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A NEW POLARISATION EFFECT IN CADMIUM TELLURIDE RADIATION DETECTORS

R. M. Bilbe* and D. H. J. Totterdell

ABSTRACT

Cadmium Telluride radiation detectors have been irradiated with 5.48 MeV alpha particles from an ^{241}Am source. For electron collection the pulse height increases with time, this effect reaches a maximum and the pulse height then decreases. For hole collection the pulse height decreases with time. The above phenomenon has been correlated with the presence of an energy level at Ev + 0.46 eV in the gap.

A mechanism is described which suggests that the defect associated with this level is an electron trap. Estimates of the $\mu\tau$ product for this material are:

$$\mu_e \tau_e = 4.6 \times 10^{-5}\ \text{cm}^2\text{V}^{-1}$$
$$\mu_h \tau_h = 1.2 \times 10^{-5}\ \text{cm}^2\text{V}^{-1}$$

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INTRODUCTION

Cadmium telluride is now used as a gamma ray detector in both medical applications and the nuclear industry. However, a major restriction on the widespread application of these detectors is the low yield of good quality material. A polarisation effect has been reported (Bell et al 1974, Malm et al 1974 and Siffert et al 1976) in which the pulse height and count rate are reduced with time when these detectors are illuminated by gamma photons. This effect has been ascribed to the gradual ionisation of deep acceptors in the bulk (believed associated with cadmium vacancies). This introduction of a negative charge in the bulk modifies the electric field such that with a fixed overall voltage the field near the negative electrode is reduced possibly to zero. The presence of defects in the crystal lattice significantly affects the performance of semiconductor radiation detectors by trapping carriers and reducing the carrier drift length, thereby reducing the pulse height. In crystals with high concentrations of traps the pulse height can be reduced to zero.

Cadmium telluride detectors are fabricated at Harwell using high resistivity chlorine doped p-type material grown by the Travelling Heater Method (Howes and Totterdell 1978, Hodgkinson et al 1978) at Hull University. The devices are fabricated by depositing palladium metal electrodes on to polished single crystals passivated by an oxide layer. These detectors can exhibit a polarisation effect as described above. In addition some crystals exhibit very small pulse heights when first illuminated by ionising radiation, and for alpha particle irradiation the initially small pulse heights increase with time. The range of 5.48 MeV alpha particles from an ^{241}Am source is $\sim 20 \mu m$ and they are suitable therefore for the investigation of the response of the shallow surface region to low energy radiation. Previously reported work relating to the detection of alpha particles by cadmium telluride (Malm et al 1974) described a time dependent decrease in pulse height similar to that reported for gamma rays, but not an increase in pulse height.

This report describes a hitherto unreported polarisation effect observed for alpha particle detection by cadmium telluride detectors. In this effect the pulse height observed for electron collection increases with time before reaching a maximum, after which time it decreases over a period of several hours (dependant upon particular sample). It is believed that both this new effect (increasing pulse height) and the previously reported polarisation effect (decreasing pulse height) are taking place in these detectors. The ultimate decrease in pulse height occurs when the new polarisation effect is negligible compared to that associated with the ionised acceptors in the bulk. The cadmium telluride samples exhibited the new effect after being exposed to daylight or daylight simulated by a 100W tungsten lamp. A mechanism is proposed for this phenomenon and a level in the energy gap assigned to the defect responsible. Detectors containing high concentrations of this defect would initially exhibit very small pulse heights.

Experimental Procedure

The cadmium telluride detectors used in this investigation were fabricated using the metal - insulator - semiconductor structure described above. The insulator is a layer of germanium oxide $\sim 150 Å$ formed by evaporating germanium in a vacuum of 2×10^{-5} torr during which the germanium getters the residual oxygen in the vacuum. This oxide layer acts as a passivating layer for the cadmium telluride surface. The crystal diameters ranged from 6mm to 10mm and the crystal thicknesses from 0.5mm to 1.0mm for the samples used in this investigation. The palladium electrodes were evaporated using a resistance heater in a vacuum of $\sim 10^{-6}$ torr. The aluminium electrodes were evaporated using an electron beam evaporator. Gold metal contacts were deposited by electroless deposition of auric chloride $HAuCl_4 - 3H_2O$. The diameters of the metal contacts were about 1 mm less than the crystal diameters. The crystals were mounted in a standard BNC mount and irradiated through a 3mm diameter aperture. The signals from the detector were fed into an AERE type 0351 head amplifier and type 3747 multi channel analyser. Bias voltages ranged from 10V to 300V. Alpha particle spectra were recorded using 5.48 MeV alpha particles from an ^{241}Am source in vacuum and in air.

This phenomenon was only observed in new detectors where the crystals had previously been exposed to daylight. In order that the crystals could be exposed to daylight under identical conditions, a 100W tungsten lamp was used to illuminate each crystal for various periods of time before the pulse height spectra were recorded. No bias voltage was applied to the crystal during illumination. A germanium filter consisting of a 1 mm thick slice of high purity germanium etched in CP4A solution was used to restrict the illumination wavelength to > 2μm. In order that spurious effects due to slow carrier collection might be eliminated the pulse height distribution was investigated with a short integrating time constant (0.1μs) and a long differentiating time constant (300μs). This investigation showed that the observed polarisation was not due to amplifier effects. The detectors were biased continually without removal of the alpha source during the recording of the pulse height distributions.

The Thermally Stimulated Current measurements were carried out at Hull University. In this technique the crystal is cooled to liquid nitrogen temperature in a cryostat and then illuminated to excite the carriers so that all energy levels in the forbidden gap are full. In this case the illumination was by a Xenon lamp. The crystal temperature is then raised in a controlled manner, the carriers are ejected from the different levels by thermal excitation and constitute a current which can be measured. The temperature at which a particular trap is emptied depends upon its position in the energy gap. This measurement enables both the trap position and concentration to be measured.

The illumination wavelength dependence of the pulse height was determined by simultaneously recording the alpha pulse height spectrum and illuminating the crystals. A Barr and Stroud Double Prism Monochromator supplied a continuously scanned source of monochromatic light.

Results

For all detectors used in this investigation the pulse height spectrum from alpha particles incident on the grounded electrode behaved in one of two ways. When the signal electrode was biased with a positive voltage, i.e. electron collection, the pulse height increased with time from its initial amplitude becoming three or four times greater after several hours, as shown in Fig. 1. All detectors with resolution adequate to give a peak from alpha particles behaved in this way. The structure in this spectrum is believed to be due to trapping and subsequent release of carriers in the lattice. The dependence of this effect on bias voltage is shown in Fig. 2. The spectra in Fig. 1 and 3 are displaced vertically for clarity. Alternatively under negative biasing the spectrum observed is shown in Fig. 3. In this case (hole collection) the mean pulse amplitude decreases with time. This effect was always observed for hole collection. The bias voltage dependence for hole collection is shown in Fig. 4. The shape of these curves is similar to those for the polarisation effect observed for gamma rays. The collected charge is proportional to the bias voltage, the data for the saturation values of collected charge are given in Fig. 5, for both electron collection and hole collection. Estimates of the $\mu\tau$ products for both carriers using this data yield values of:

$$\mu_e \tau_e = 4.6 \times 10^{-5}\ \mathrm{cm}^2\ \mathrm{V}^{-1} \text{ and } \mu_h \tau_h = 1.2 \times 10^{-5} \mathrm{cm}^2 \mathrm{V}^{-1}$$

where μ - carrier mobility
and τ - carrier lifetime

The pulse amplitude observed for electron collection increases to a maximum after a time of 2 or 3 hours depending on individual smaples and thereafter begins to decrease; under conditions of hole collection the pulse height simply falls monotonically with time. The pulse height continues to decrease for a time which is sample dependent but this can be >10 hours. These effects have been observed for detectors with the following metal electrodes Pd, Al, Au and are observed whether or not the germanium oxide is present.

All the results reported above were obtained after the detectors had been illuminated for 30 min by a 100W tungsten lamp. Similar effects are observable after very short illumination times. No significant change is observed for times ranging from 1 min to 2 hours (Fig.6). However, to ensure uniform illumination and saturation of this effect, unless otherwise stated the crystals were illuminated by the tungsten lamp for 30 min.

The wavelength dependence of the illumination for the polarisation to be observed is shown in Fig. 7. In Fig. 7a the detector configuration is for electron collection, the pulse height is initially small, the detector is illuminated immediately and the wavelength scanned continuously. At a photon wavelength of approximately 2.7μm an increase in pulse height is observed corresponding to the saturation value referred to above. For hole collection (Fig.7b) there is a corresponding decrease in pulse height for $\lambda \sim 2.7\mu m$. This effect of illumination wavelength is confirmed by the results of Fig. 8. In this figure the usual alpha spectrum time dependence for 100V bias is shown together with a similar spectrum time dependence recorded after the detector had been illuminated through a germanium filter. The band gap of germanium is 0.66eV. This latter time dependence is similar to those of Fig. 2 for higher detector bias voltages where the carrier collection will be better.

In order to demonstrate that the presence of irradiation induced carriers is not essential for the crystal to return to electrical equilibrium the following procedure was adopted. The detector was illuminated by white light, and the bias voltage then applied. The detector was left in the dark (under bias) without being irradiated by alpha particles for 2 hours. After 2 hours the detector was exposed to alpha particle irradiation and the pulse height observed was equivalent to that which would have been recorded for continuous alpha particle irradiation throughout the 2 hours. This result was also observed if the detector was not being biased throughout the 2 hours. After this 2 hour period the effect was observed to saturate and then decrease for longer times in agreement with Fig. 2. Thermally Stimulated Current measurements for several samples confirmed that for crystals exhibiting this polarisation effect, a defect with a level at E_V + 0.46eV was always present. The concentration of these centres varied for each crystal but were in the range $10^{11} - 10^{12} cm^{-3}$.

Discussion

The important features of the results reported here are, that after white light illumination cadmium telluride detectors:-

(1) exhibit an alpha particle spectrum whose pulse height:
  (a) increases with time for electron collection and eventually decreases and
  (b) increases with voltage then saturates.

(2) exhibit an alpha particle spectrum whose pulse height:
   (a) always decreases for hole collection and
   (b) increases with bias voltage within the range of voltages available before breakdown;

(3) exhibit a polarisation effect (as above) which can be eliminated by illumination with light of wavelength approximately 2.7 μm ($h\nu = 0.46eV$)

(4) exhibiting this polarisation effect contain a defect with an energy level in the gap at $E_V + 0.46eV$.

A mechanism which could account for the above observations is now suggested. Consider Fig. 9a, after illumination the defect centres are ionised (positively charged). When this crystal is now irradiated with alpha particles a high concentration of electrons and holes is created within approximately 20 μm of the irradiated surface. The ionised centres will trap the drifing electrons, however the pulse height in this configuration is determined by electron collection. The pulse height is therefore small. As the concentration of ionised centres is gradually reduced by electron trapping, the fraction of electrons collected increases and so does the pulse height. When all of these electron traps are filled, the increasing ionised acceptor concentration (gamma ray polarisation effect) is reducing the field at the front surface of the detector. The pulse height now gradually decreases due to the reduction in the sensitive volume of the detector.

Consider now Fig. 9b, the situation initially is similar, however the pulse height now depends upon hole collection. Rather than trap electrons the ionised centres repel the holes to contribute to the pulse height. As the electrons annihilate these centres the hole repulsion decreases and therefore the hole collection decreases. After the ionised defects are neutralised completely the irradiation induced electrons are available to recombine with the holes and further reduce the observed pulse height. For hole collection both the alpha polarisation effect and the gamma polarisation effect reduce the observed pulse height.

The Thermally Stimulated Current measurements have indicated the presence of a defect level at $E_v + 0.46$eV in all samples showing this polarisation effect. In Fig. 10a we show this level initially electrically neutral, illumination by white light ionises the centre leaving it positively charged (Fig. 10b). Subsequent illumination with infra-red light excites an electron to this level to return it to the neutral charge state. (Fig.10c).

Previous work (Martin et al 1976) has suggested that a level at Ev + 0.46eV is associated with a singly ionised vacancy. This result is not supported by the present results. The model suggested here invokes a neutral defect with a level at $E_v + 0.46$eV. Irradiation by ^{60}Co gamma rays at room temperature reduces the concentration of this defect. (Bilbe 1981). Such treatment would not be expected to decrease the vacancy concentration in the lattice.

Conclusions

Cadmium Telluride radiation detectors which have been illuminated with white light can have a concentration of positively charged centres in a shallow layer near the illuminated crystal surfaces. If the detectors are now irradiated by ionising radiation with a low penetration in the lattice, some of the irradiation induced charge is trapped at these centres which are then electrically neutral. The observed pulse height associated with this radiation is initially small therefore but increases as the concentration of ionised centres is reduced by further carrier trapping. This phenomenon is only observed for electron collection and is absent when all of the centres are in the neutral charge state.

The effect can be eliminated by illuminating the crystal with infra red radiation ($\lambda \sim 2.7\mu$m). These defect centres have an energy level at Ev + 0.46 eV in the gap and act as electron traps.

Acknowledgements

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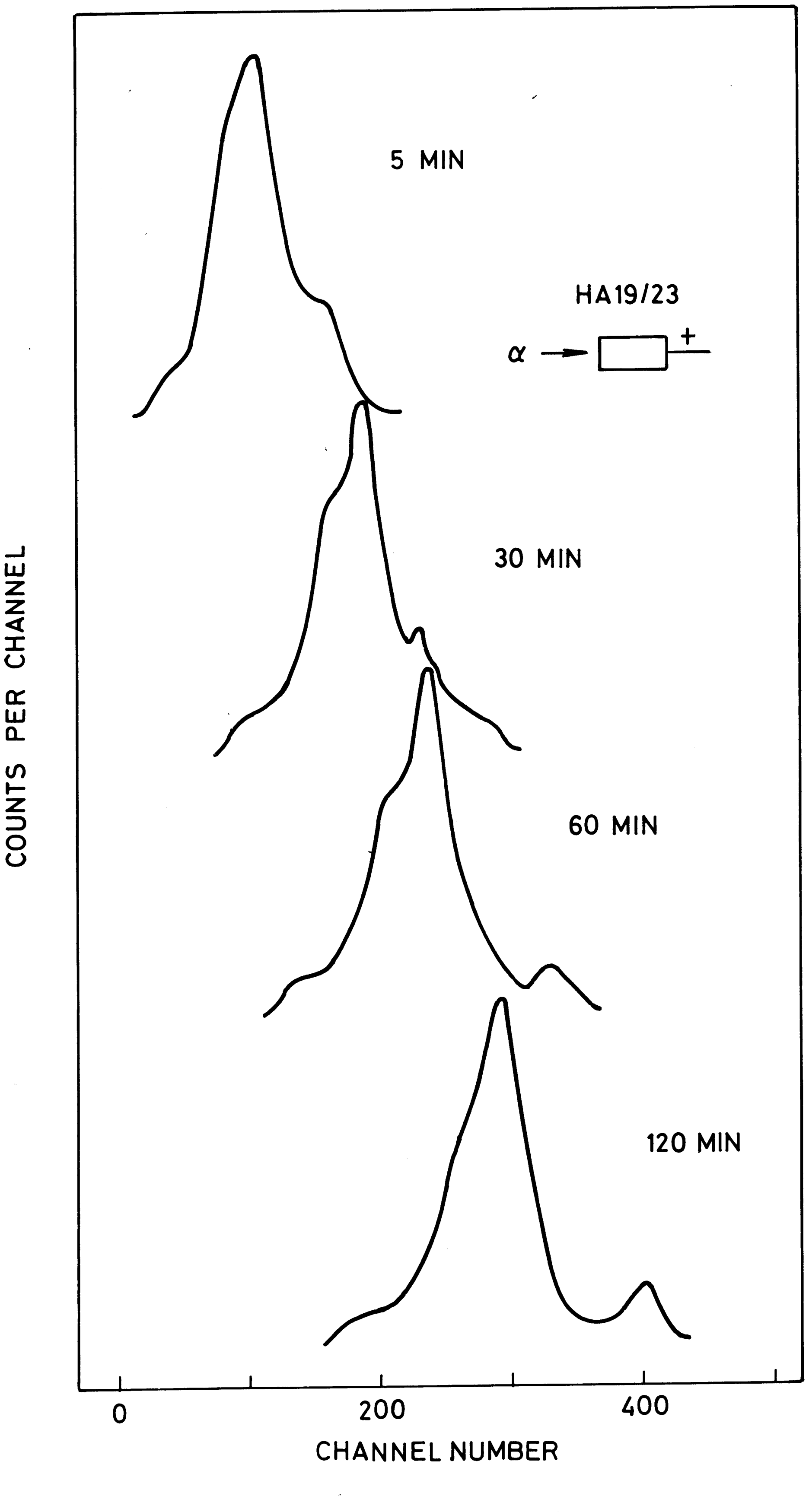
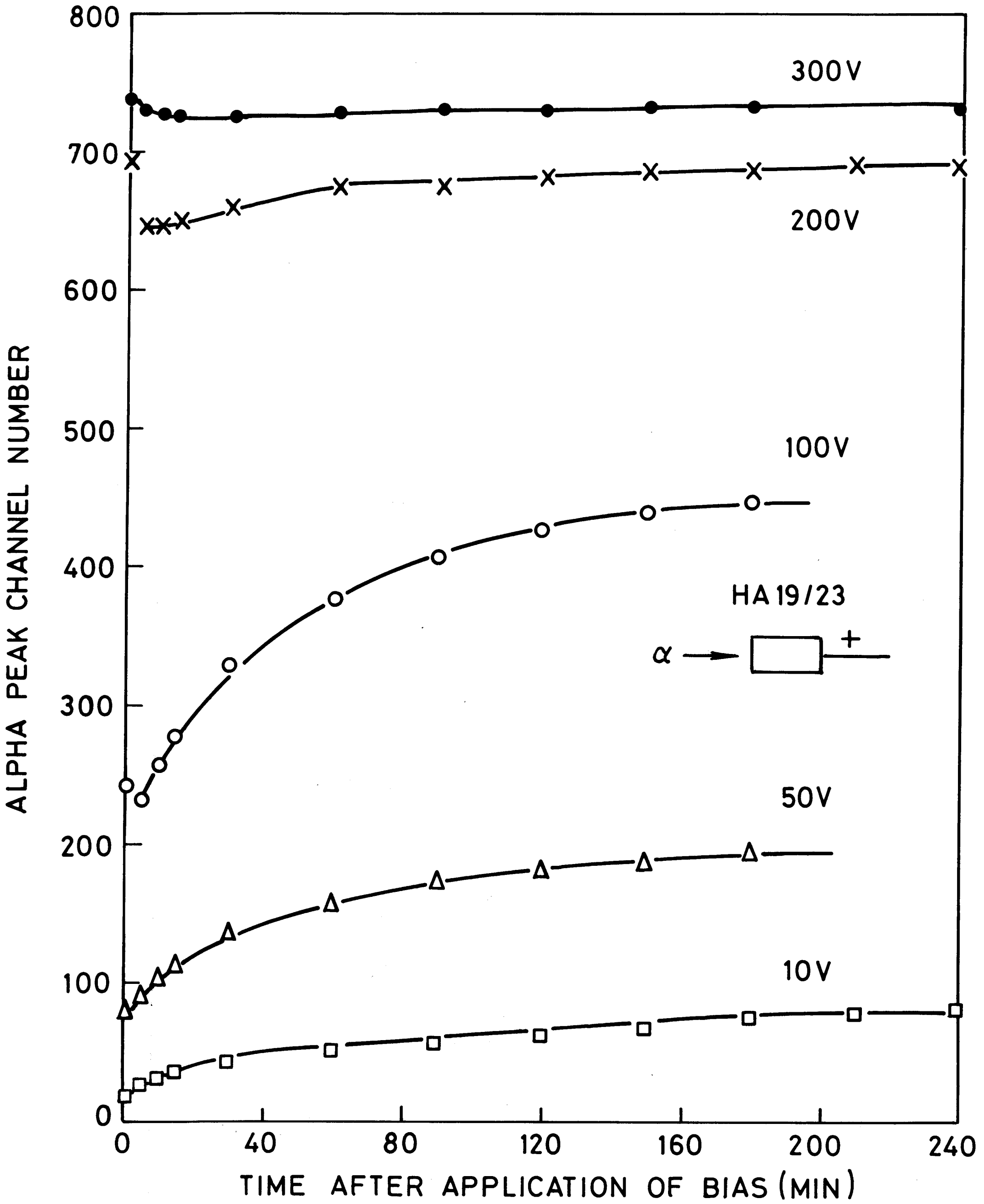
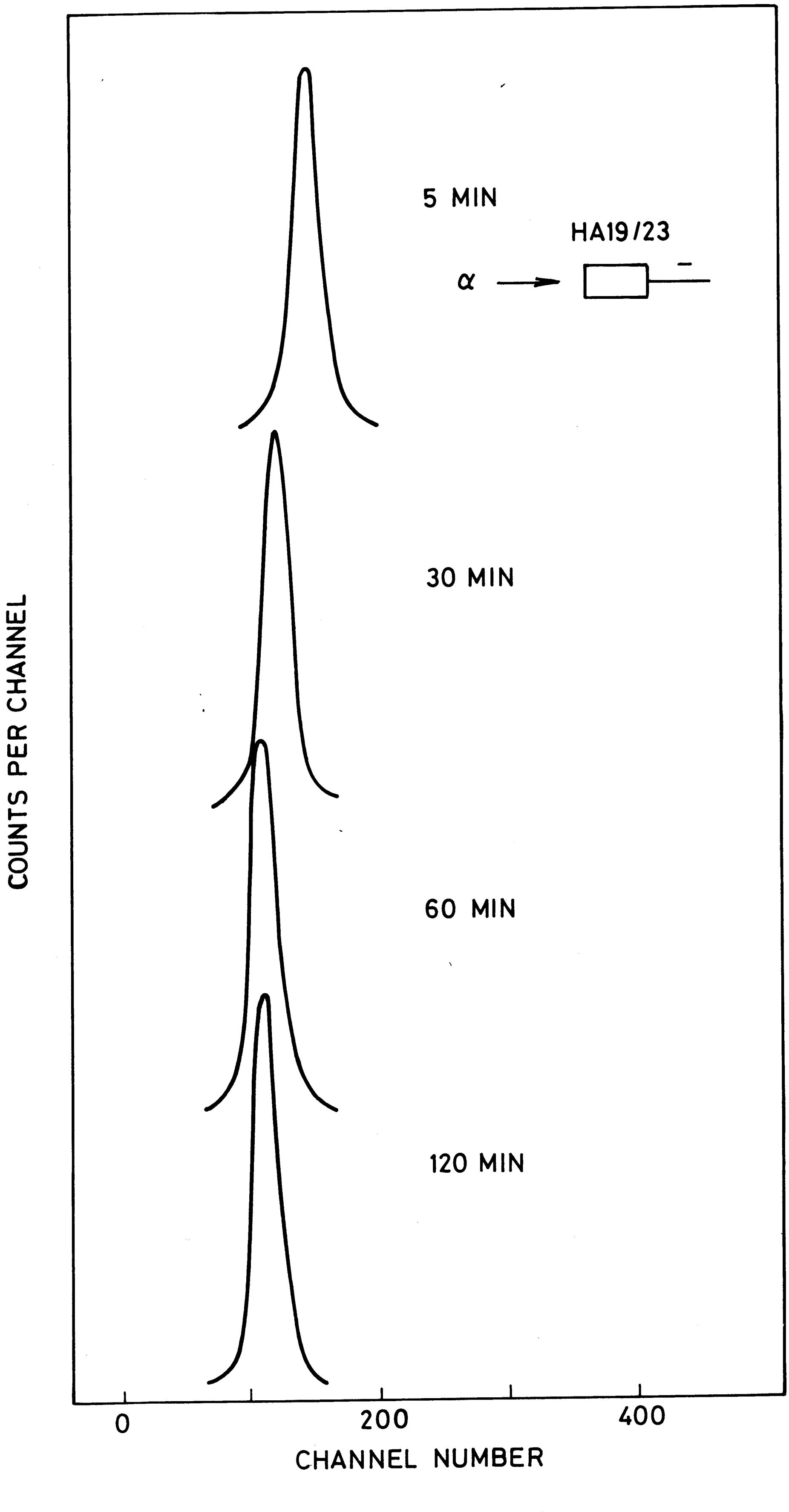


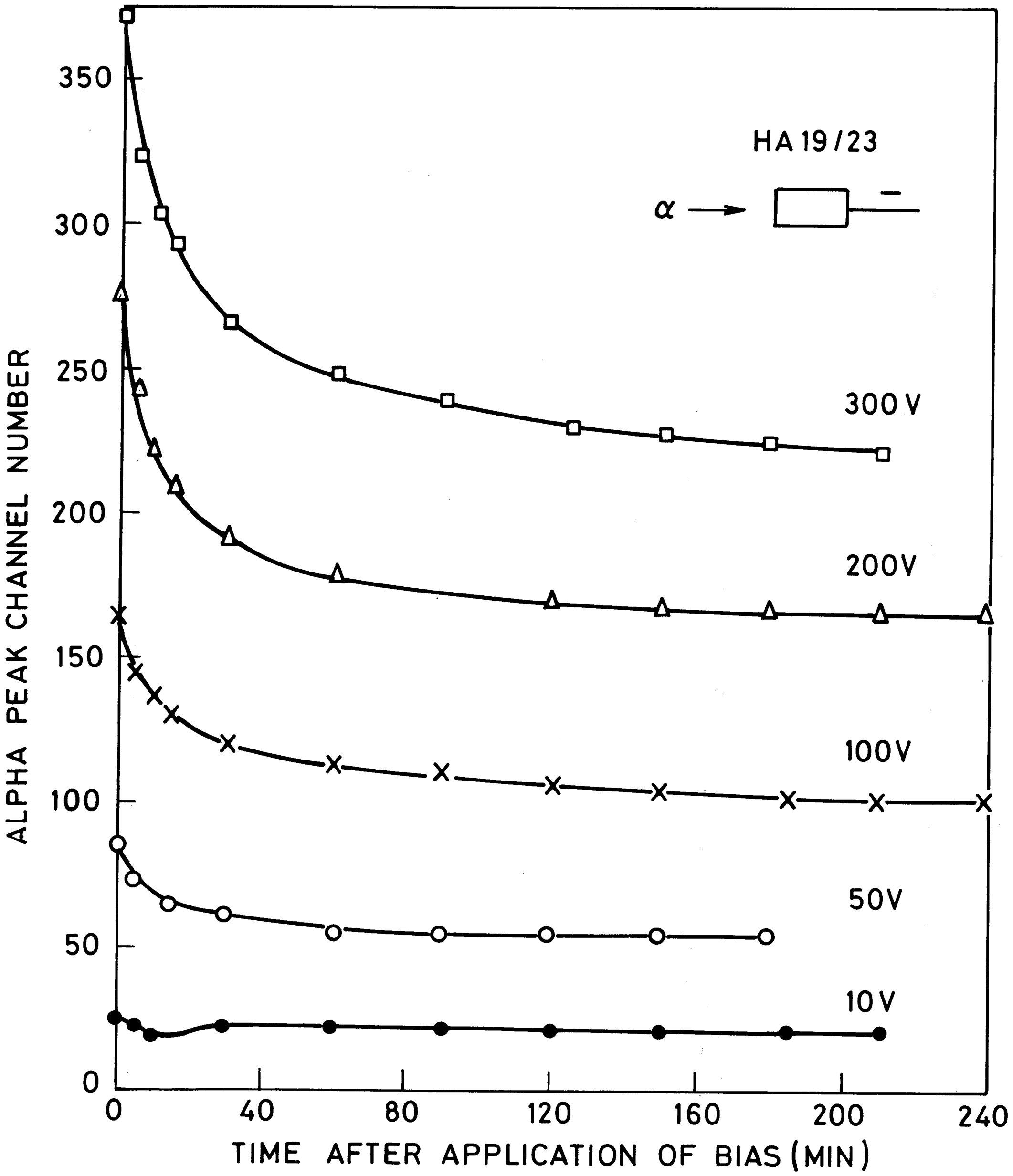
AERE - R 10118 Fig. 1
Pulse height distribution for alpha particles incident on a cadmium telluride detector (biased for electron collection) showing pulse height increasing with time. The spectra are displaced vertically for clarity.



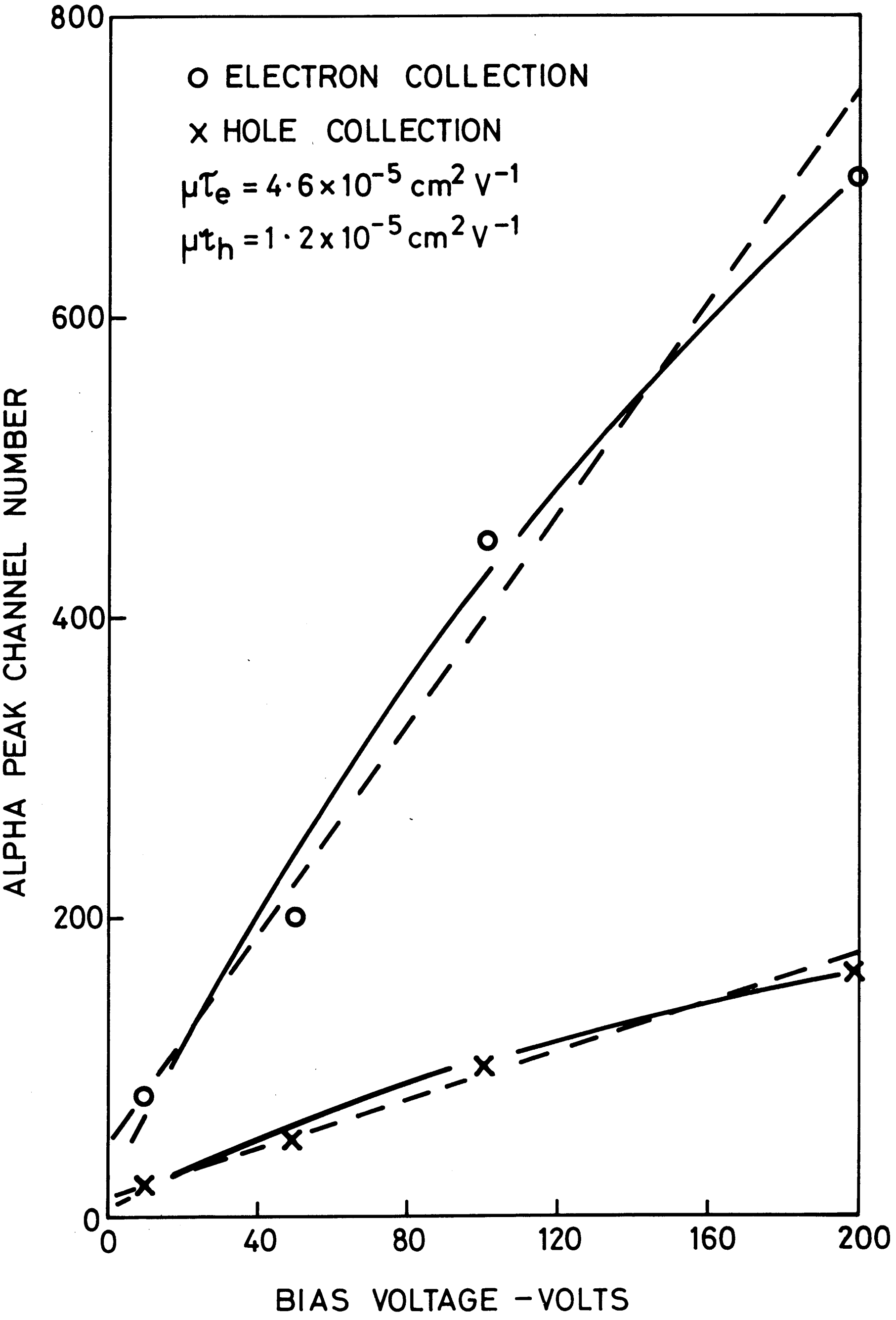
AERE - R 10118 Fig. 2
Time dependence of alpha peak channel number for various detector bias voltages (electron collection).



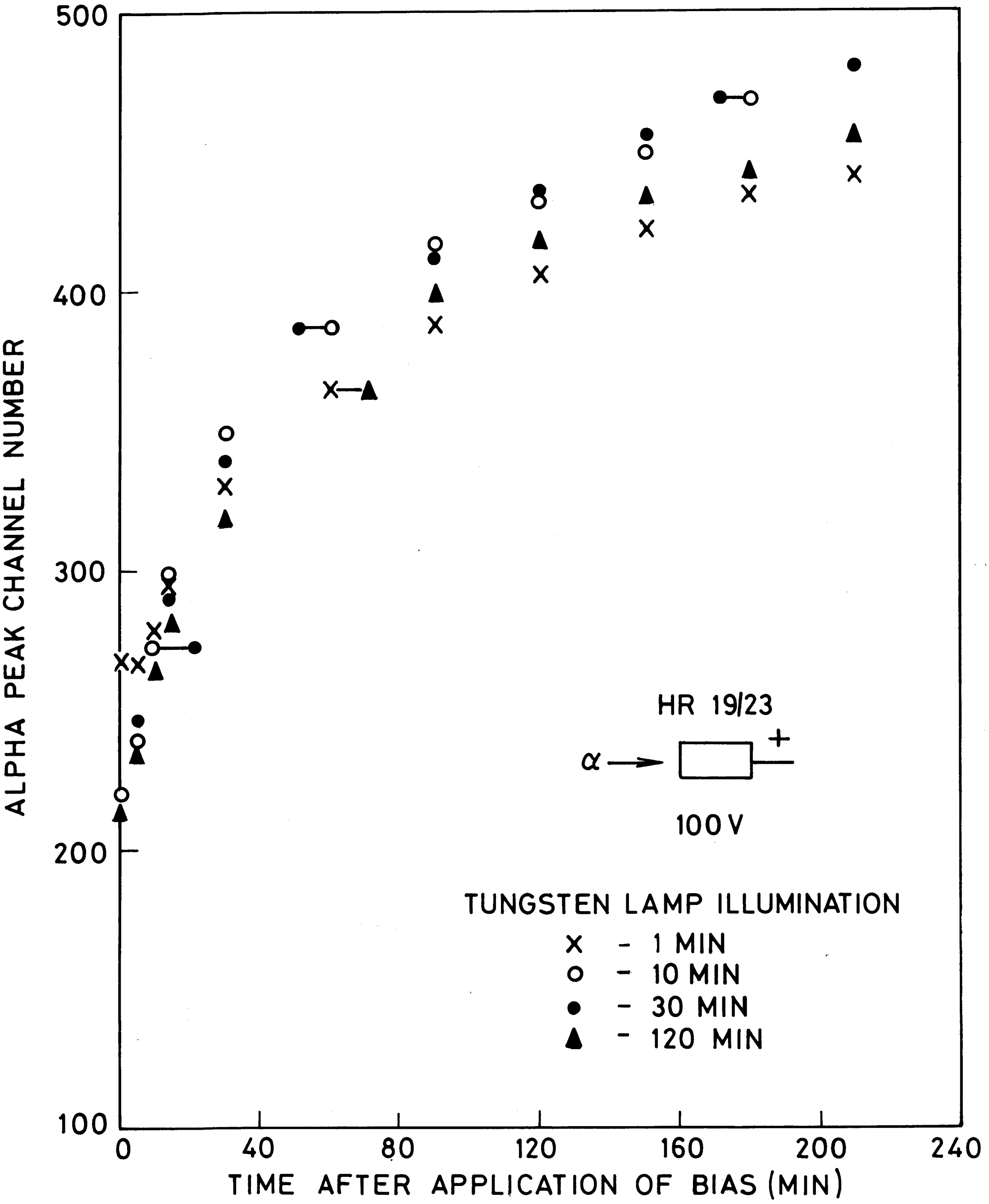
AERE - R 10118 Fig. 3
Pulse height distribution for alpha particles incident on a cadmium telluride detector (biased for hole collection) showing pulse height decrease with time.



AERE - R 10118 Fig. 4
Time dependence of alpha peak channel number for various detector bias voltages (hole collection).



AERE - R 10118 Fig. 5
Dependence of alpha peak channel number on detector bias voltage after biasing for 3 hours (i.e. saturation).



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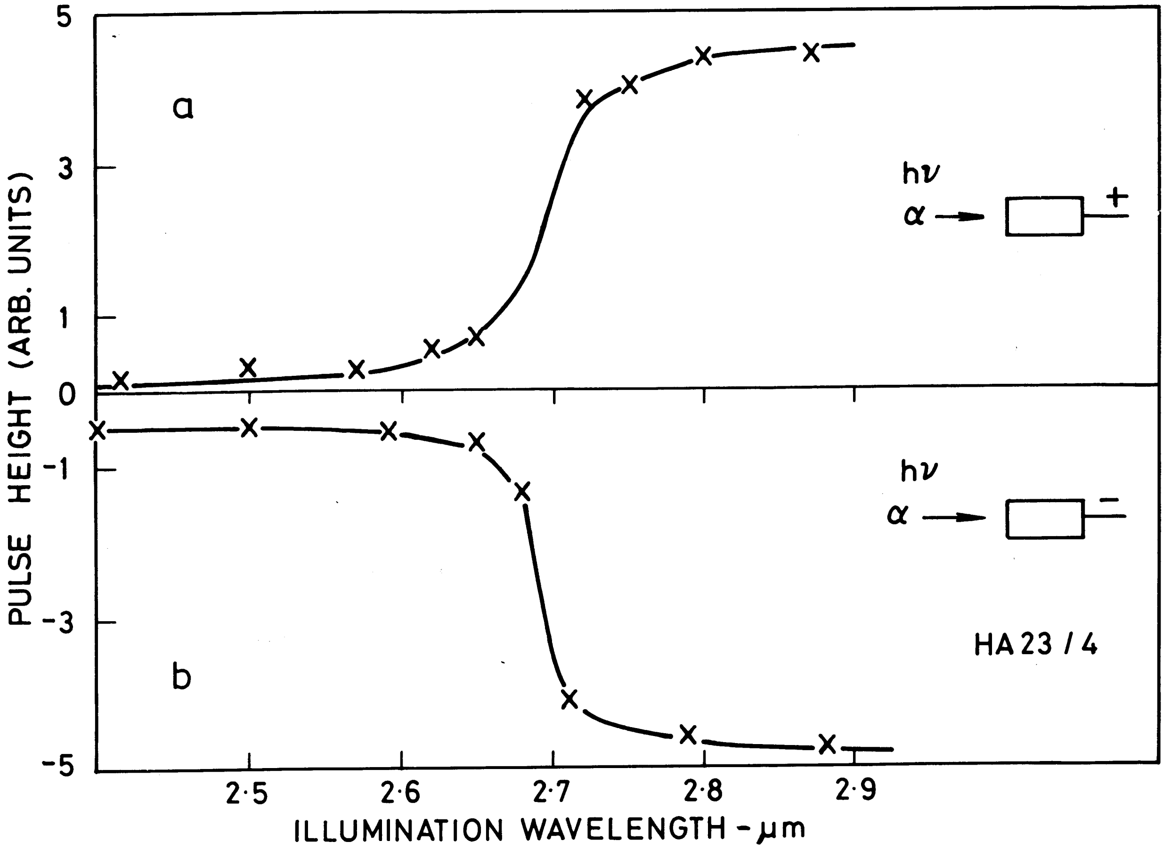
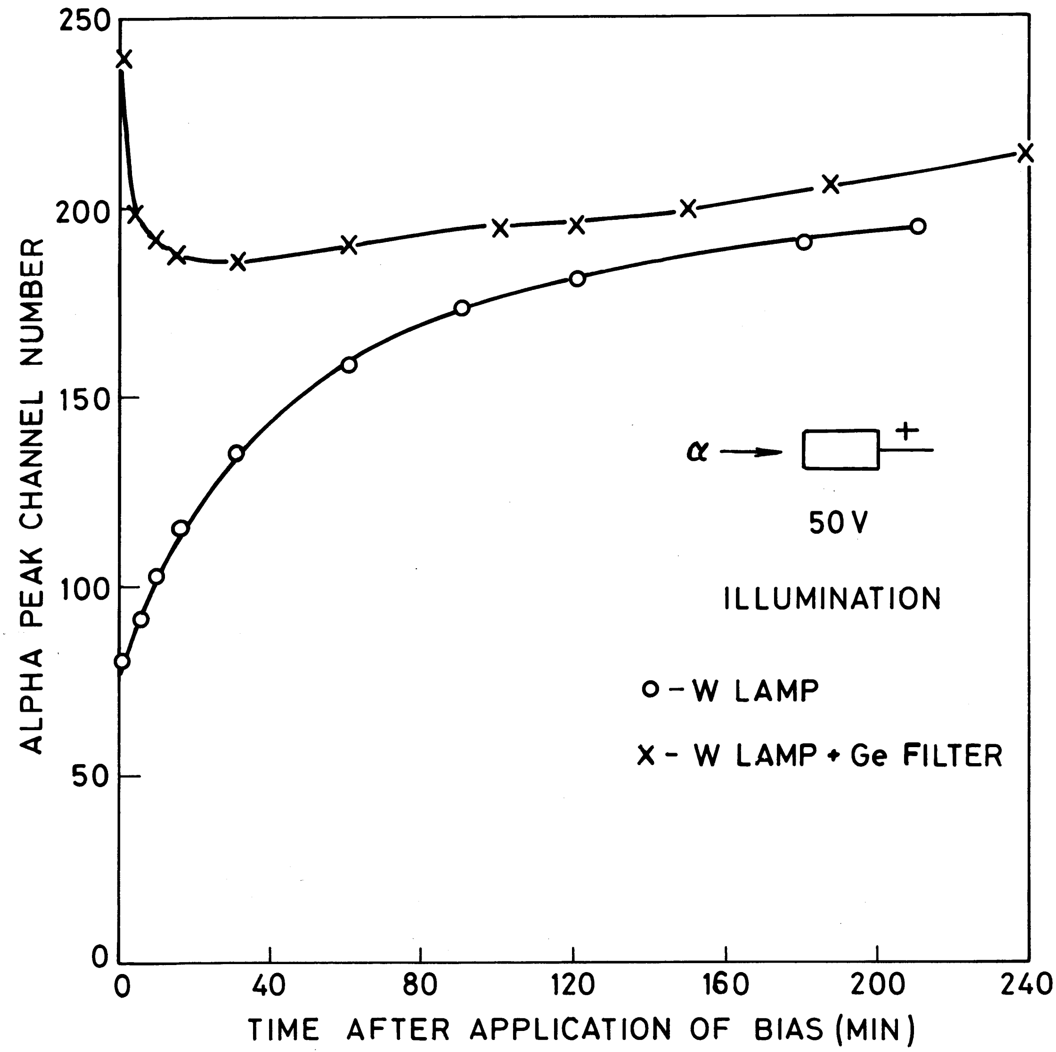
Time dependence of alpha peak channel number for several illumination times (electron collection).

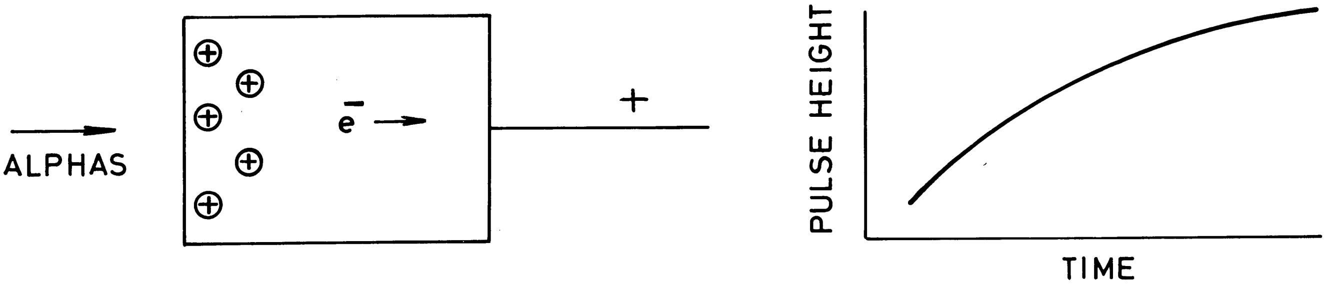


AERE - R 10118 Fig. 7
Alpha particle pulse height dependence on wavelength of illumination for continuous exposure for:

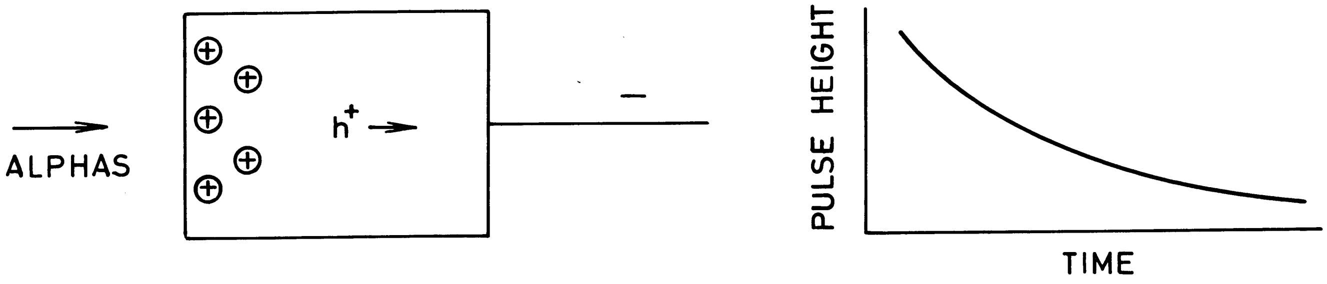
(a) electron collection and
(b) hole collection.



AERE - R 10118 Fig. 8
Time dependence of alpha peak channel number for white light illumination and infra red illumination (electron collection).



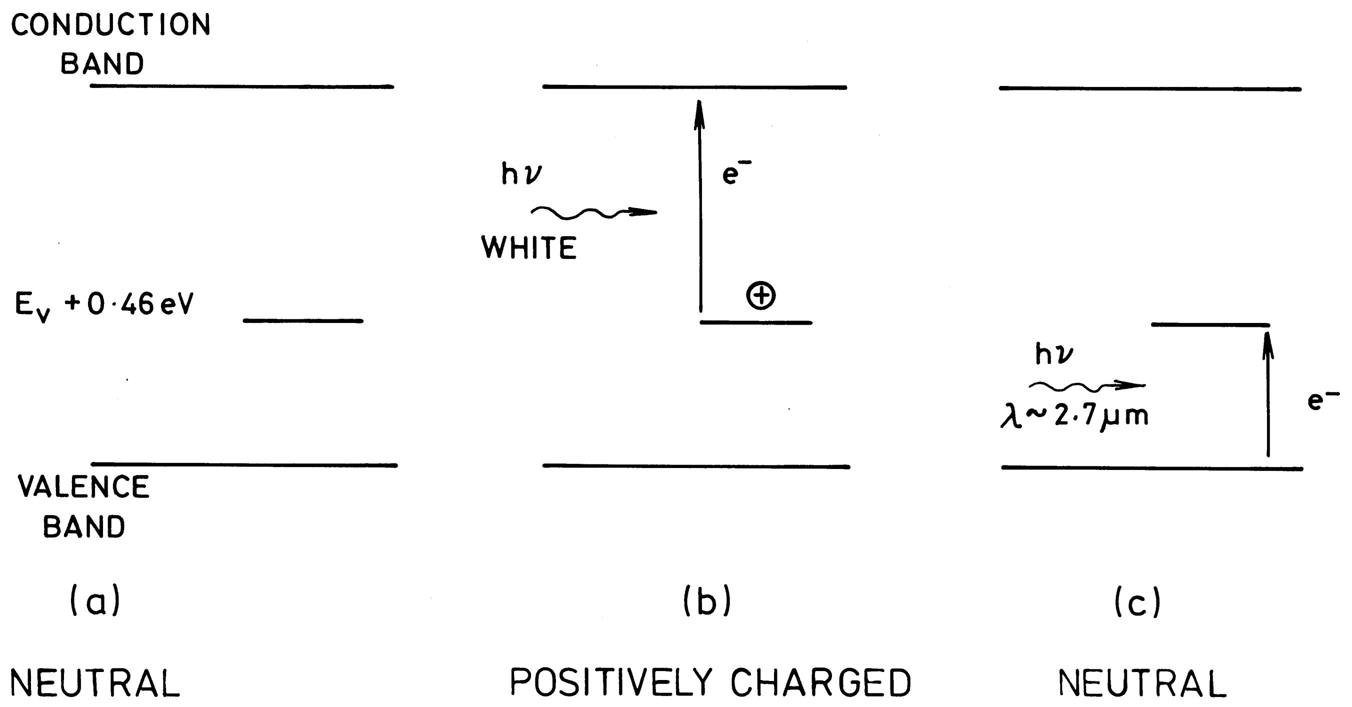
(a)



(b)

AERE - R 10118 Fig. 9
Schematic induced charge distribution in a cadmium telluride crystal after white light illumination for:

(a) electron collection and
(b) hole collection.



AERE - R 10118 Fig. 10
Energy level diagram for defect level at E_V + 0.46 eV.