, University of Freiburg, Germany
5 - Dipartimento di Fisica dell'Universita' and INFN Florence, Italy
6 - Dept. of Electronic and Electrical Engineering, University of Glasgow, U.K.
7 - Dept. of Physics and Astronomy, University of Glasgow, U.K.
8 - Dept. of Physics, University of Lancaster, U.K.
9 - Physics Department, University of Melbourne, Australia
10 - Dipartimento di Fisica dell'Universita' and INFN Modena, Italy
11 - Prague group, (*a*) Czech Technical University, *b*) Charles University,
c) Institute of Physics, Academy of Sciences), Prague, Czech Rep.
12 - I.H.E.P. Protvino, Moscow, Russia
13 - Rutherford - Appleton Laboratory, Chilton, Didcot, Oxon., U.K.
14 - Dept. of Physics, University of Sheffield, U.K.
15 - Dept.of Electrical Engineering, University of Sheffield, U.K.
16 - S.P.T.I., Tomsk, Russia
17 - University of Udine, Italy
18 - Institute of Semiconductor Physics, Vilnius, Lithuania

Introduction

The main objectives of the collaboration since the last Status Report [1] have been

- continued investigation of alternative industrial wafer materials and detector fabrication technologies
- testing of commercial and 'in-house' microstrip detectors to LHC specifications with LHC speed read-out electronics
- understanding of the properties and limitations of these detectors
- theoretical modelling of the electric field distribution in unirradiated GaAs detectors and of the charge trapping in radiation-damaged devices
- intensive evaluation of the radiation-hardness of GaAs detectors to charged pions and protons
- detailed characterisation of irradiated GaAs detectors using a wide range of experimental techniques
- investigation of differences between industry-standard, SI-U (Semi-Insulating, Undoped), LEC (Liquid-Encapsulated Czochralski) and epitaxially-grown GaAs layers
- evaluation of GaAs pixel detectors, fabricated 'in-house' and commercially
- continued efforts towards improved understanding of the costs of commercial detectors

GaAs microstrip detectors have now achieved almost all of the performance goals for operation at the Large Hadron Collider in terms of low temperature operation, signal to noise ratio, speed and spatial resolution.
Optimisation of the detector strip geometry is now possible, using data obtained from a range of prototypes. Operation at low temperatures, compatible with the requirements of silicon microstrip detectors, has been shown to present no problems other than a signal loss of around a few per cent. The unexpectedly greater sensitivity to radiation damage by pions and protons, however, coupled with the improved performance recently achieved using silicon detectors, now makes it unlikely that GaAs microstrip detectors will be utilised, at least in the initial phase, for LHC tracking applications. Detailed investigations of the nature of the radiation damage are in progress, and may provide new insights into ways of enhancing the radiation hardness to restore the competitiveness of GaAs.

GaAs pixel detectors have been successfully tested in high energy pion test beams with Omega3/LHC1 read-out chips [2] supplied by the CERN Microelectronics Group and bump-bonded by GMMT, Caswell Labs. They have also shown great promise for applications in X-ray imaging, as discussed below.

Material and Processing Issues

The charge released by ionising radiation in SIU-LEC GaAs Schottky diode detectors has been shown to increase approximately linearly with increasing reverse bias [1, 3], corresponding to a sensitive thickness which increases at a rate of around 0.7μm per volt of applied bias. Improvements have recently been made to a Monte Carlo model which simulates this behaviour [4, 5]. The model is based on the effect of deep traps, close to the Fermi Level in the middle of the bandgap, particularly the EL2 level commonly found in Si-LEC GaAs. Band bending at the metal-semiconductor boundary leaves these traps ionised and the resulting space charge creates an electric field distribution which differs from that found in silicon junction devices. Detector performance is then sensitive to small variations in the Fermi level position due to dopants or irradiation damage, for example. The simulation utilises values of the mean free path before trapping for electrons and holes, λ_e and λ_h respectively, which are determined from the measured response to alpha particles illuminating the front or back side of the detector, respectively. (The range of ^{241}Am alpha particles in GaAs is $< 20\mu m$, so that the charge signal in a detector of thickness 200μm is due almost entirely to one sign of charge carrier.) Figure 1, which shows the values obtained using GaAs LEC substrate material from different suppliers, illustrates the range of detector parameters which are accessible by appropriate choice of substrate.

Very recently, measurements have been made of the voltage profile across the wafer thickness of a reverse biased GaAs detector, on a surface which was cleaved under high vacuum and so free of any surface oxide layer [6]. These were found to be in agreement with the predictions of the Monte Carlo model quoted above, as shown in Figure 2.

Similar measurements made on the same sample after exposure to air gave a voltage profile more consistent with earlier direct measurements which appeared incompatible with the model. Other experimental efforts are also in progress, however, using simple pad detectors to reach an improved understanding of the charge collection process. These include comparative studies by the Prague group [7] of the response of LEC and VPE diodes, using low energy protons to probe the variation with depth of the charge collection efficiency (c.c.e.). By varying the proton energy so as to create the peak of the Bragg ionisation curve at different depths, they may lead, in particular, to improved understanding of the transition region between the 'high' field and 'low' field regions adjacent to the Schottky and ohmic contacts, respectively.

Detailed studies [8, 9] have been made of the correlation between detector performance and the concentration of deep level defects in GaAs detectors, using near infrared absorption and resistivity measurements. Particular attention was paid to the concentration of the EL2 trap and its ionised state, EL2$^+$ in a range of substrates, including wafer material having lower than normal concentrations of carbon dopant atoms and correspondingly low values of resistivity, both before and after irradiation with 24GeV/c protons at the CERN PS. Details of these measurements are given below in the discussion of the effects of radiation damage.

The improved reverse bias operating range resulting from improvements in GaAs de-

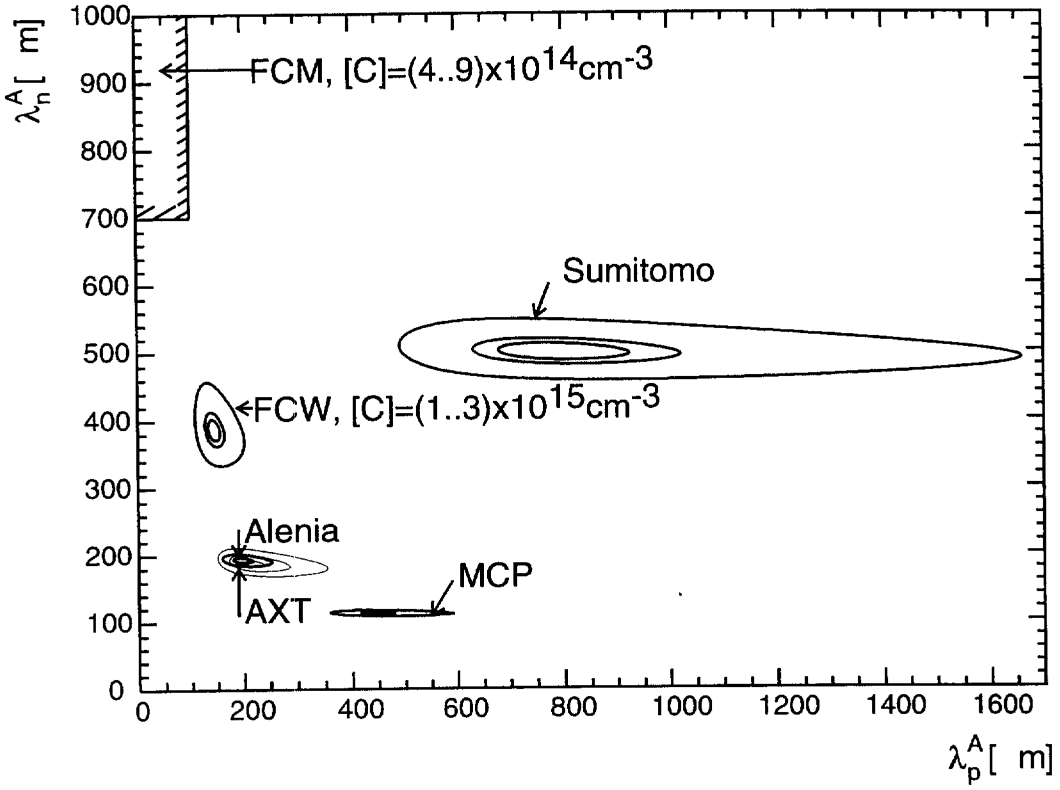

Figure 1: Mean free paths before trapping for different substrates

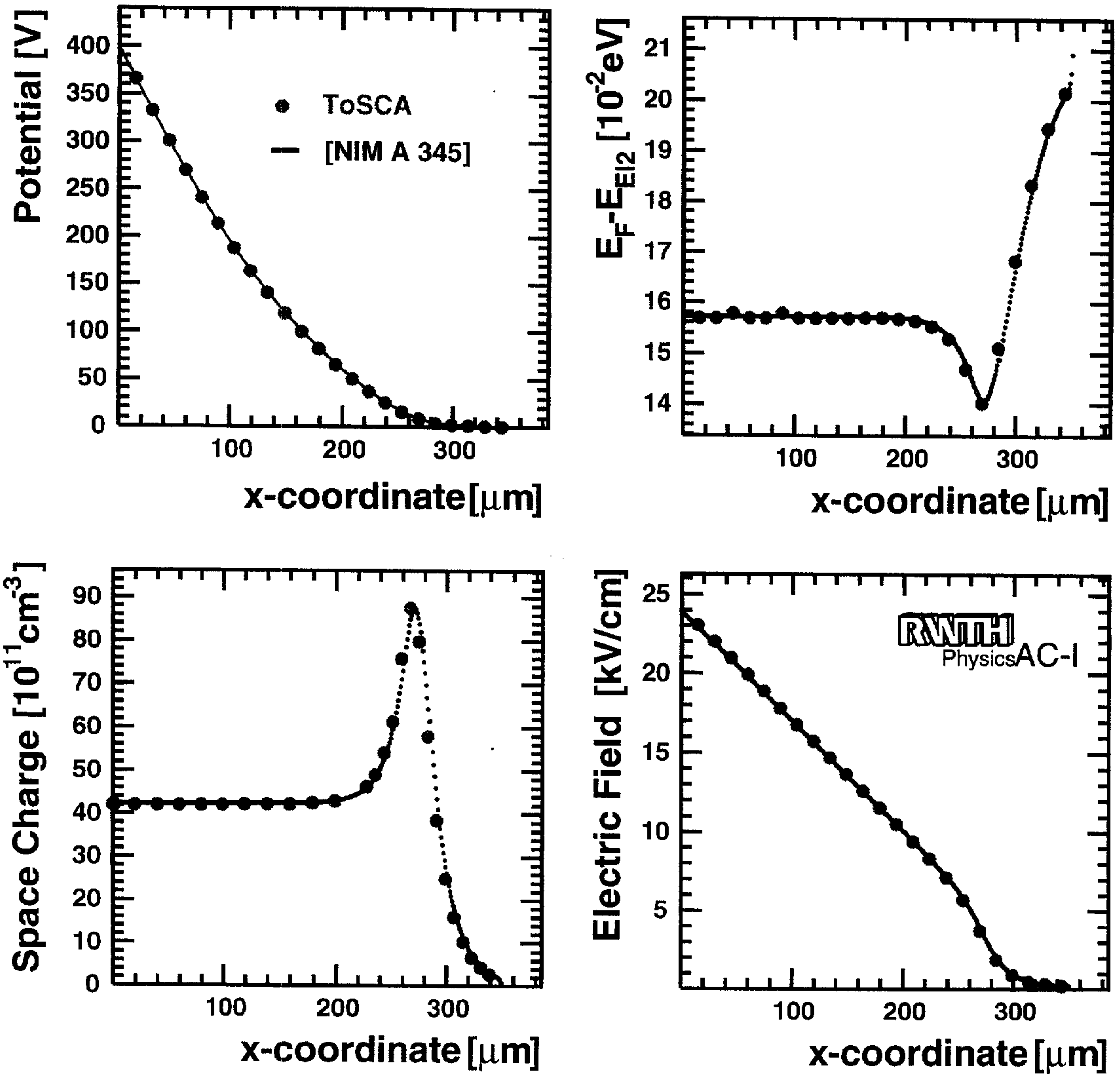

Figure 2: Comparison of new and old Aachen Monte Carlo field simulation

tector fabrication technology, demonstrated originally by Alenia SpA, Rome, using ion implantation or non-alloyed ohmic contacts [10] has now been obtained by other groups within the RD8 collaboration, thereby creating additional 'headroom' for operation of the detectors at much higher reverse bias and achieving maximum charge collection efficiency more reliably.

The Russian groups in Protvino and Tomsk have continued to develop the fabrication technology which creates a $\pi - \nu$ region by a concentration gradient of iron or chromium deep level dopants across the wafer thickness [11]. Excellent radiation hardness against neutron irradiation was shown by early versions of these detectors, but attempts to increase the sensitive fraction of the wafer thickness by varying the diffusion process, while successful in increasing the charge signal from the detectors, may have compromised the radiation hardness, the reasons for which are still under investigation.

Microstrip Detectors

Microstrip detectors have now been successfully fabricated in University laboratories and in industry on, typically, 200-250μm thickness GaAs substrate wafers, with typical strip pitch 50μm, a range of metal:gap aspect ratios and strip lengths of up to 52mm. An example of how the simulation of the electric field configuration in a microstrip detector using the TOSCA software package permits the optimisation of detector parameters such as the metal width:pitch ratio is given in Figure 3.

The detector structures can incorporate integrated decoupling capacitors and the bias voltage is provided either by punch-through structures or by in-built germanium or 'cermet' bias resistors. The performance of a typical microstrip detector is illustrated in Figures 4,5,7,6, with details of the measured resistor and decoupling capacitor uniformity now attainable. The charge signals from the strips have been read out successfully in test beam runs and in the laboratory, using FELIX and PREMUX128 ($\sim$40ns shaping time) analogue front-end chips and also with an ATLAS prototype, LBIC binary read-out system.

Total efficiencies of $> 95\%$ have been obtained [12], (97.5% when corrected for noisy channels). The measured signal-to-noise has reached the level of 30:1 [12, 13] and the observed spatial resolution is compatible with (pitch/$\sqrt{12}$) or better.

Microstrip detectors have also been tested at temperatures around -8°C, (dictated by the need to avoid reverse annealing effects in irradiated silicon detectors). A detector was irradiated with 6×10^{13}protons/cm^2 (in the T7 beam of the CERN PS) at -8°C. The signal was then measured at -8°C (before warming up). After warming to 27°C for 4 hours the signals were measured again. Finally the detector was again cooled to -8°C and the signals measured. No significant difference can be seen among these measurements, indicating that there is no significant contribution from room temperature annealing with corresponding time constants. This point was checked in view of possible operation of the detectors in a cooled tracker. The charge signal loss is negligibly small, as illustrated, for example, in Figure 8.

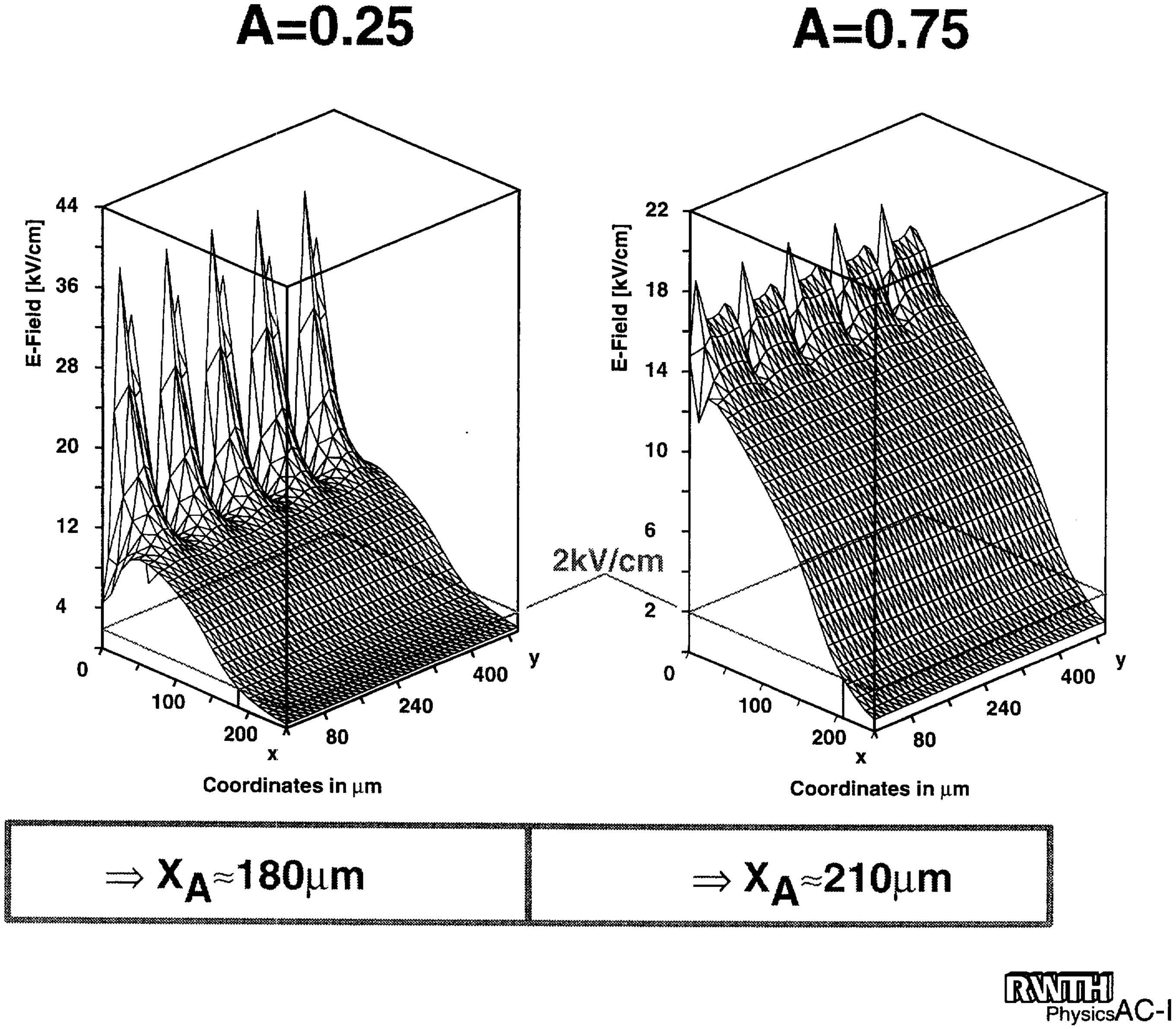

Figure 3: Electric field computed using TOSCA for two metal:pitch aspect ratios A=0.25 and 0.75

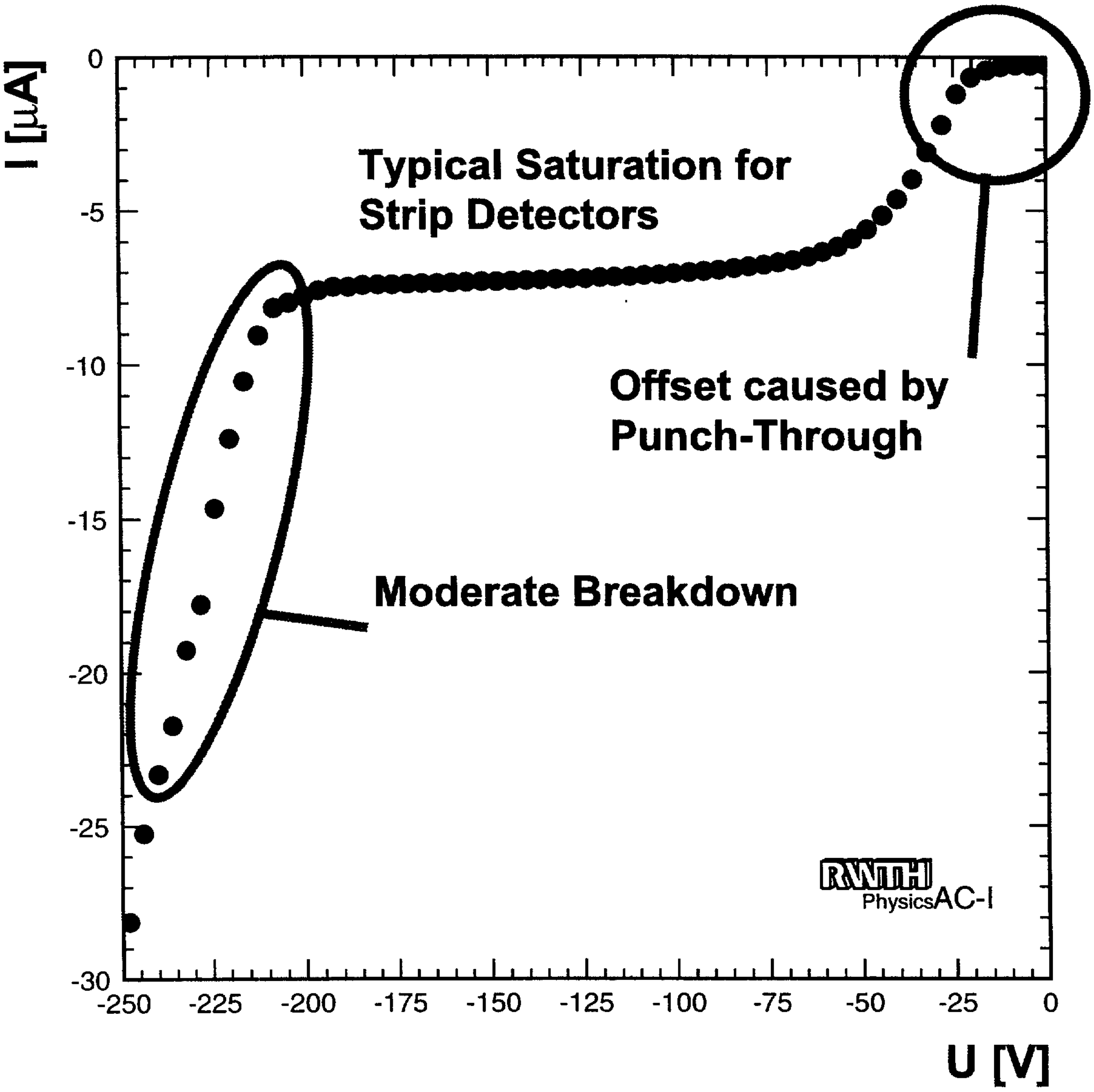

Figure 4: Strip I-V characteristic

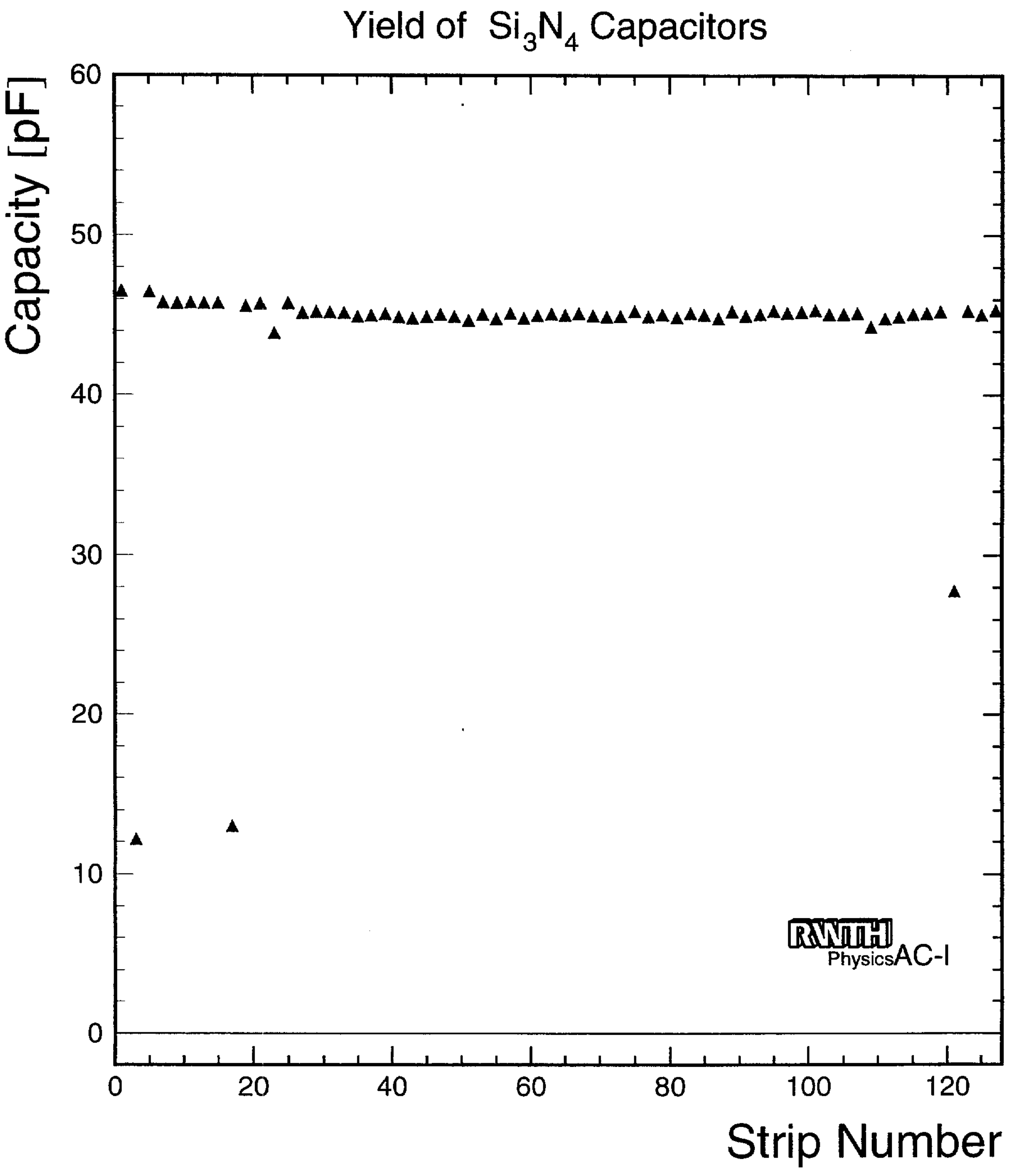

Figure 5: Capacitor yield

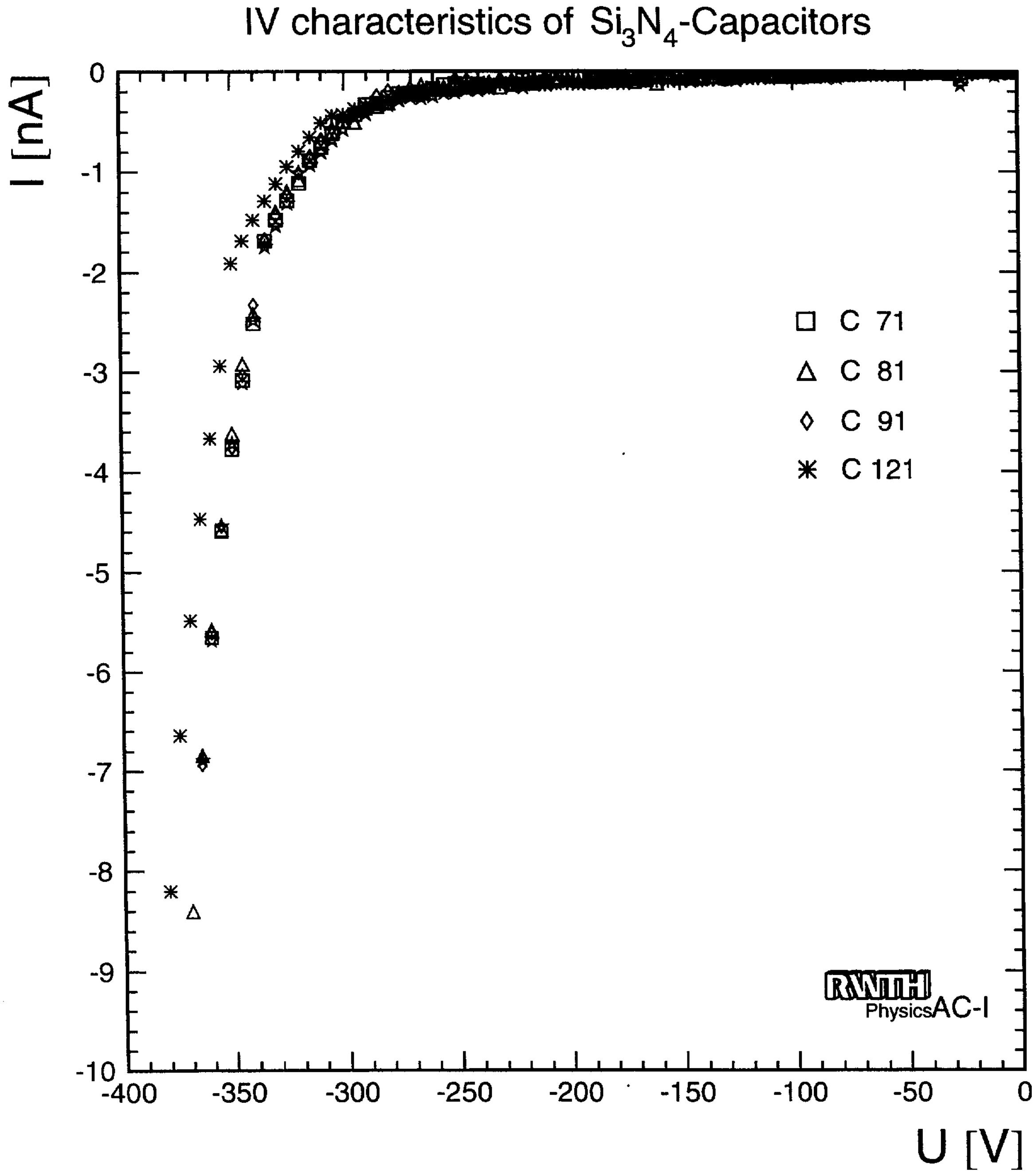

Figure 6: Capacitor I-V characteristic

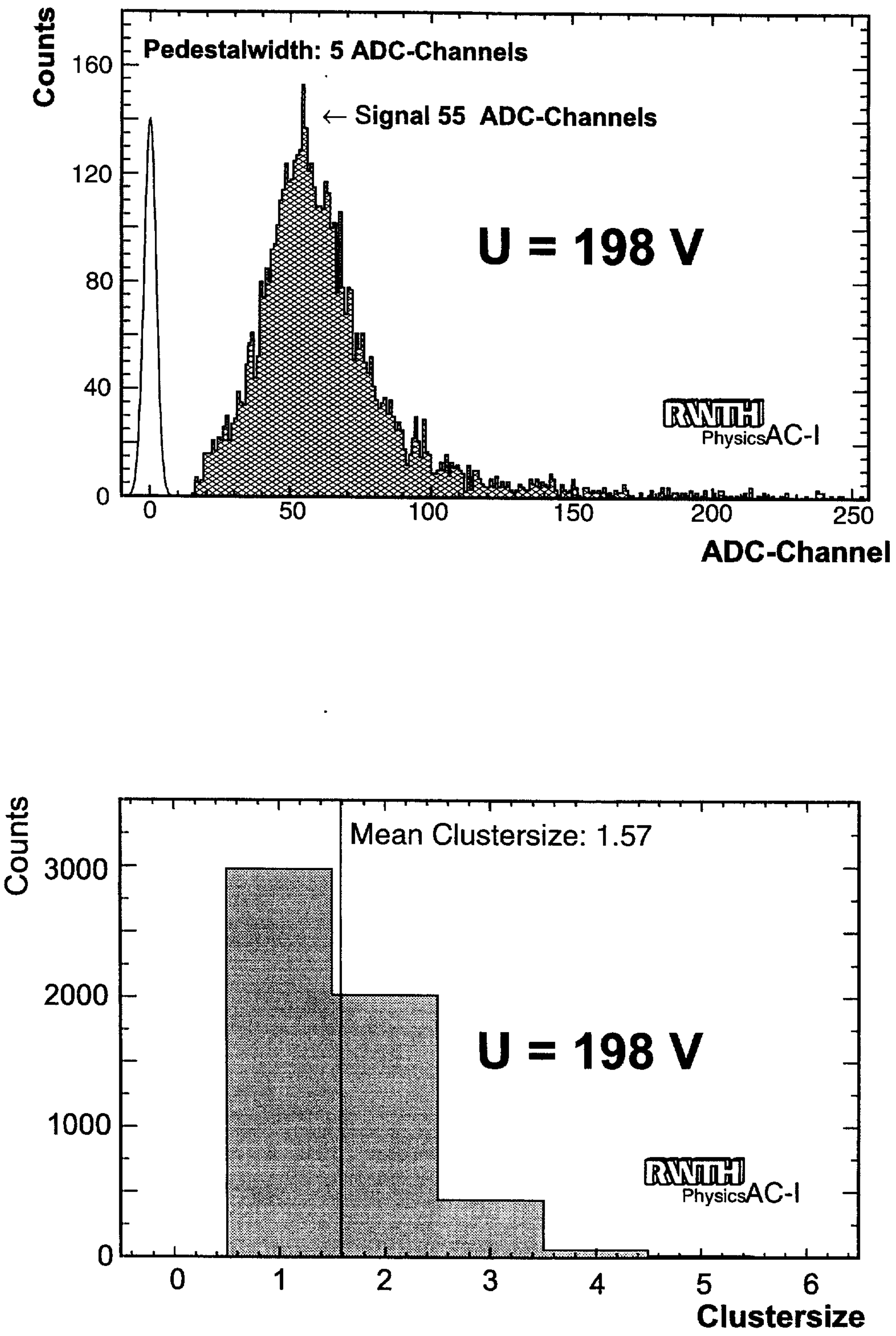

Figure 7: MIP Strip signal

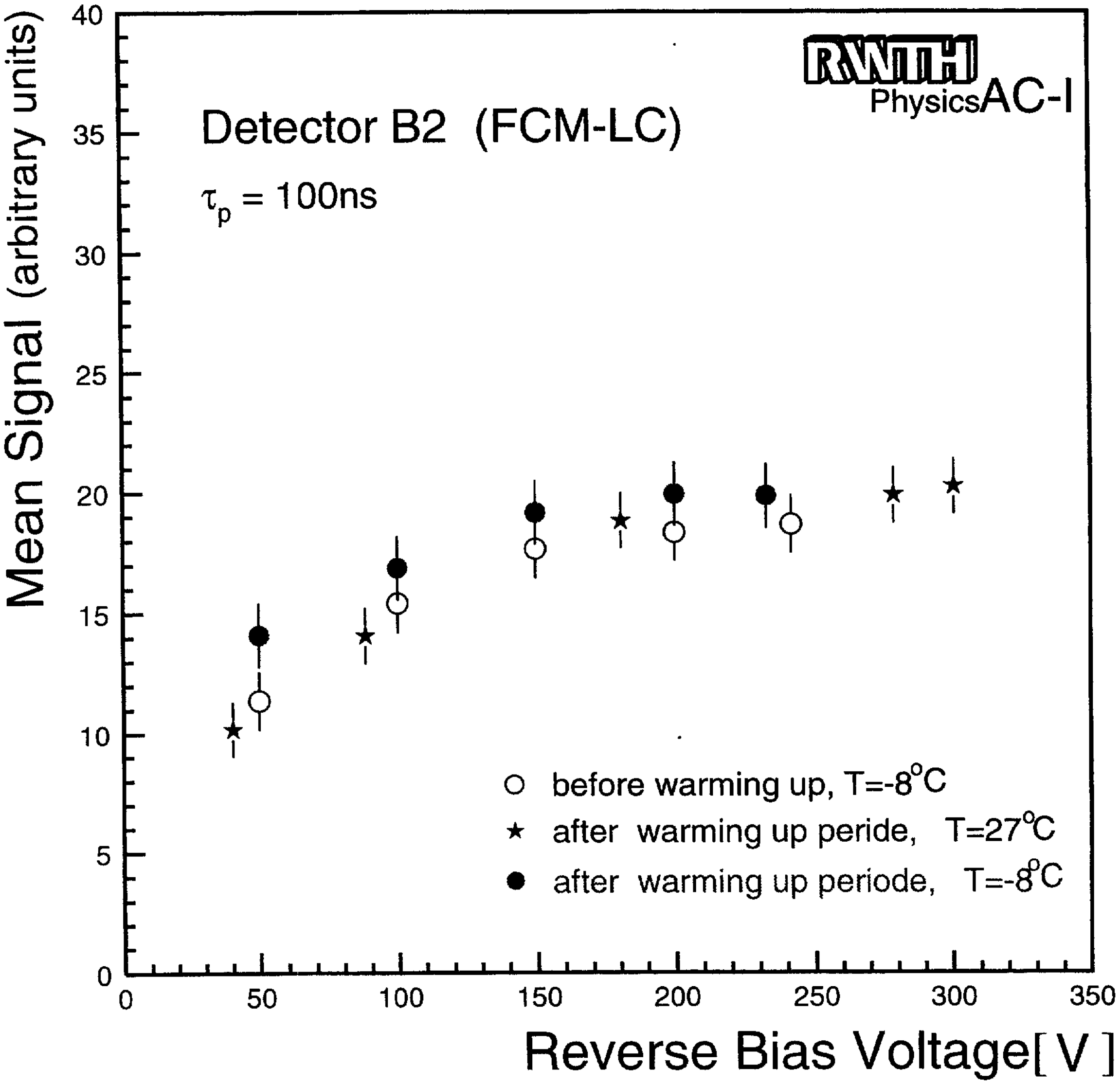

Figure 8: The mean signal for mips (arbitrary units) as a function of bias voltage under different conditions.

Pixel detector tests

GaAs pixel detectors matched to the 16×128 array of 50×500μm^2 Omega3/LHC1 pixel read-out electronics developed by the CERN Microelectronics group [2] have been fabricated commercially and in University laboratories [14]. In order to permit operation at the highest possible bias voltage, the rear contact was ion-implanted, while the Schottky contact was conventional Ti/Pt/Au. The back contacts were also rendered more robust against possible damage due to mis-handling or scratching by a protective layer of Al_2O_3 [15]. The detectors were bump-bonded to the read-out chips by GMMT, Caswell Laboratories using low temperature solder bumps. The yield of successful placements, while not completely satisfactory due to problems with the bonding technology, was as good as that achieved with silicon pixel detectors. Full detection efficiency was measured over a satisfactorily wide range of comparator threshold and bias voltage in a high energy pion test beam evaluation of three of these detectors mounted as a telescope. GaAs pixel detectors have also been shown to have considerable potential in X-ray and other medical imaging applications, (mammography, DNA sequencing and dental radiology, for example) [16, 17].

Spectroscopic applications for GaAs pixel arrays were studied using a 6×6 pixel detector array with pixel size 200 μm square and pitch of 210 or 220 μm, fabricated for the Modena group on 200μm SI-LEC GaAs substrates from different suppliers, (Sumitomo, Outukumpu), by Alenia Spa, Rome, Italy [18]. The Schottky contact was realized with Au/Pt/Ti metallisation, while two ohmic contact recipes were tested, based on different surface treatments at room temperature. The study was carried out in collaboration with the INFN section of the Politecnico di Milano, Italy. In order to study the device response to X- and gamma-rays, each single pixel was connected to a customized low noise, charge sensitive amplifier, with the six nearest pixels connected to ground and the ohmic contact positively biased. Up to a bias of around 200V the reverse current remained constant at $\sim$ 2nA, low enough to achieve a satisfactory performance in X-ray detection. The 59.5 keV gamma-ray line of ^{241}Am can be detected at room temperature with a resolution of 3.35 keV (FWHM) and a charge collection efficiency of 87% at a bias of 200V. For increasing applied bias, an improvement of the c.c.e. to 97% at 500V was observed, accompanied by a degradation of the FWHM induced by the increase of the leakage current.

In spite of the charge signal loss due to exposure to high fluences of high energy charged particles, SIU-LEC GaAs Schottky diode detectors have found a practical application in monitoring the beam profile in the CERN PS [19]. Their great advantage over silicon detectors in this application is the relative modest increase in leakage current observed after irradiation. A GaAs pixel detector array which has recently been designed specifically to provide a rapid beam monitor signal is due to be tested soon in the PS.

Radiation Hardness Studies

Simple pad detectors, with 2mm diameter contacts, were fabricated for the Modena group on 100μm thick, SI-LEC GaAs substrate material from Nippon Mining and Sumitomo by Alenia Spa, Rome, Italy. The Schottky contact was realized with Au/Pt/Ti metallisation while the ohmic contacts were realized by ion implantation followed by heat treatment or by surface treatment at room temperature. The detectors were exposed to 24 GeV proton fluences up to $1.6\times 10^{14}/\mathrm{cm}^2$ for radiation hardness studies. The analysis was carried out in collaboration with the INFM (National Institute of Matter Physics) sections of Italy and with the INFN section of Torino, Italy. The characterisaton of irradiated detectors was carried out using several techniques such as PICTS, P-DLTS and TSC in order to identify the hole trapping centres responsible for the degradation in the detector performance. One hole trapping centre was found to play a major role. It is characterized by an energy level at 0.56 eV from the valence band and trapping and de-trapping times of 0.8 ns and 290μs, respectively. As far as the electron collection is concerned, the density of the positively charged arsenic antisite defect $EL2^+$, which plays the main role in limiting the c.c.e. value, was determined by reflection and transmittance measurements in the near infrared region as a function of the proton fluence. The evolution of the c.c.e. with reverse bias and its spatial distribution in non-irradiated and irradiated detectors were measured using a 2 MeV proton micro-beam of cross-sectional area 10μm square, raster scanned across the front and back contacts. It was found that the irradiation with a high fluence of high energy protons decreases the mean free drift length of both charge carriers and makes it more uniform across the detector area. Finally, the lower c.c.e. measured with short range alpha particles and protons, compared with that measured with long range particles (MIPS) in proton-irradiated detectors, is attributed to the high electron-hole density created by alpha particles or protons and the consequent plasma time being comparable with or even larger than the carrier lifetime.

Further, extensive investigations have been made of the sensitivity of GaAs Schottky diode detectors to high energy charged particles. Samples of pad detectors were exposed to 192MeV charged pions at the P.S.I., Villigen, and to 24 GeV protons at the CERN PS, in both cases to fluences above the level of $10^{14}cm^{-2}$. The substantial charge signal loss with fluence reported previously [1] was confirmed, as shown in Figure 9.

Following the observed correlation in silicon detectors between radiation damage and non-ionising energy loss (NIEL) [20], an estimate was made of the corresponding NIEL of high energy charged particles in GaAs. This was handicapped by a lack of detailed information on the NIEL of such high energy particles, (the literature containing only data up to a proton energy of 1GeV). The calculation was therefore made [21] with the assumptions that (a) the NIEL in GaAs for energies above 1GeV may be obtained by scaling up the corresponding NIEL in silicon by the GaAs:Si NIEL ratio at 1GeV and (b) the ratio of NIEL by high energy pions and protons is the same in silicon and in GaAs. The resulting NIEL dependence is shown in Figure 10.

In Figure 9, the charge collection efficiency (c.c.e.) is plotted versus this calculated NIEL for pions and protons as well as for 1MeV neutrons. The correlation between signal

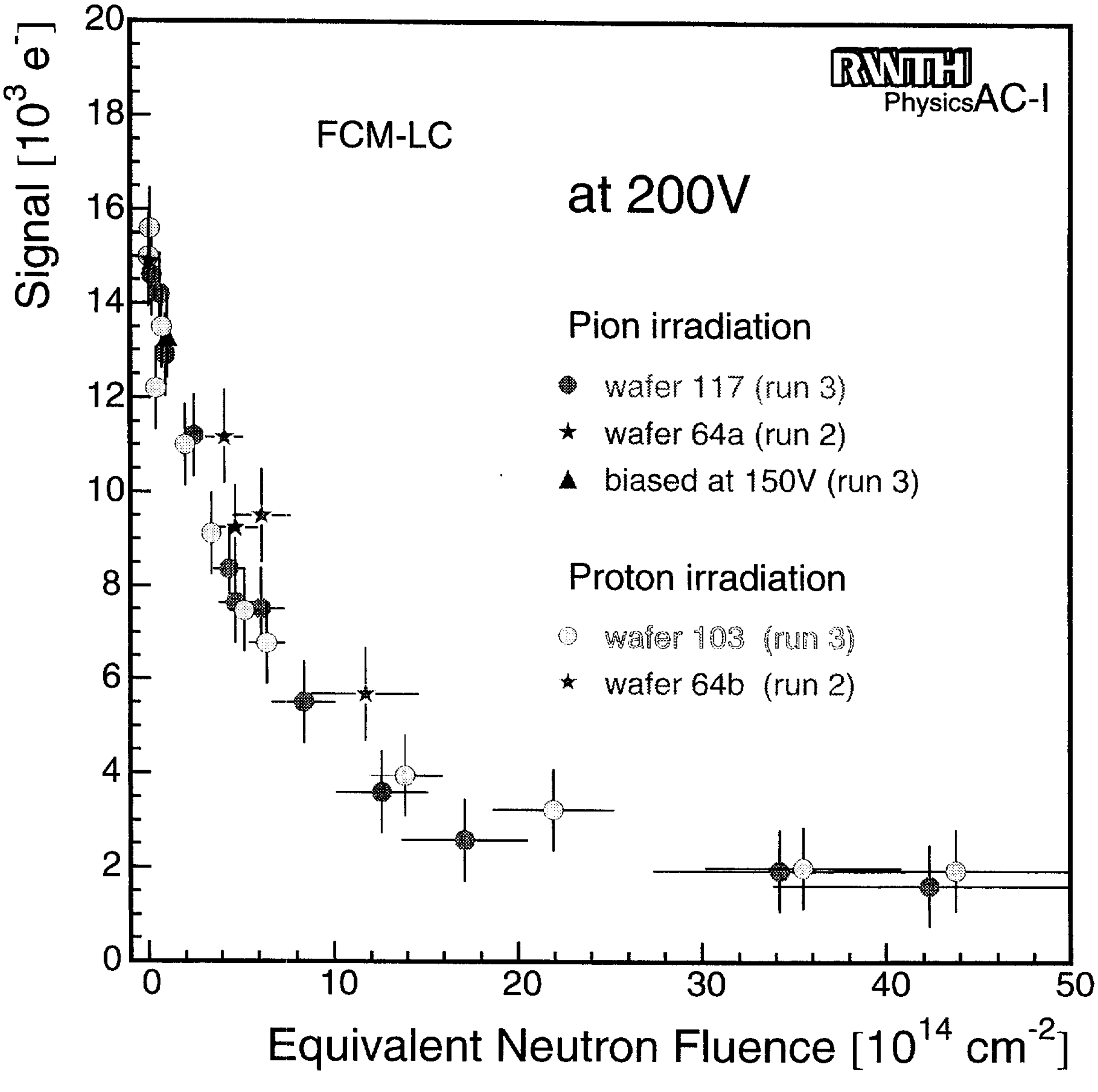

Figure 9: The signal due to mip's at 200V bias in FCM-LC material as a function of equivalent neutron fluence (normalized). The data shown are from π and p-irradiation taking into account the corresponding damage factors of 9 and 7.

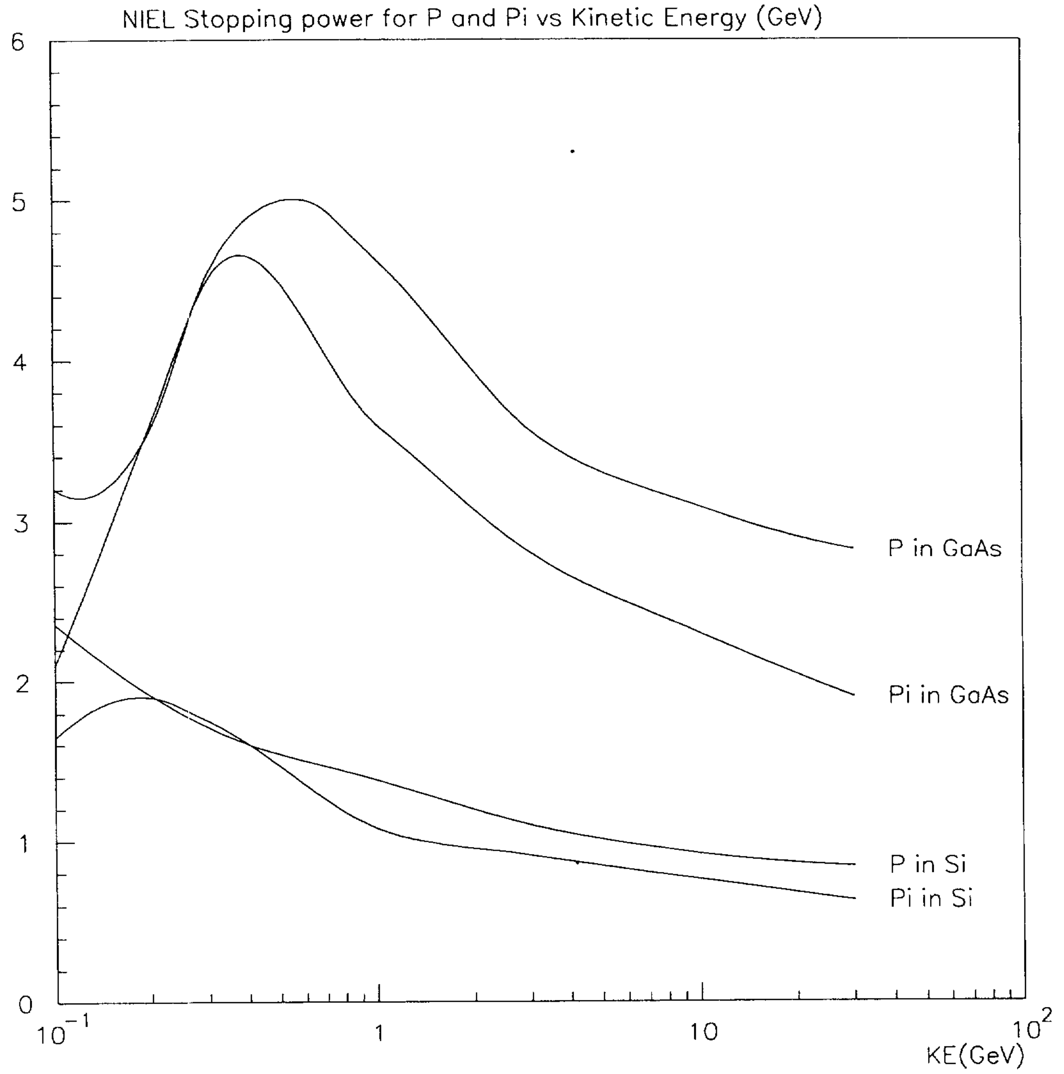

Figure 10: Calculations of the NIEL stopping power for pions and protons in $(\mathrm{keV}(\mathrm{gm\,cm}^{-2})^{-1})$ in Si and GaAs as a function of kinetic energy

degradation and NIEL appears to be well established by these data. The 'hardness factor' which converts a fluence of 300MeV pions or 24GeV protons to equivalent fluence of 1MeV neutrons is determined from these studies [22] to be 7± 0.7 for protons and 9.5± 1.4 for pions.

The nature of the charge trapping centres has also been extensively studied within the RD8 collaboration [24, 25, 23]. The charge collection efficiency of Schottky diode pad detectors was first measured with alpha particle illumination of the back and front faces of the detector. The mean free path before trapping was then deduced from

$$CCE = \frac{q}{d}\left[\int_{\overline{x}}^{d} N(x)\frac{1}{\lambda_e}exp\left(-\frac{x}{\lambda_e}\right)dx + \int_{0}^{\overline{x}} N(x)\frac{1}{\lambda_h}exp\left(-\frac{x}{\lambda_h}\right)dx\right] \tag{1}$$

and the corresponding electron lifetime, τ_e from either

$$\tau_e = \frac{\lambda_e}{v_{drift}} \tag{2}$$

or from Schockley-Read-Hall statistics

$$\tau_e = \frac{1}{\sigma_e \langle v_{th} \rangle N_{EL2^+}} \tag{3}$$

where σ_e is the electron capture cross-section and $\langle v_{th} \rangle$ the mean thermal velocity. The concentration of the ionised EL2 level was determined experimentally from near infrared absorption measurements and also from the more easily measured concentration of the neutral EL2 states and the electrical conductivity, using

$$N_{EL2^+} = N_{EL2}\left[1 - \frac{1}{1 + g^{-1}exp\left(\frac{q(E_{EL2}-E_F)}{kT}\right)}\right] \tag{4}$$

where the electronic degeneracy, $g = 0.84$. Figure 11 (a) shows the variation with NIEL of the concentration of EL2 deep level defects, in both the neutral and charged state, in LEC Schottky diode GaAs detectors.

The variation of the charge carrier lifetimes, τ_e and τ_h with radiating fluence is given by

$$\lambda_e = \mu_e * E * \tau_e$$
$$\lambda_h = \mu_h * E * \tau_h$$

The values of the mobility-lifetime product $\mu\tau$ for the two types of charge carrier, given as the slope of the mean free drift length as a function of the electric field intensity, are shown in Figure 11 (b) for five different wafer materials. The lifetime variation is illustrated in Figure 11 (c). The Fermi level is observed to move towards the centre of the band gap with irradiation, whatever the initial resistivity of the wafer material, and the limiting behaviour is seen to be largely independent of the initial values.

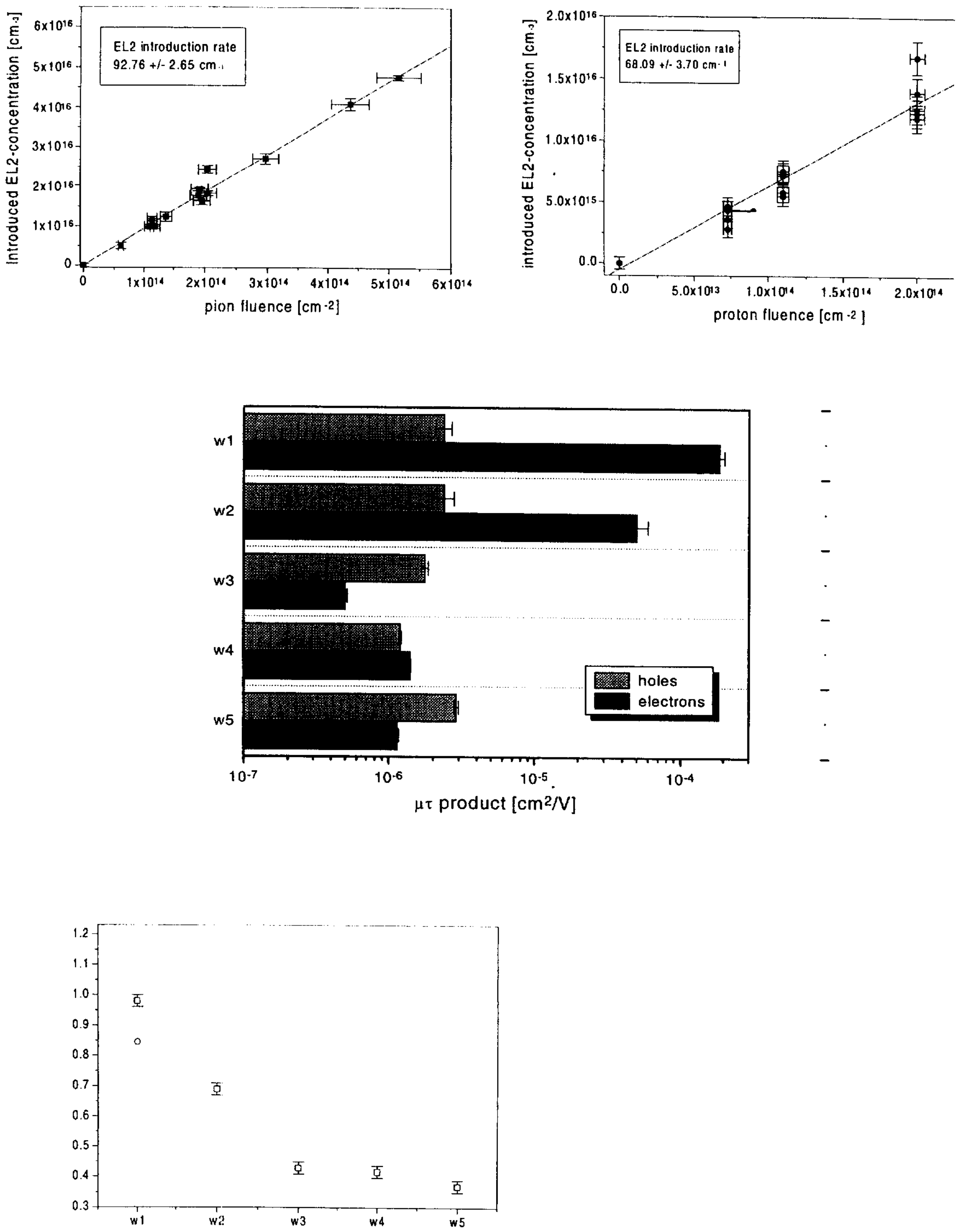

Figure 11: (i)Rate of increase of EL2 and EL2 $^+$ traps with fluence of (a)pions and (b)protons, measured using near infra-red absorption; (ii)The $\mu\tau$ product of electrons and holes in five different wafer materials; (iii)Charge carrier lifetime versus fluence of protons

The initial concentration of EL2 is much lower in high purity epitaxial GaAs, and so there is considerable interest in investigating the EL2 concentration in VPE material before and after proton irradiation, to verify that the introduction rate is the same as in LEC material and the charge signal loss directly related to the overall $EL2^+$concentration, as seems to be favoured by present data. Preliminary results have already been reported from an initial study [26] of the deterioration in a VPE GaAs diode detector fabricated on commercially-grown material with charge carrier concentration $\sim 3\times 10^{14}/cm^3$. After irradiation by 1.25×10^{14} 24GeV p/cm^2, this shows a better c.c.e. than LEC devices irradiated at this level, but a higher leakage current. (Samples of higher purity VPE have been irradiated in the June 1997 PS irradiation run and should provide additional information within the next few weeks.)

Conclusions

Detailed studies of the performance of simple Schottky diode GaAs pad detectors have revealed systematic differences in the properties of commercial substrates from different suppliers. It is now possible to characterize the substrates and to specify the parameters most likely to provide good quality detectors, optimizing for either hole or electron charge carrier collection. Surface preparation techniques and device processing details are now sufficiently well understood that charge collection efficiencies close to 100% are routine. This progress has benefitted in particular from recent developments in back-side contact processing which allow operation of the detectors with tolerable leakage currents up to much higher reverse bias voltages.

GaAs microstrip and pad particle detectors have now achieved almost all of the performance specifications required for LHC operation. Commercially made Schottky diode microstrip detectors of ATLAS forward tracker dimensions, with integrated bias resistors and decoupling capacitors, have been successfully tested using fast read-out electronics developed for silicon. Operation at the low temperatures required for irradiated silicon presents no significant difficulties.

The radiation damage induced by high energy protons and pions in GaAs has now been confirmed as between seven and nine times as severe as that due to 1MeV neutrons and represents the major obstacle to the use of GaAs detectors at the LHC, where pions represent the main source of radiation..

Substantial progress has been made within the collaboration in the understanding of the detailed nature of the radiation damage in GaAs Schottky diode detectors. The ionized state of the EL2 charge trapping centre has been clearly implicated in the loss of signal in irradiated samples, for example. Investigations of other (particularly hole) traps continue. The RD8 community will continue to evaluate possible explanations for the magnitude of the relative radiation sensitivity, together with any possible methods for alleviating the problem. These studies will be based on the continuation and extension of microscopic characterisation of radiation damaged LEC-substrate and epitaxial material by a comprehensive range of techniques. In this programme we hope to continue to benefit from the generous advice and assistance of world experts in semiconductor physics.

GaAs pixel detectors bump-bonded to Omega3/LHC1 read-out chips have been successfully operated in test beam and medical imaging applications. The X-ray imaging potential of GaAs, which has stimulated a great deal of interest outside of high energy physics, has also been demonstrated. Coupled with the newly available MEDIPIX read-out chip [27], GaAs pixel detectors offer an attractive option for X-ray imaging applications, particularly in the energy range above 20 keV, where the detection efficiency of silicon devices falls off very rapidly.

Acknowledgements

We wish to acknowledge financial support for this work from our government funding agencies: the Australian Research Council, the Ministry of the Atomic Energy Industry in Russia, the BMFT (Germany), the SERC (now PPARC,U.K.) and the INFN (Italy). We are also indebted to R.A.L. and to MCP Wafer Technology (U.K.) for sponsorship of CASE postgraduate studentships. The support from CERN, originally through the DRDC Committee, which is warmly acknowledged, has assisted members of the collaboration to obtain local funding for the programme described above.

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