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GALLIUM ARSENIDE MICROSTRIP DETECTORS FOR CHARGED PARTICLES

The RD8 Collaboration

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(submitted to Nuclear Instruments and Methods)

Abstract

Microstrip detectors have been constructed from gallium arsenide (GaAs) wafers made from undoped LEC (Liquid-encapsulated Czochralski) semi-insulating substrate material. Tests were performed using minimum ionising particles to ascertain their properties as charged particle detectors. The results show that the devices work well, with good signal-to-noise ratio, (typically 7). The effects of gamma ray and neutron irradiation have been studied and shown to be small up to levels exceeding 20 MRads and $10^{14} n/cm^2$, respectively.

I. Introduction

GaAs is a III-V semiconductor which has been shown to be suitable for gamma-ray detection[1], and could be used to detect the ionisation produced by the passage of fast charged particles. It has the following advantages when compared with the more commonly used silicon:

(a) It is radiation hard (see below)

(b) Optoelectronic components in compatible III-V materials offer the prospect of optical read-out of GaAs detectors

(c) The electron mobility is very high so that, in principle, high speed detectors could be constructed.

However, it suffers from the disadvantage compared with silicon that imperfections in the crystal lattice produce traps for charge carriers liberated by ionising radiation[2]. Such traps will decrease the pulse amplitude compared to that obtained from the same amount of ionisation deposited in silicon. In spite of this disadvantage, we have shown in previous work[3-7] that GaAs detectors capable of detecting minimum ionising particles can be constructed. While GaAs detectors may be initially somewhat inferior in performance to silicon devices, (which have 100% charge collection efficiency), after heavy doses of radiation they are likely to become superior. Such heavy doses of radiation are expected at the LHC[8], the proton-proton collider proposed as the next accelerator to be built at CERN. The recent advances in GaAs technology and ready availability of GaAs wafers on an industrial scale make it a candidate material for fabricating detectors for use at the LHC.

In this paper we describe the performance of several microstrip detectors and demonstrate the radiation hardness of GaAs from studies using individual pad detectors. Table I gives a summary of the microstrip devices tested. All were constructed from LEC material with an ohmic electrode on one side. The microstrip electrodes took the form either of evaporated Ti-Au Schottky contacts or of MBE epitaxial layers grown on the reverse side.

II. Description of the Construction of the Devices (Table I)

(1) Schottky contact microstrips

Sample detectors were fabricated from undoped LEC substrate wafers in the Department of Electrical Engineering of Glasgow University, the INFN laboratory for research and development in semiconductor detectors in the University of Modena and in a commercial process by Telettra SPA, Milan. The three sources provided the opportunity to test different recipes for ohmic contacts, (Glasgow/Modena), and the comparison between unpassivated detector surfaces with those protected by a layer of silicon nitride, (Glasgow/Telettra).

The Glasgow detectors were made using wafers from MCP Wafer Technology and from Sumitomo. The material, as supplied, was cleaned using trichloroethylene, acetone, isopropyl alcohol and deionised water, and de-oxidised using dilute hydrochloric acid. Rinsing with de-ionised water and drying in dry nitrogen, preceded evaporation of the ohmic contact. This consisted of layers of Ni (5nm), Ge (25 nm), Au (43 nm), Ni (30 nm) and Au (50 nm), evaporated at a base pressure of less than 6×10^{-6} mb. The contact was annealed for 20 seconds at 360°C in a rapid thermal annealer, to allow in-diffusion of the Ge and the creation of an n^+ region. The wafer was then re-cleaned, and spun with photoresist (Shipley S1400-31) before exposure with the appropriate photomask; the resist was then developed. The wafer was again de-oxidised before evaporating the Schottky contact, which consisted of 30 nm Ti followed by 80 nm Au. Lift-off of the photoresist was achieved using warm acetone, and the finished devices were cut from the wafers by Micron Semiconductor Ltd. Details of the dimensions of the various devices tested are given in Table I.

The substrates used in Modena were obtained from Wacker-Chemitronic and were 600 μ m thick. They were first rinsed in HCL:H_2O (1:1 by volume) until completely hydrophobic. After rinsing in de-ionised water and drying in a flow of nitrogen, they were loaded into an electron-beam evaporation system equipped with ion and Ti sublimation pumps. The base pressure was 2×10^{-8} torr. The ohmic contact was made first by depositing thin films of Pd and Si sequentially and by annealing the samples with the Si/Pd/GaAs configuration in a furnace under a flow of forming gas (5% H_2, 95% N_2) at 370°C for 30 minutes. The typical thicknesses of the layers of Si and Pd were 13 nm and 8 nm, respectively, and the pressure during evaporation was $2-3\times10^{-7}$ torr. This contact system is based on solid-state reactions at low temperatures and the experimental results show that the ohmic behaviour is probably due to a surface n^+ region highly doped with Si atoms. During the heat treatment, a highly conducting layer of Pd_2Si grows on top of the n^+ region and acts as a metallic contact to it.The Schottky strips were made by depositing thin films of Ti and Au sequentially, through a metallic mask, on to the optically lapped surface. The typical thicknesses of the layers of Au and Ti were 50 nm and 10 nm, respectively, and the pressure during evaporation was lower than 1×10^{-7} torr. A thick layer of gold was necessary in order to perform the wire-bonding to the strips.

The detectors fabricated in a commercial process by Telettra SPA from a LEC substrate of 450 μm thickness, were passivated by a layer of silicon nitride. Dimensions of the detectors are given in Table I. While there is no direct proof that contamination of the surface of the GaAs occurs on exposure to air, the surface protection is desirable. In view of the adverse effects of neutron and gamma-ray irradiation on surface passivation layers in silicon detectors, however, we wished to evaluate the effect of passivation in comparable structures in GaAs.

(2) $p-i-n$ Detectors

As an alternative to Schottky barrier detectors of the type discussed above, p-i-n detectors have been fabricated at the SERC III-V facility in the University of Sheffield Department of Electrical Engineering. In these devices, a 0.25 μm thick n^+ layer was grown by molecular beam epitaxy (MBE) on one side of the wafer. Strips of InGe-Au were deposited on the MBE layer and the wafer annealed at 420°C. The annealing allows the InGe to diffuse into the MBE layer, allowing a good contact to be made. The strips are protected and an etch ($H_2SO_4 : H_2O_2 : H_2O$ in the ratio 1 : 8 : 80) is used to provide inter-strip isolation. On the reverse side, after cleaning with trichloroethylene, Au-Zn-Au is deposited. The wafer is then annealed at 420°C, allowing the Zn to diffuse into it to form a p^+ layer with an ohmic contact.

III Performance as Detectors of Minimum Ionising Particles

The GaAs devices described above and listed in table I were each tested in the X1 test beam at CERN using mainly pions of momentum 70 Gev/c. Fig 1 shows a diagram of the apparatus which consisted of two planes of 32 silicon microstrips, Si1 and Si2, of pitch 100μm, two locations for GaAs devices and three scintillation counters, P1, P2 and P3, used in coincidence as a trigger for an incident charged particle. The Si and GaAs devices were read out using an Amplex read out system[9], multiplexed into a fast buffer memory and ADC. The data were stored on the disc of an on line computer.

Fig 2 shows typical pulse amplitude spectra for 70 Gev/c pions passing through the silicon detector Si1 and the GaAs detector, (detector SB5). These spectra were obtained as follows; the silicon strip containing the maximum pulse amplitude after pedestal subtraction was first found. Some sharing of charge between the 100μ wide Si strips was observed and so the amplitude in each neighbouring strip was added to the pulse amplitude from the strip containing the maximum. The resulting distribution of pulse amplitudes is shown in Fig 2a. The peak at channel 250 shows a typical Landau distribution expected from the passage of minimum ionising particles. The peak at channel 30 corresponds to the maximum noise amplitude found when a particle passed outside the detector Si1. The scintillation counters (width 5 mms) were somewhat broader than the total width of the device Si1 (3.3 mm). Good minimum ionising particles were defined as those with a pulse amplitude greater than channel 144 in Fig 2a.

The silicon strips were aligned with the horizontal strips of the GaAs detector (GaAs1 in fig. 1) and for a particular hit in Si1 the pulse amplitude in the appropriate strip of GaAs1 was entered into the histogram shown in Fig 2b. For those silicon strips defining particles close to the edge of a particular strip of the GaAs detector, the pulse amplitude of the neighbouring GaAs detector strip was added. This ensured that the charge from all the deposited ionisation was collected. Fig 2b shows a typical Landau distribution with a peak at channel $\sim$ 180.

Fig 3 shows another spectrum from the same detector as that in Fig 2b. The smooth curve is the result of a fit of the Landau distribution into which a Gaussian noise distribution has been folded, together with a Gaussian shaped background of arbitrary position and width[10]. The standard deviation of the noise distribution from the fit, 34.8 ± 1.4 channels, is 15% broader than that expected from the measured pedestal width due to fluctuations in gain from strip to strip. This is illustrated in Fig 4 where the peak position in the appropriate strip of the GaAs detector is plotted as a function of the hit strip in the Si detector (Si1). The distributions for the edge strips 1 and 2 contained long tails and these have been omitted from the spectra in Figs 2b and 3. Channels 30 and 32 were also omitted since the corresponding channels in the Si1 detector were clearly not working properly. Apart from these channels, small fluctuations in gain ($\sim$ 10%) from strip to strip are observed. This demonstrates the lateral uniformity of the detector. It should be noted that each GaAs strip corresponds to more than three Si strips in Fig 4.

The peak amplitude from the GaAs detector was observed to change with the bias voltage. The peak positions were determined from plots similar to Fig 2b at several different voltages. Fig 5 shows the peak position as a function of the bias voltage for the detector. This demonstrates that the charge collection efficiency increases with voltage.

The charge collection efficiency can be determined from the spectra of Figs 2b and 3 in either of two ways. The simplest way is to take the ratio of the peak positions in the GaAs and silicon spectra. The efficiency is calculated from this ratio after correcting for the different values of dE/dx for minimum ionising particles in GaAs and Si and for the different thicknesses (600μm for the detector SB5 and 300μm for Si) and densities (ρ = 5.32 g/cm^3 in GaAs and 2.33 g/cm^3 in Si). For this calculation the assumption is made that the charge collection efficiency in the silicon device is 100%. The second method requires an absolute calibration of the amplex electronics which was measured to be 82 electrons per ADC channel. The charge collection efficiency is then the ratio of the number of electrons corresponding to the peak channel to the number of electron-hole pairs calculated from the known value of the stopping power (dE/dx) of the material of the detector. For this calculation, we assume that the energy deposited to create an electron-hole pair is 4.2 eV in GaAs [11]. The values obtained from the two methods agreed well with each other.

The signal to noise ratio was determined for each detector as the ratio of the peak position in Fig 2b to the standard deviation of the pedestal distributions averaged over all the strips. The mean standard deviation of the pedestal distributions for the GaAs microstrips was 20.4 ADC channels compared to 16.1 channels for the Si detectors. The measured electronic noise charge for the Amplex electronics was 15.8 channels. Thus a significant fraction of the measured noise in each detector was generated in the readout electronics.

Fig. 6 shows the spectra, obtained as described above, for some of the GaAs microstrip devices tested. Table I gives a summary of the measured properties of each device. The detection efficiencies for minimum ionising charged particles are all high and the signal to noise ratios are about 7 i.e. about half that of typical silicon detectors. The charge collection efficiencies vary between 10-40% for these devices of thickness 400-650μm. However, tests of thinner detectors (thickness 100-200μm) give higher charge collection efficiencies [12] indicating that one source of charge loss in the thicker devices described here could be ascribed to the fact that they are not "fully depleted". The Schottky and $p-i-n$ devices performed equally well but exhaustive tests have not yet been made to compare them.

V Radiation Hardness

Tests were performed on devices made in the form of single pad detectors usually 3 $\times$ 3 mms^2 with a (1 mm diameter) Schottky contact on one side and an ohmic contact covering the reverse side. Most of the devices were 125μm thick and the Schottky contact was negatively biased. Measurements were made using Am^{241} α particles and Sr^{90} or Ru^{106} β particles. For the latter, the pulse amplitude was read out only if the β particle triggered a downstream scintillation counter, defining particles which had traversed the device. Such β particles correspond approximately to minimum ionising particles. It was shown that the device was only sensitive to ionisation in the volume defined by the geometrical limits of the Schottky contact [13].

Several detectors were irradiated by γ rays with integrated doses up to 20 Mrads. No significant deterioration in the performance of the devices was observed. However, it is known that silicon charged particle detectors are much more severely damaged by fast neutron irradiation than by γ rays. This is thought to be caused by a fast neutron ejecting an atom from the crystal lattice during a collision, producing a Frankel defect. To test the sensitivity of GaAs devices to damage by fast neutrons several pad devices were irradiated at the ISIS irradiation facility at the Rutherford Appleton Laboratory [14], in which the fast neutron spectrum approximates that expected at the LHC. The associated fluence of slower neutrons (E<10 KeV) has been ignored in this analysis since slow neutrons are not believed to damage semiconductors significantly. Fast neutron fluences $\geq 10^{14}$ cm^{-2} are expected in 1-10 years running at the LHC in a central tracking cavity at a luminosity of 2×10^{34} cms^{-2} sec^{-1}[8].

Fig. 7a) shows a "minimum -ionising" β particle spectrum from a single pad detector before irradiation. The spectrum shows a typical Landau distribution peaking at channel $\sim$ 500. There is also a peak at channel $\sim$ 100 from pedestal pulses produced by particles which missed the GaAs detector. Fig. 7b) shows the spectrum from the same detector taken a few days after irradiation by a total fluence of 7×10^{14} neutrons/cm^2. Comparing figures 7a) and b) shows that the noise, indicated by the width of the pedestal peak, did not change significantly as a result of the irradiation. However, the minimum ionising peak position decreases by a factor $\sim$ 4 indicating that the charge collection efficiency decreases. Nevertheless, even after a fast neutron fluence of 7×10^{14} cm^{-2}, the minimum ionising peak is well resolved from the pedestal, so that the detector could still be used to detect minimum ionising particles. The signal to noise ratio for these detectors, taken under ideal laboratory conditions using a single channel low noise amplifier, is a factor 2-3 better than that observed with the microstrip devices, described above, taken with the multiplexed Amplex read out electronics.

Fig. 8 shows the peak pulse amplitude position from the Am^{241} α particles measured as a function of the neutron fluence suffered by each of a set of pad detectors (Table II). It can be seen that there is no significant deterioration in the charge collection efficiency up to neutron fluences of 10^{14} n/cm^2. The data indicate a decrease in the charge collection efficiency at fast neutron fluences greater than this.

Conclusions

Several GaAs microstrip detectors have been tested using minimum ionising particles. All were shown to work as charged particle detectors with a signal:noise ratio ~ 7, and a smaller charge collection efficiency than that observed in silicon. Single pad devices were still usable as minimum ionising particle detectors after suffering fast neutron fluences up to 7×10^{14} n/cm^2. No significant deterioration in performance was observed after γ ray irradiations of up to 20 M Rads.

Acknowledgement

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Table I

Summary of results

Detector	Microstrip width (μm)	Microstrip pitch (μm)	thickness (μm)	Maximum applied field (V/cm)	ϵ(charge) (%)	Detection efficiency, threshold=2.5 pedestal width	S/N
(SB3)	300	330	500	4600	10	-	5.1
(SB4)	300	330	500	4600	11	94%	5.5
(SB5)	275	375	600	6667	16.5	97%	8.6
GLADYS	275	375	600	4167	14	97%	9.1
Telettra I	100	200	450	9444	19	90%	7.4
Telettra II	100	200	450	6670	16	90%	6.3
Sheffield $p-i-n$	275	375	400	9375	-	85%	6.0
Modena I	200	400	650	13077	41	–	17.5
Modena II	200	400	650	12300	27	–	11.5

Table II
Performance of the Pad Detectors After Neutron Irradiation

SCHOTTKY PAD DETECTOR NUMBER	FAST n FLUENCE n cm^{-2}	SLOW n FLUENCE ($<$10 KeV) n cm^{-2}	α PARTICLE PEAK PULSE AMPLITUDE (Arbitrary Units)
B27S4	0	0	1.4
B11S3	4.4×10^{13}	Not available(NA)	1.6
B11S4	4.4×10^{13}	NA	1.6
B27S5	7.6×10^{13}	8.7×10^{14}	1.4
B27S6	4.8×10^{14}	9.4×10^{14}	0.58
B20S6	1.9×10^{15}	1.3×10^{15}	0.16
B20S1	5.6×10^{11}	2.5×10^{13}	1.6
B20S2	2.9×10^{12}	2.2×10^{13}	1.6
B20S5	2.9×10^{12}	NA	1.53
B21S4	5.0×10^{13}	7.5×10^{14}	1.33
B27S5	7.6×10^{13}	8.7×10^{14}	1.33
B27S6	4.8×10^{14}	9.4×10^{14}	0.61
B27S1	1.4×10^{15}	8.6×10^{14}	0.16

References

1. J E Eberhardt, R D Ryan and A J Tavendale, Appl. Phys. Lett. **17** (1970) 427.
2. M Shur. GaAs Devices and Circuits, Plenum Press, New York (1987).
3. R Bertin et al, A Preliminary study of GaAs solid-state detectors for High Energy Physics, *Nucl. Instr. Methods in Physics Research* **A294** (1990) 211.
4. S Beaumont et al, Results on GaAs solid-state detectors for High-Energy Physics, *Nuclear Phys.* **B23A** (1991) 417-418.
5. S Beaumont et al, New Results on GaAs solid state detectors for High-Energy Physics, *Proc. 4th San Miniato Topical Seminar on Experimental Apparatus for High Energy Physics and Astrophysics*, World Scientific (1991) 200-208.
6. A Zichichi et al, The LAA Project, *La Rivista del Nuovo Cimento* **13** No. 5 (1990).
7. A Zichichi et al, Advances in Technology for High-Energy Subnuclear Physics, Contribution of the LAA Project, *La Rivista del Nuovo Cimento*, **13**, No. 10-11 (1990) 88.
8. G R Stevenson, *Proceedings of the LHC Workshop at Aachen*, Volume III, page 566 (1990) Edited by G Jarlskog and R Dein. G R Stevenson, D E Groom et al, *Nuclear Inst. and Methods.* **A279** (1989) 1.

9. R Ansari et al. Nucl. Inst. and Methods in Physics Research **A279** (1989) 388.

10. The principles of the fit are described in detail in S Hancock et al, *Phys. Rev.* **A28** (1983) 615.

11. J E Eberhardt, R D Ryan and J Tavendale, Nucl. Inst. and Methods **94** (1971) 463.

12. P G Pelfer; Proceedings of the Eloisatron Workshop on GaAs detectors; Editors K Smith and C Del Papa (to be published).

13. J Santana. MSc Thesis, University of Lancaster (1991).

14. M Edwards and D R Perry. The Radiation Hardness Test Facility, RAL-90-065.

Figure Captions

Fig. 1 Arrangement of the Apparatus in the X1 Test Beam.

Fig. 2 Pulse Amplitude spectra from 70 GeV/c pions.

a) In the silicon detector Si1, b) In a GaAs detector (detector SB5).

Fig. 3 Pulse amplitude spectrum from the detector SB5 (as in fig. 2b) with a fit of the Landau distribution with Gaussian noise folded in and a Gaussian background[10].

Fig. 4 The variation of the peak pulse amplitude in the GaAs detector (SB5) across the width of the detector i.e. the hit Si strip number. Each Si strip has width 100 μm and each GaAs strip 375 μm so that approximately 4 Si strips correspond to each GaAs strip.

Fig. 5 The variation of the peak pulse amplitude in the GaAs detector SB5 versus the detector bias voltage.

Fig. 6 The pulse amplitude spectra from the different detectors tested. The smooth curves are the available fits of the same model as described in fig. 3 (see text).

a) The Sheffield $p-i-n$ detector. This detector was mounted in a different read out system and placed 57 cms downstream from the apparatus in fig. 1. The gain was different from the other GaAs detectors.

b) The Detector SB4.

c) The Detector SB3.

d) A Telettra Detector.

e) The GLADYS Detector.

f) A Modena Detector.

7. Spectra for β particles traversing a single pad device

   (a) spectrum taken before irradiation

   (b) spectrum taken a few days after irradiation by a fast neutron, fluence of 7×10^{14} cm^{-2}.

8. Response of pad detectors to Am^{241} α particles as a function of fast neutron fluence (see table II).

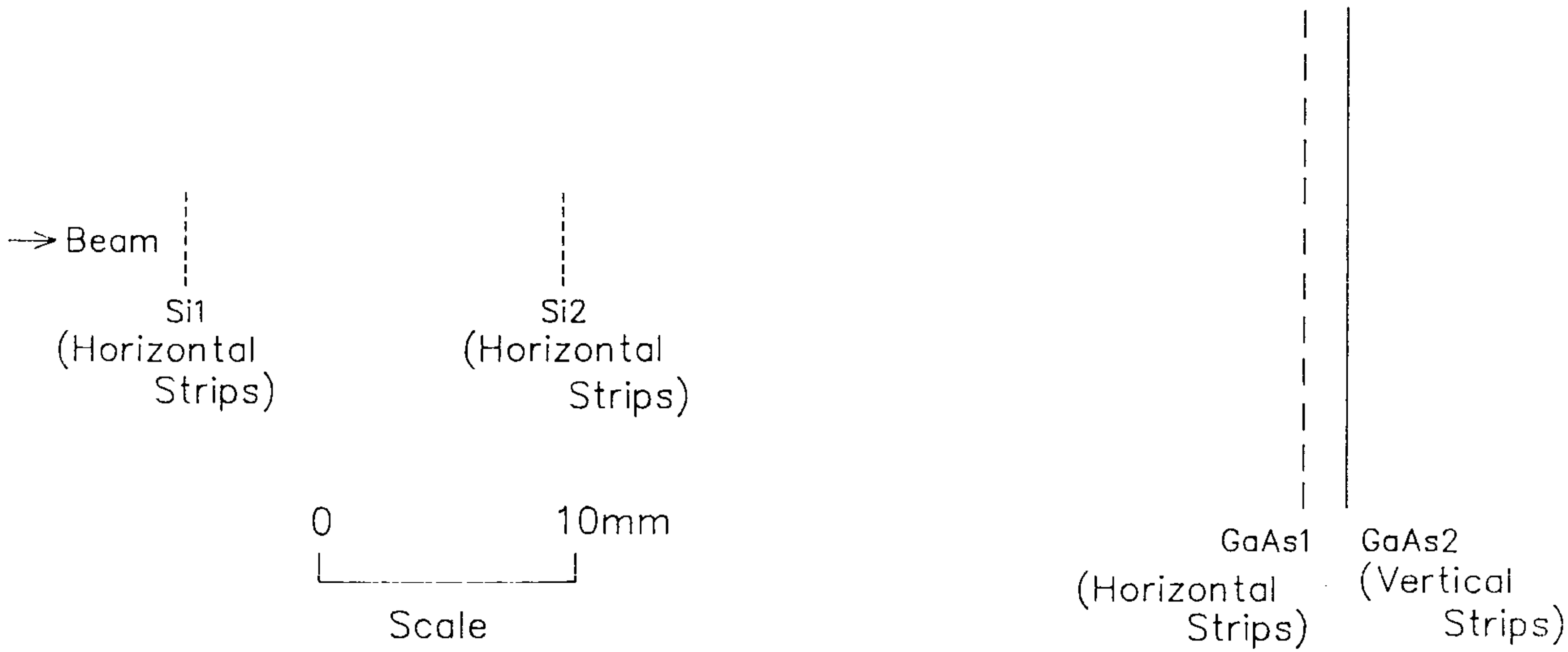

Beam
Si1
(Horizontal
Strips)
Si2
(Horizontal
Strips)
0
10mm
Scale
GaAs1
(Horizontal
Strips)
GaAs2
(Vertical
Strips)

Fig.1

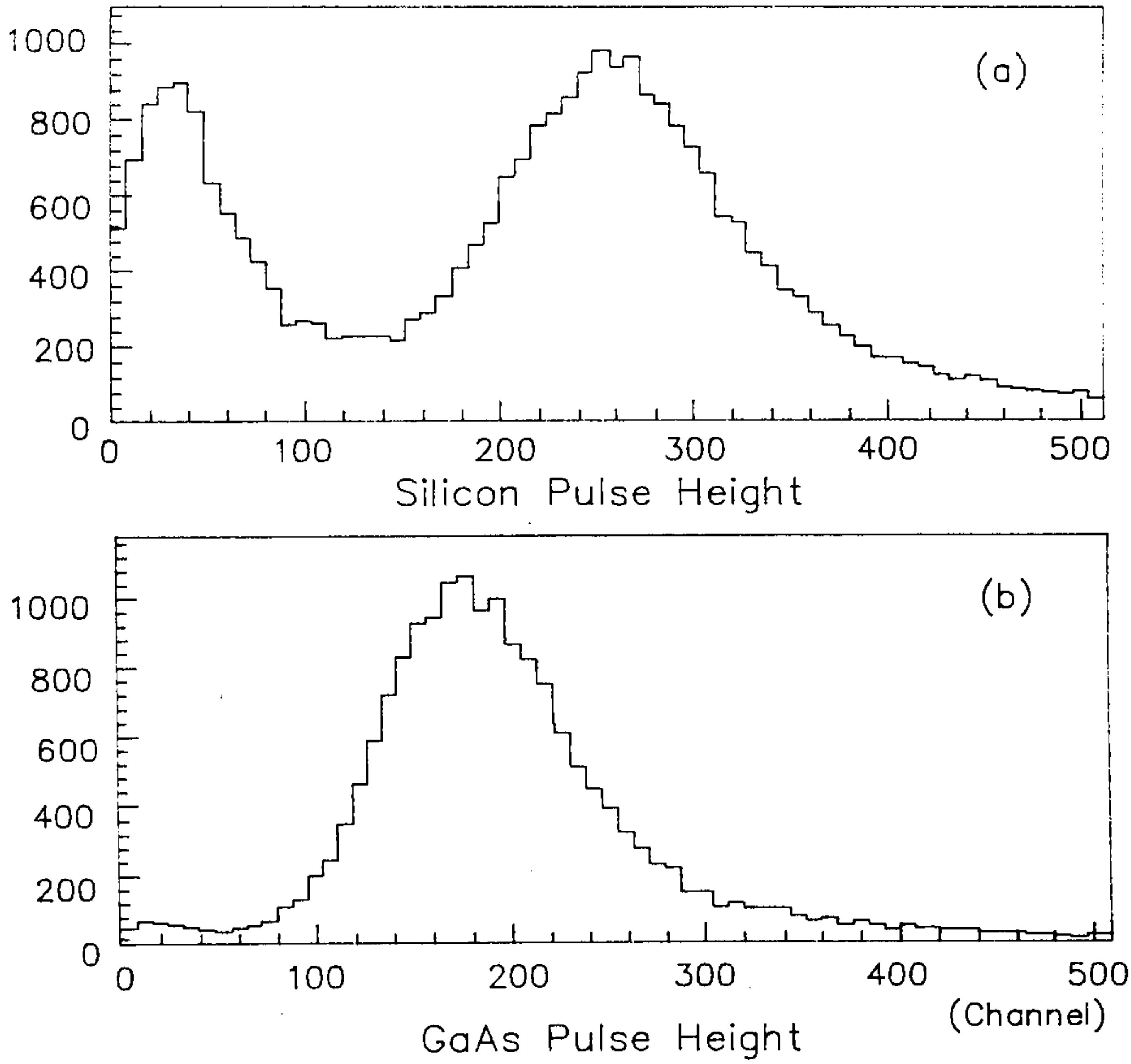

1000
800
600
400
200
0
0
100
200
300
400
500
(a)
Silicon Pulse Height
1000
800
600
400
200
0
0
100
200
300
400
500
(b)
(Channel)
GaAs Pulse Height

Fig.2

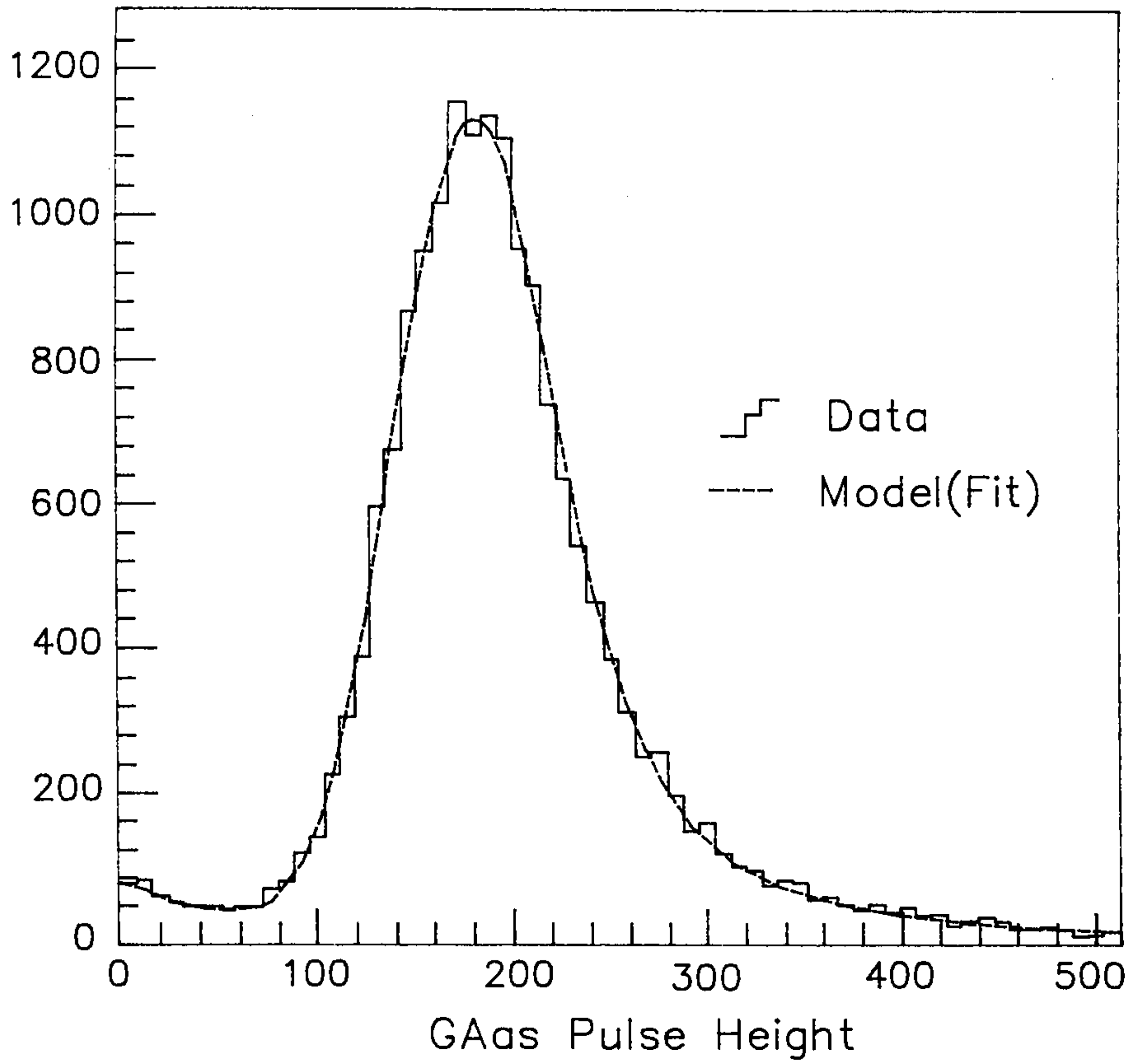

1200
1000
800
600
400
200
0
100
300
500
Data
Model(Fit)
GAas Pulse Height

Fig.3

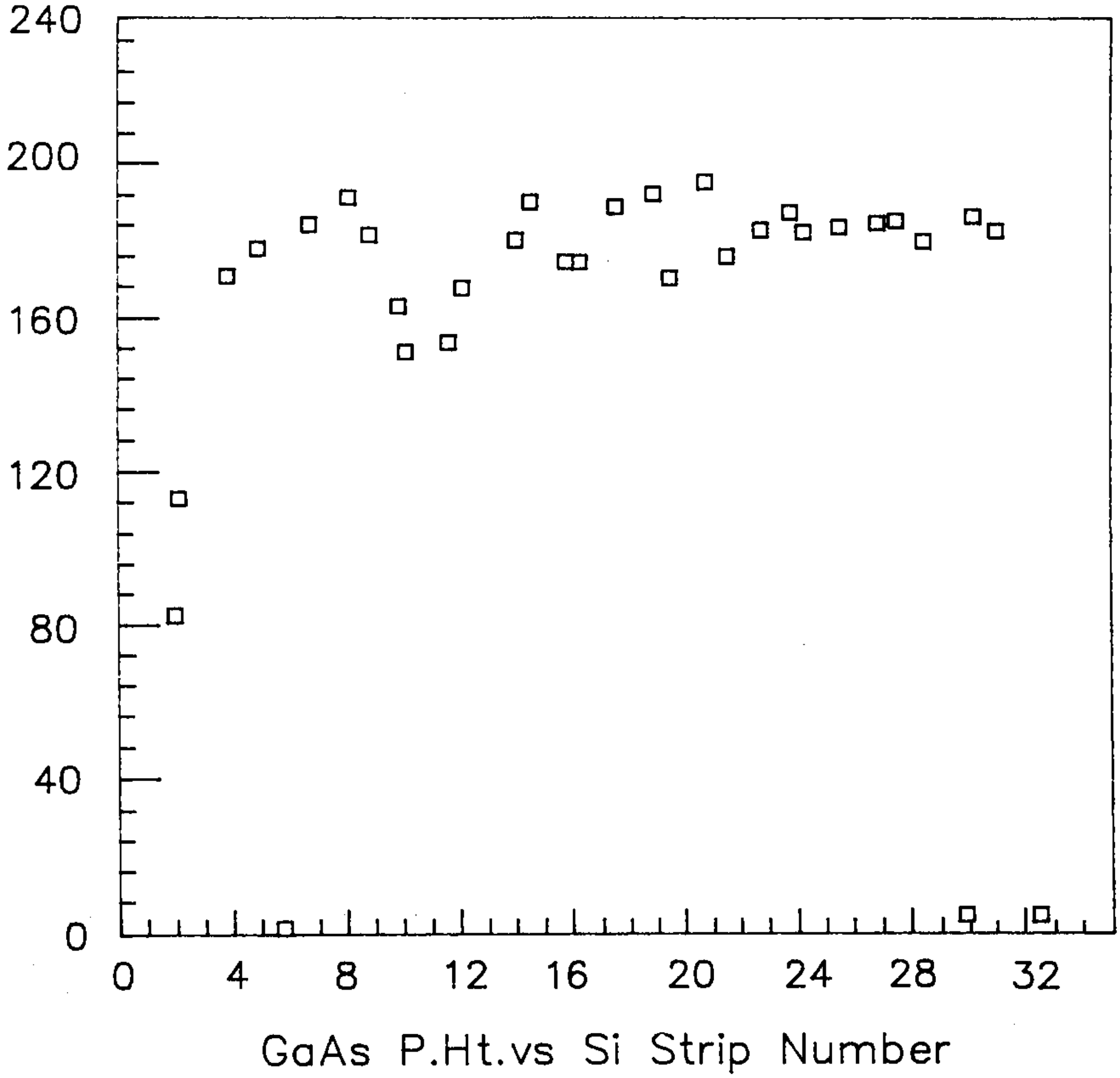
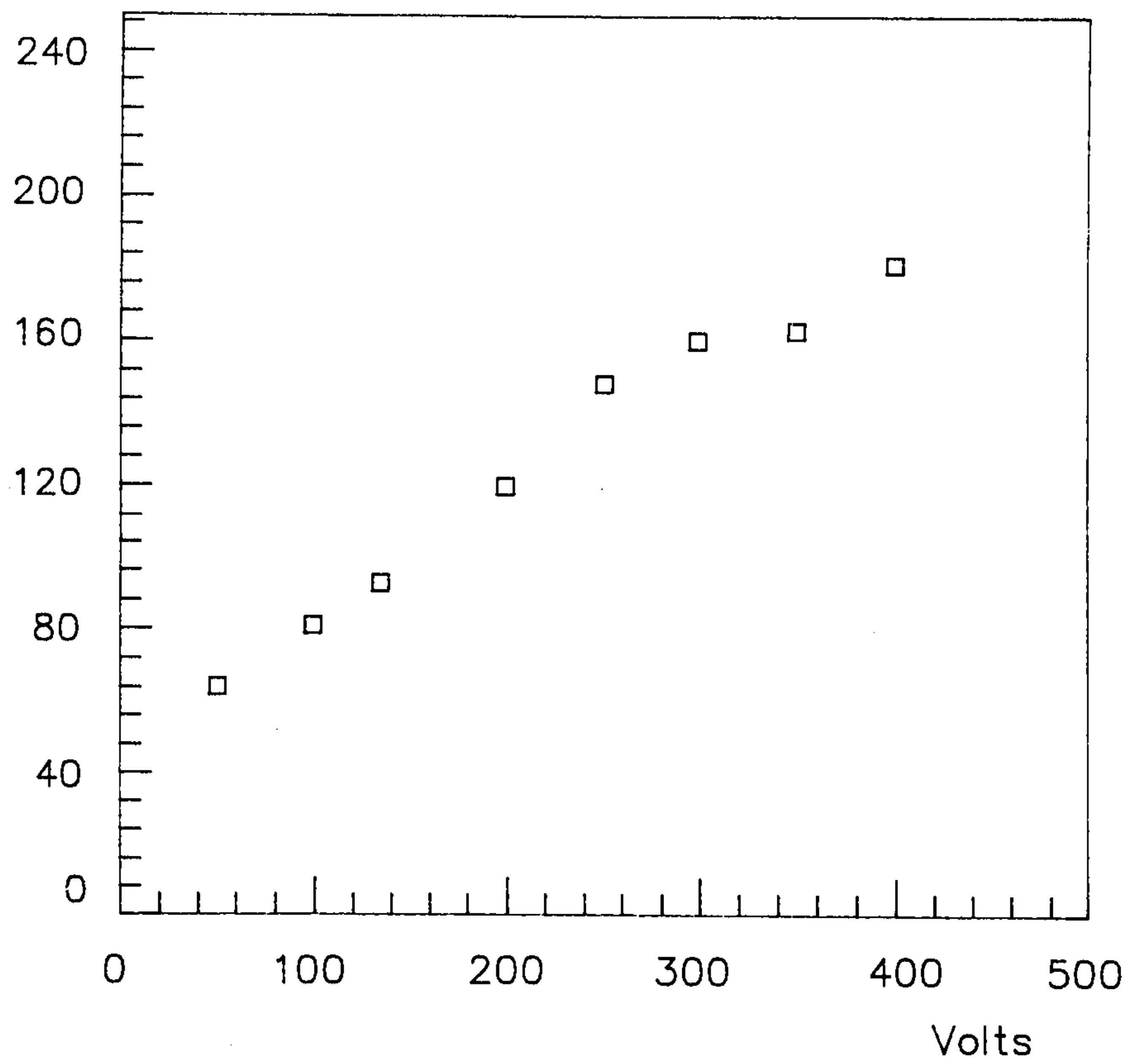
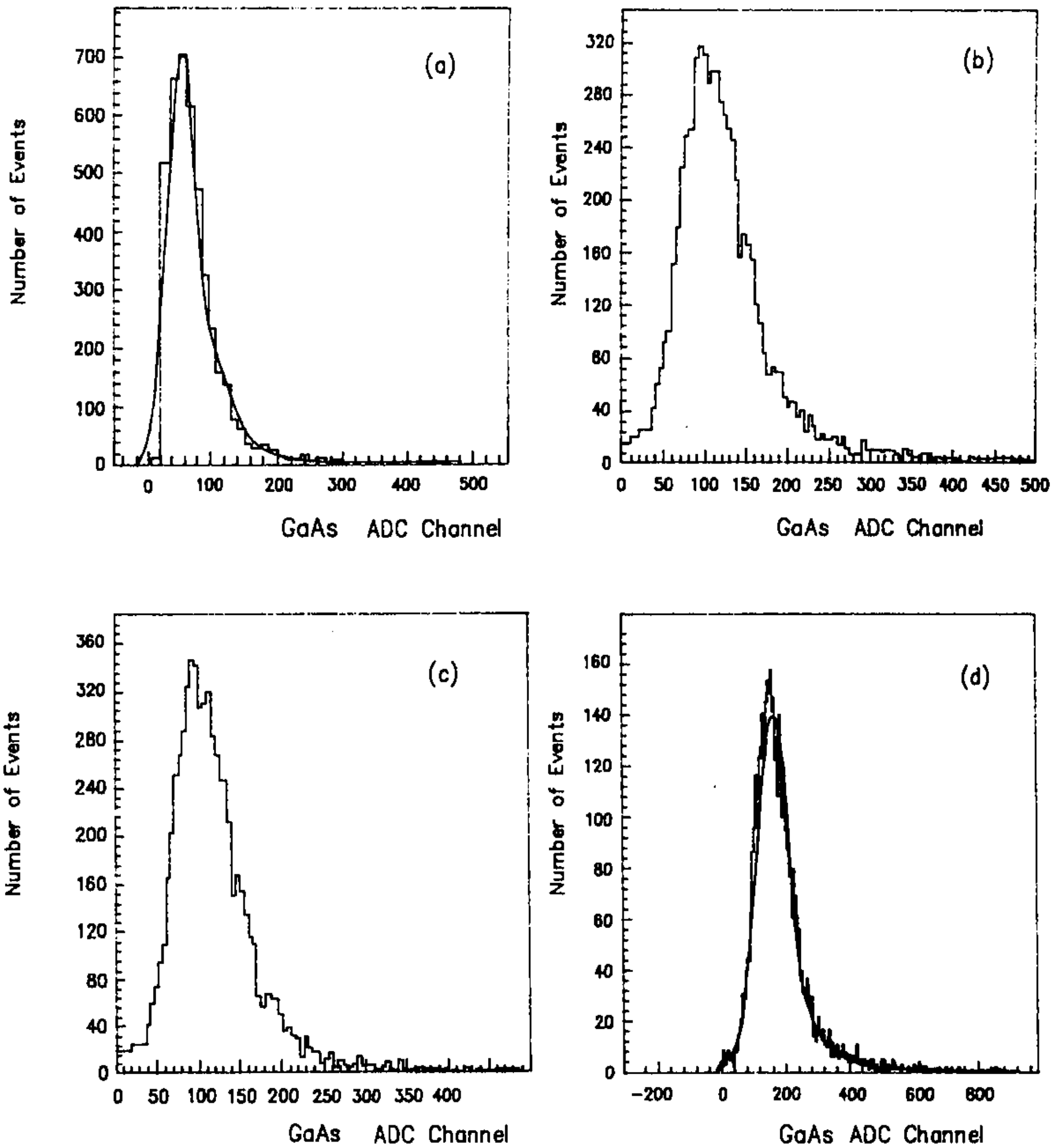

240
200
160
120
80
40
0
0
4
8
12
16
20
24
28
32
GaAs P.Ht.vs Si Strip Number

Fig.4

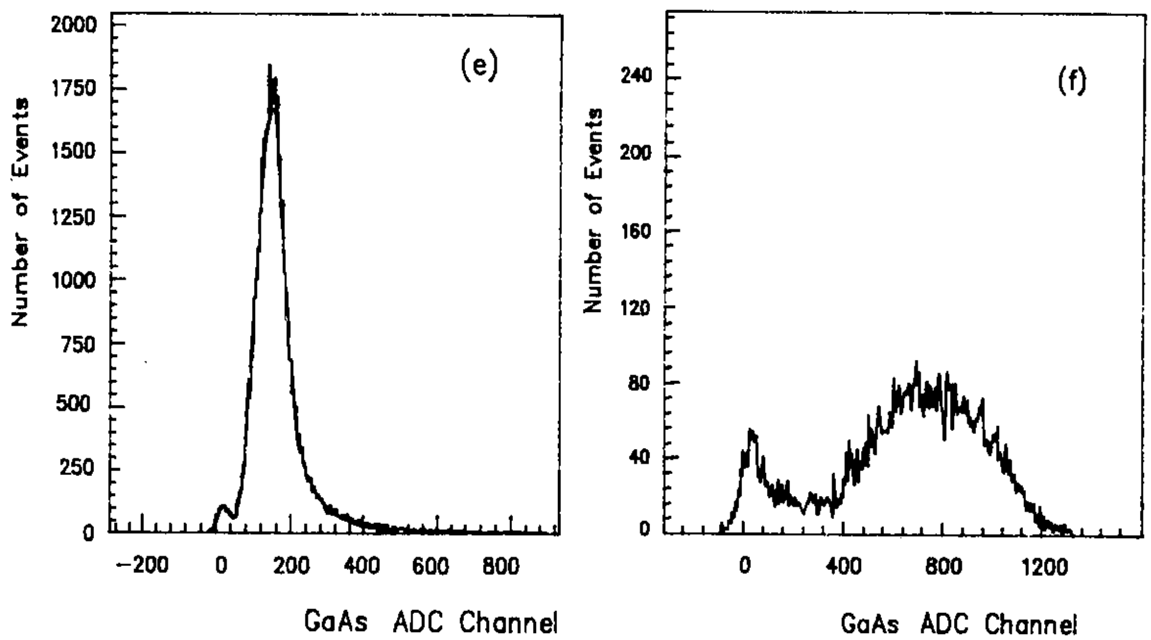


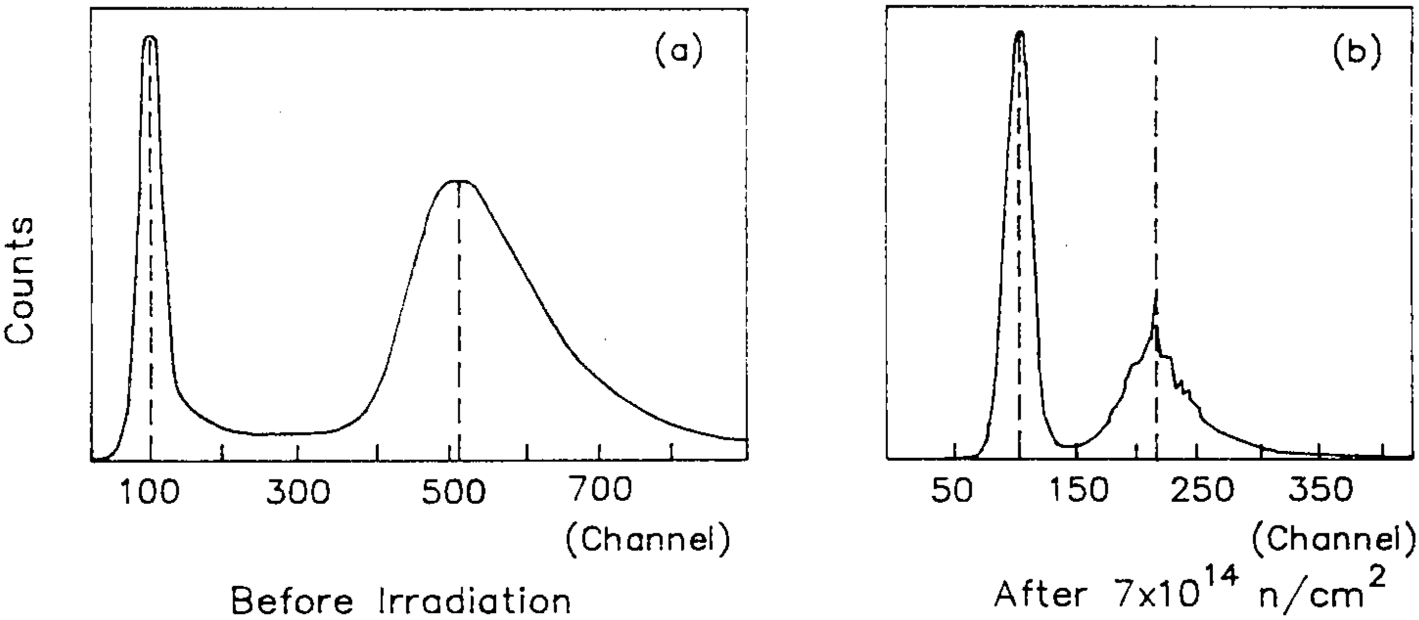
GaAs Peak Position vs Bias Voltage

Fig.5



(a)
(b)
(c)
(d)
Number of Events
GaAs ADC Channel


(e)
Number of Events
2000
1750
1500
1250
1000
750
500
250
0
-200
0
200
400
600
800
GaAs ADC Channel
(f)
Number of Events
240
200
160
120
80
40
0
0
400
800
1200
GaAs ADC Channel
Fig.6



Effect of Irradiation

Fig.7

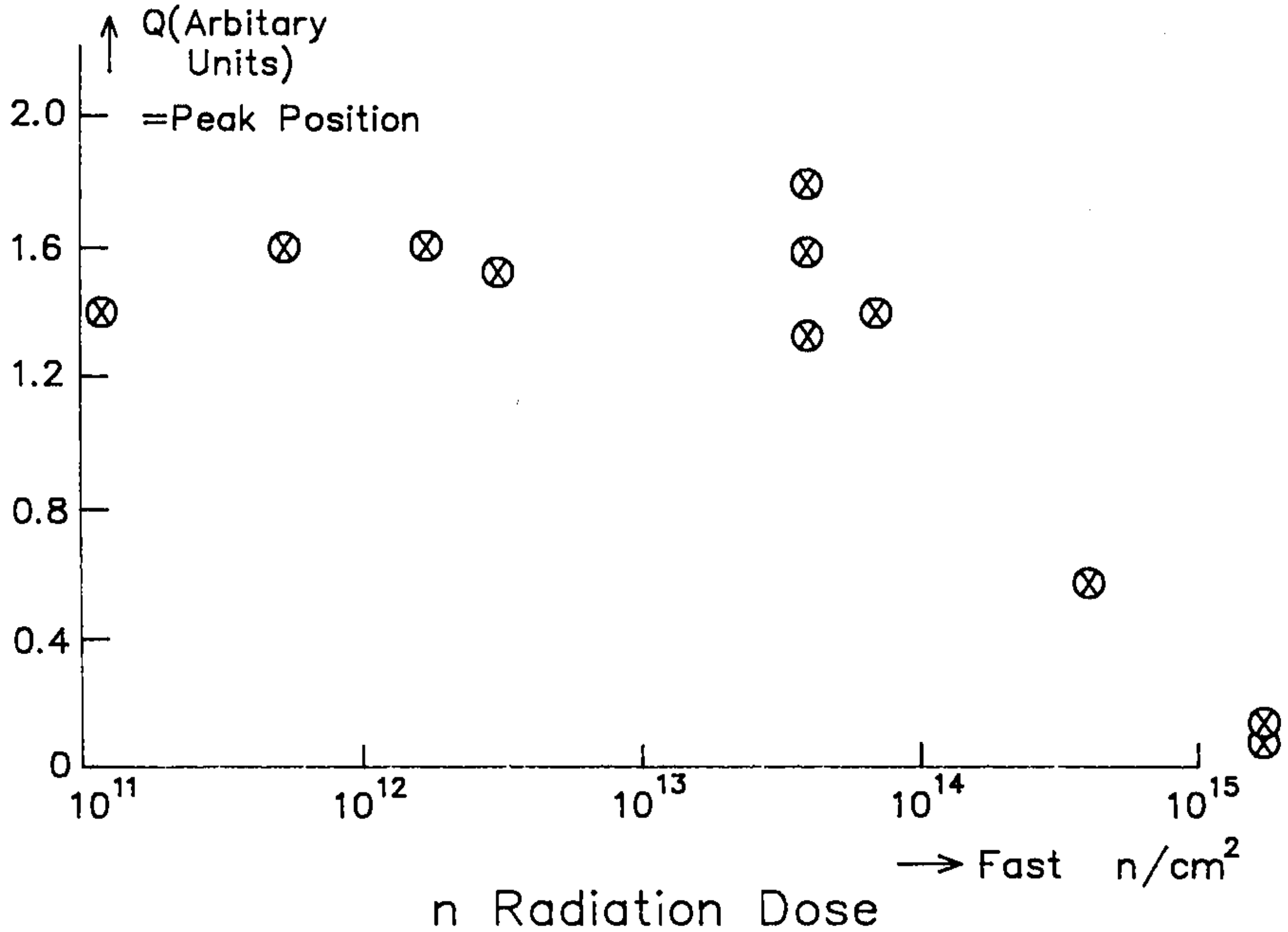

Q(Arbitary
Units)
=Peak Position
2.0
1.6
1.2
0.8
0.4
0
10^11
10^12
10^13
10^14
10^15
→ Fast n/cm^2
n Radiation Dose

Fig.8