

Radiation studies for GaAs in the ATLAS Inner Detector

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We estimate the hardness factors and the equivalent 1 MeV neutron fluences for hadrons fluences expected at the GaAs positions wheels in the ATLAS Inner Detector. On this basis the degradation of the GaAs particle detectors made from different substrates as a function of years LHC operation is predicted.

1 Introduction

It was proposed by the ATLAS collaboration to use GaAs strip detectors as a part of the inner tracker at LHC because of the good radiation resistance to fast neutron irradiation up to $4 \cdot 10^{14}$ n cm⁻²[1]. The high hadron radiation levels with fluences in the range of 10^{13} cm⁻² yr⁻¹ in the forward region of the ATLAS inner detector will effect the main parameters for the operation of the GaAs detectors: leakage current density, space charge density, mean free drift length and charge collection efficiency. In the first part of this paper we discuss the radiation level for the GaAs wheels (R=26-32.7 cm,Z=85-170 cm)[3] and calculate the hardness factors for the integrated neutron and proton spectra. Then an attempt is made to estimate the 1 MeV neutron equivalent fluence for a ten year LHC operation. In the second part we summarize damage functions deduced experimentally from pad detectors irradiated in the ISIS spallation neutron source at the Rutherford Appleton Laboratory[4] and with 24 GeV/c protons at the proton synchrotron (CERN).

2 Radiation levels and extraction of equivalent 1 MeV neutron fluences

The radiation levels for the ATLAS inner detector have been calculated by A.Ferrari[5] using the FLUKA code with DTUJET. Table 1 summarizes the expected hadron radiation fluences assuming a p-p cross section of 80 mb and a maximum luminosity of $1.0 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ (operating time 10^7 s per year) for the LHC. For the following we assume that the charged hadron fluences only consists of pions and protons.

Table 1

Mean, peak energy and fluences (10 years operation) of hadron radiation level at the position of the GaAs wheels ($R = 30 \text{ cm}$) in the ATLAS inner detector.

	peak energy [MeV]	mean energy [MeV]	fluence [cm^{-2}]
pions	600	1900	$1.86 \cdot 10^{14}$
charged hadrons without pions	840	230	$3.05 \cdot 10^{13}$
neutrons	-	28	$1.54 \cdot 10^{13}$

The basic assumption to estimate the radiation damage for GaAs in the inner detector is that all bulk damage effects scale linearly with the total non-ionizing energy loss (NIEL) $D(E)$. This quantity has been calculated as a function of kinetic energy for the interaction of several particles with GaAs[6][7]. Using this functions it is possible to relate the damage from monoenergetic 1 MeV neutrons to the damage from other particles with different energies via the hardness factor κ . For a radiation source with known energy spectrum $\varphi(E)$ and cut-offs at E_{min} and E_{max} we define

$$\kappa = \frac{1}{D(1 \text{ MeV}, n)} \frac{\int_{E_{min}}^{E_{max}} \varphi(E) D(E) dE}{\int_{E_{min}}^{E_{max}} \varphi(E) dE} \quad (1)$$

Thus, for a measured fluence $\Phi_{meas} = \int_{E_{min}}^{E_{max}} dE \varphi(E)$, the equivalent 1 MeV fluence is given by $\Phi = \kappa \Phi_{meas}$. For the normalization factor $D(1 \text{ MeV}, n)$ we use 3.1 keV/cm calculated by E.A.Burke[7]. Figure 1 shows the estimated non-ionizing energy loss of protons and neutrons as a function of kinetic energy in GaAs. The solid lines are the calculated values of A.M. Ougouag[6] and E.A.Burke[7] for protons and neutrons respectively.

For neutrons there are only values up to 14 MeV available and we assume a plateau of the NIEL for higher neutron energies (dashed line) as for Silicon because of the expected decrease of the cross section and the saturation of the Lindhard function. This uncertainty leads only to a small error of the

Table 2

Hardness factors of the hardrons at $R = 30$ cm in the ATLAS inner detector and estimate equivalent 1MeV neutron fluences (GaAs) for a ten year LHC operation.

	hardness factor κ	$\Phi(1MeV, n)[cm^{-2}]$
pions	8	$1.48 \cdot 10^{15}$
protons	8	$2.5 \cdot 10^{14}$
neutrons	0.5	$7.7 \cdot 10^{12}$
total		$1.75 \cdot 10^{15}$

hardness factor for the neutron spectra in the inner detector because 98% of the neutrons have energies below 14 MeV. For protons the NIEL up to 1 GeV is known. Additionally we determine from the comparison of neutron and proton irradiated detectors a hardness factor of 7 for 23 GeV protons[2]. To determine the hardness factors of the proton spectra in the inner detector we extrapolate between 1 GeV and 23 GeV. At this time there is no calculation of the NIEL for pions in GaAs. Only experimental data for the radiation damage of 200 MeV pions are available[8] which give a hardness factor of about 9 in comparison to proton irradiated samples. Due to the delta resonance we expect a maximum of the NIEL as a function of kinetic energy at 200 MeV (similar to Silicon). The peak and mean energy of the pions expected at the GaAs wheel position is much higher and from this we can estimate a value of about 8 as an upper limit of the hardness factor. Table 2 summarizes the calculations of the hardness factors and also shows the equivalent 1 MeV neutron fluence estimated for ten year LHC operation. The total fluence in ten years comes up to a level of about $1.75 \cdot 10^{15} cm^{-2}$ and is mainly due to pions.

3 Detector parameters of GaAs as a function of LHC operation years

The pad detectors, for investigation of radiation hardness, are Schottky diodes made on semi-insulating GaAs with a thickness of 200 μm and a diameter of 2 or 3 mm. The contacts and substrates are described elsewhere [2]. The detectors were irradiated using neutrons (ISIS) and 23 GeV protons (CERN). Figure 2 shows the leakage current density as a function of $\Phi(1MeV, n)$. We observe for high ohmic material a slight increase of the leakage current density to a value of 30 nA/mm² at 20°C and for medium ohmic material a decrease down to the same value. This means the leakage current density after ten year LHC operation is independent of the value before irradiation and small in comparison to Si pad detectors [9]. The typical behavior of the MIP signal

height (^{90}Sr -Source) of irradiated pad detectors is an exponential decrease down to about 4000 e^- for an equivalent fluence of $1.3 \cdot 10^{15} \text{ cm}^{-2}$ (e.g. wafer MCP90 Figure 3). For the measurements we used a bias voltage of 200 V and a shaping time of 500 ns. To investigate this behavior we determined the mean free drift lengths by irradiating the detector from the front and backside with alpha particles (^{241}Am). The charge collection efficiency (CCE) is then given by

$$CCE = \frac{\lambda_n}{d} \left[1 - \exp\left(-\frac{d-x_0}{\lambda_n}\right) \right] + \frac{\lambda_h}{d} \left[1 - \exp\left(-\frac{x_0}{\lambda_h}\right) \right] \quad (2)$$

where λ_n and λ_h denotes the drift lengths of electrons and holes, d the detector thickness and x_0 represents the generation point of electron hole pairs. We assume that the mean free drift length is independent of the position within the detector. In any case this is valid for electrons because of the saturation of the drift velocity at electric fields higher than 10^4 V/cm . For holes we observe a plateau of the CCE for bias voltages higher than 200 V [2] which indicates also a saturation of the hole drift length. Figure 4 shows the mean free drift length of electrons and holes (20 °C, 300 V bias) as a function of the 1 MeV equivalent neutron fluence for diodes from wafer FR41. We observe a strong decrease of the mean free drift length for both carriers down to 32 μm for electrons and 22 μm for holes. A comparison of different materials shows that there is a dependence of the electron mean free drift length on the resistivity. The material with the lowest resistivity shows for all irradiation levels the highest electron mean free drift length but is still going down to about 36 μm (Figure 5). CV-measurements have shown that the space charge density decreases with increasing irradiation [2]. Figure 6 plots shows corresponding bias voltage to make the detector full active. This voltage decreases for diodes on Wafer FR76 from 250 V down to 10 V after ten years of LHC operation.

4 Summary and Conclusion

The calculation of the hardness factors of the proton and neutron spectra and the estimation for pions result in a 1 MeV neutron equivalent fluence of $1.75 \cdot 10^{15} \text{ cm}^{-2}$ at $R = 30 \text{ cm}$ in the ATLAS inner detector for ten years of LHC operation. Therefore we expect at 20 °C for the GaAs detectors leakage current density of 30 nA/mm² independent of the resistivity of the semi-insulating GaAs substrates. This value is low in comparison to silicon detectors. Also the voltage to make the detector fully active is smaller than 200 V. The signal loss due to trapping and the reduction of the carrier mobility is a severe problem. But the signal height of pad and strip detectors are not the same, because of the different weighting fields. A concept proposed by Th.Schmid et

al. [10] predicts for a strip detector with special bias a signal height of 7000 e^- considering only the electrons with a mean free drift length of 40 μm after ten years of LHC operation.

5 Acknowledgments

We are grateful to M.Edwards (RAL) and F.Lemeilleur (CERN) for the help with the irradiation. We also thank A.Ferrari for providing the data of the radiation levels in the ATLAS inner detector. This work has been supported by the BMBF under contract 057FR11I.

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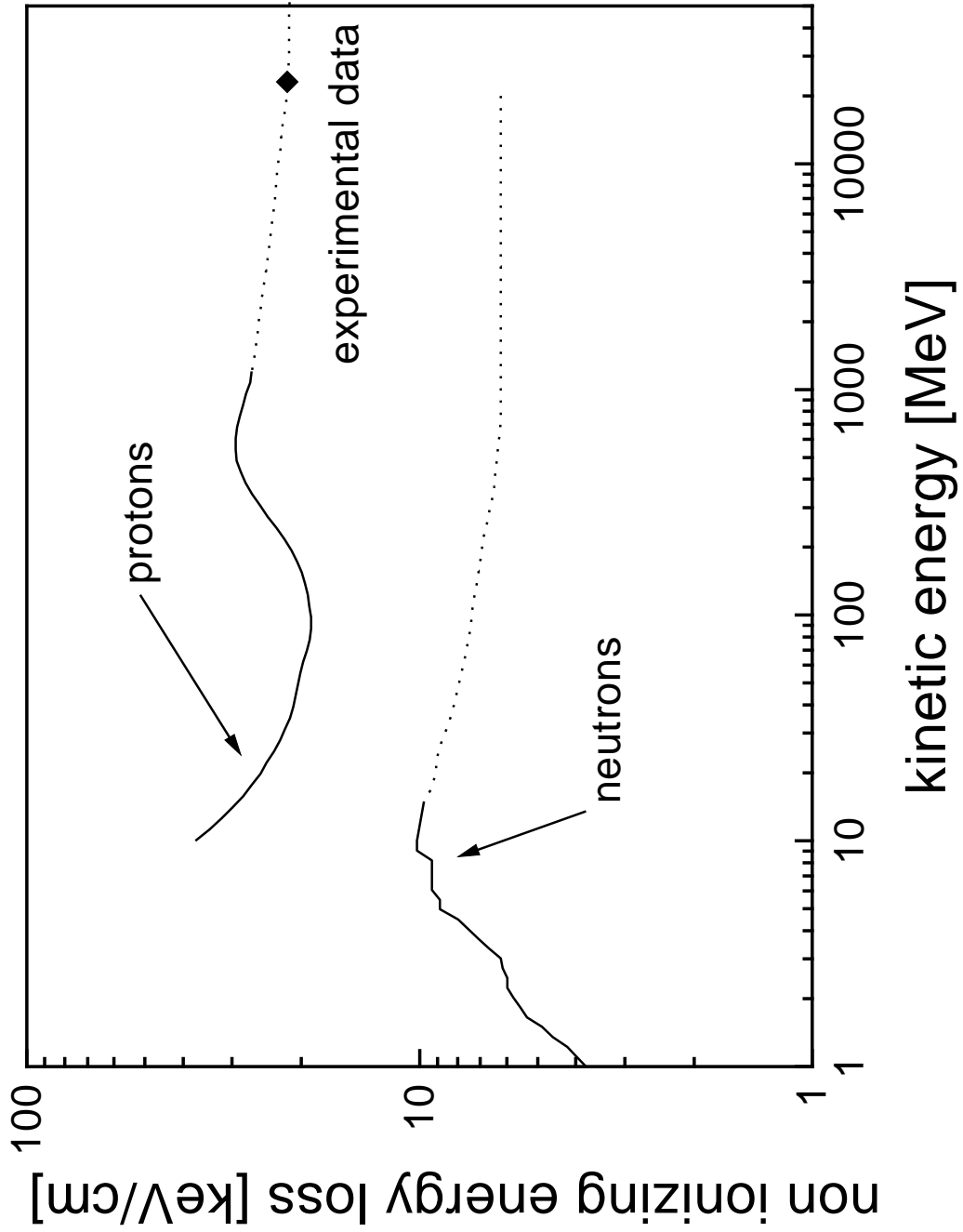


Fig. 1. The estimated non ionizing energy loss (NIEL) of protons and neutron as a function of kinetic energy in GaAs.

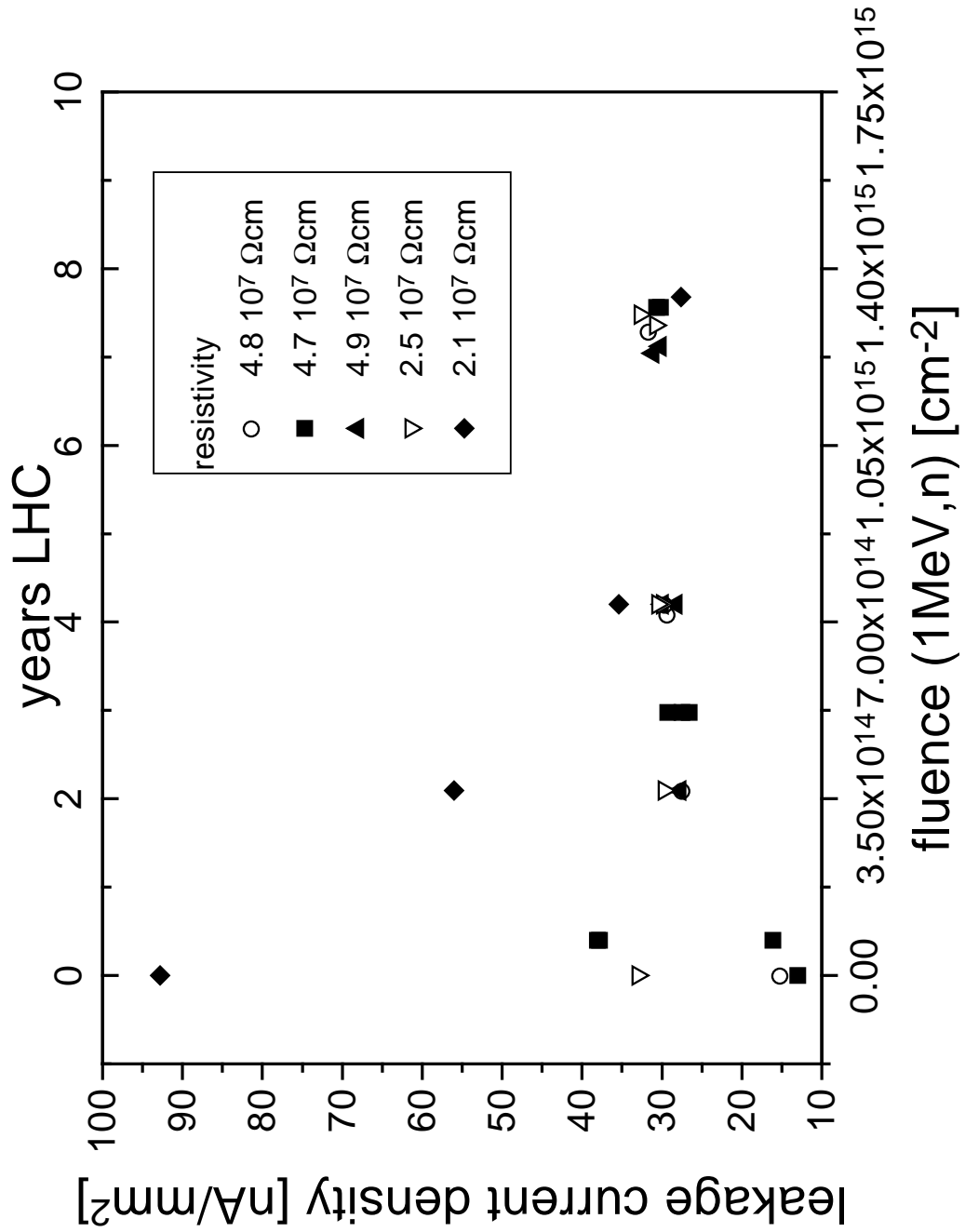


Fig. 2. The leakage current densities at 20°C of Schottky diodes made on different substrates versus the 1 MeV neutron equivalent fluence.

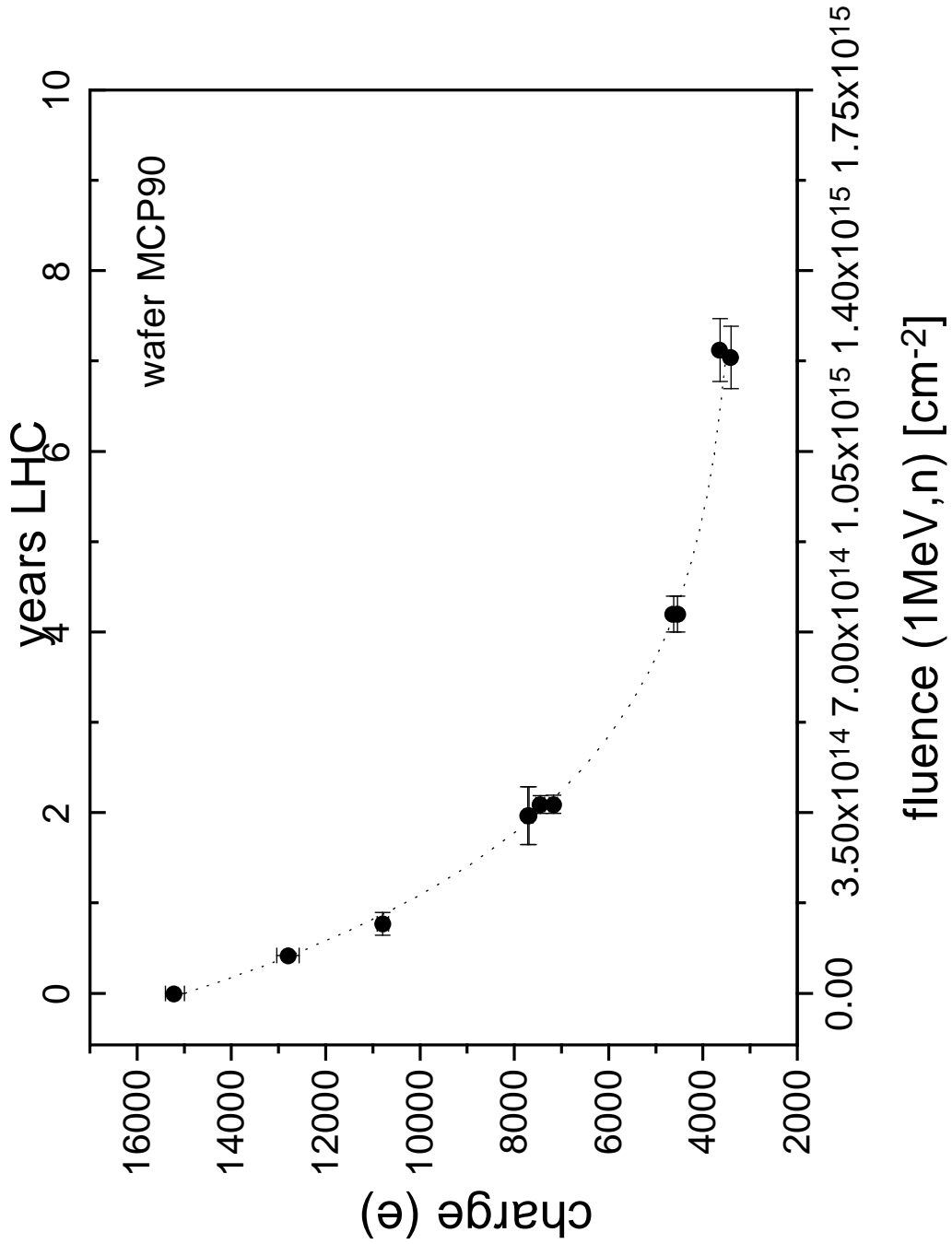


Fig. 3. The typical behavior of the MIP signal height as a function of the 1 MeV neutron equivalent fluence (⁹⁰Sr, 200 V bias, 500ns shaping time, wafer MCP90).

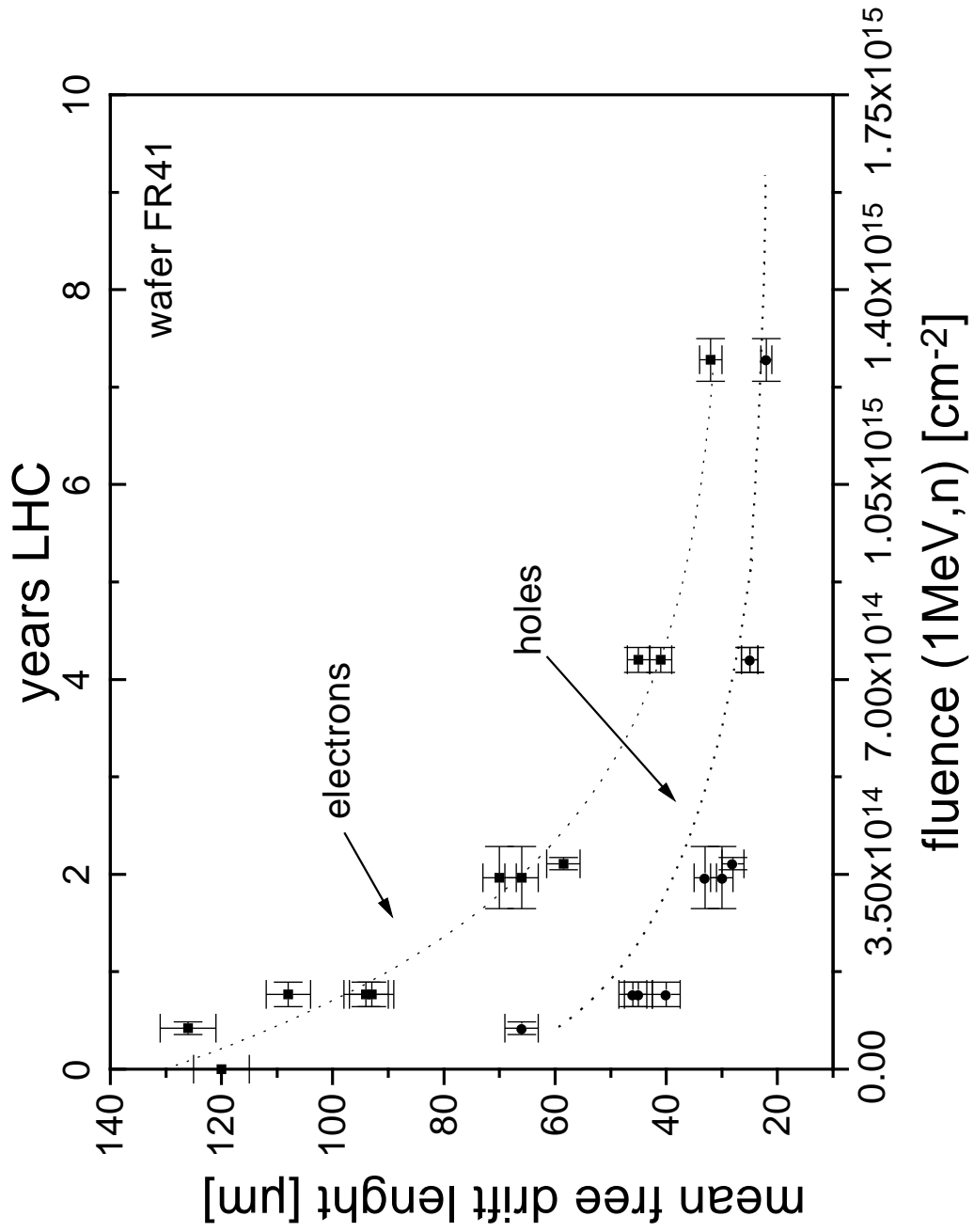


Fig. 4. The mean free drift length of electrons and holes obtained from alpha spectra as a function of the irradiation level (20°C, 300 V bias, wafer FR41).

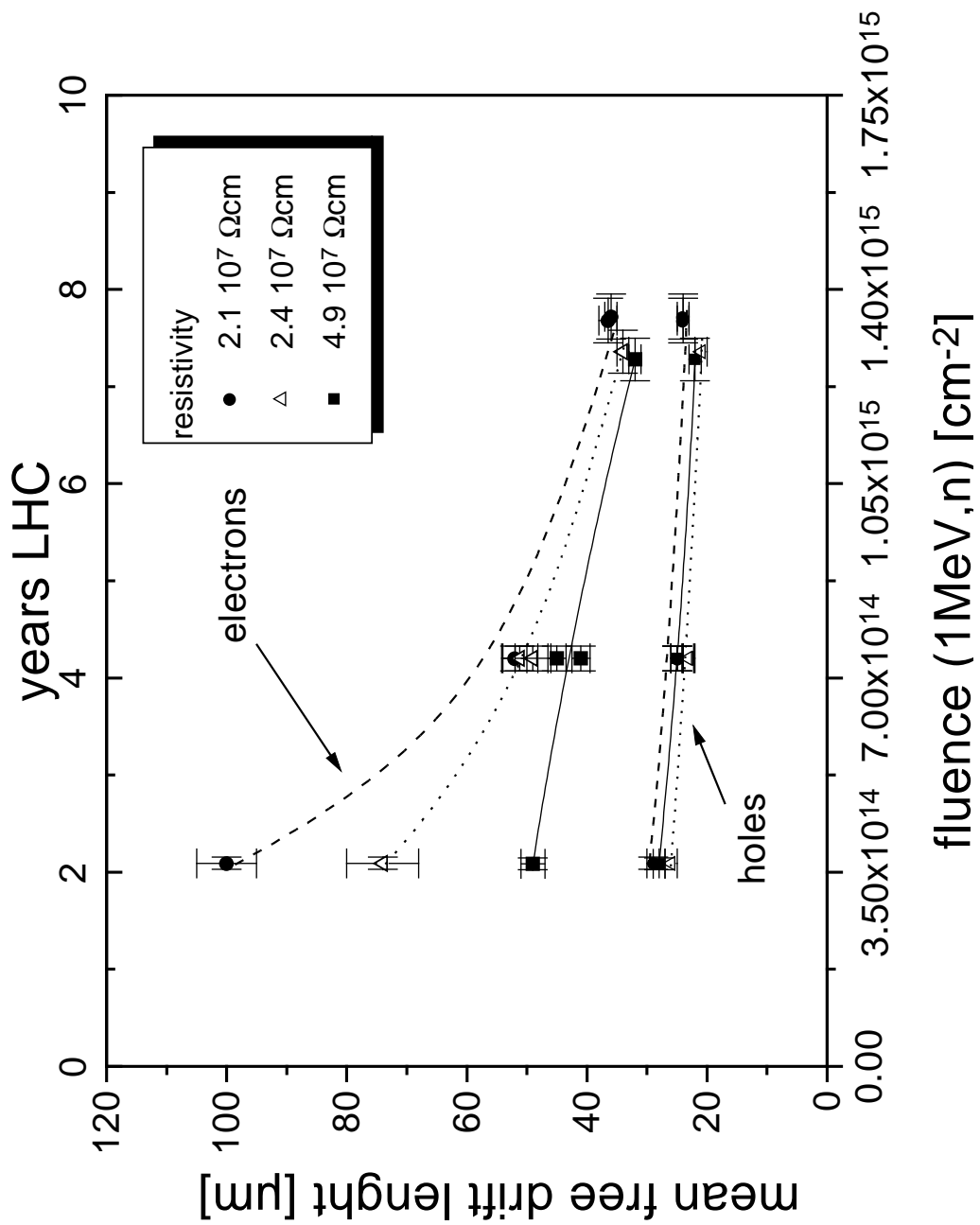


Fig. 5. The mean free drift length of electrons and holes versus the 1 MeV neutron equivalent fluence for different materials.

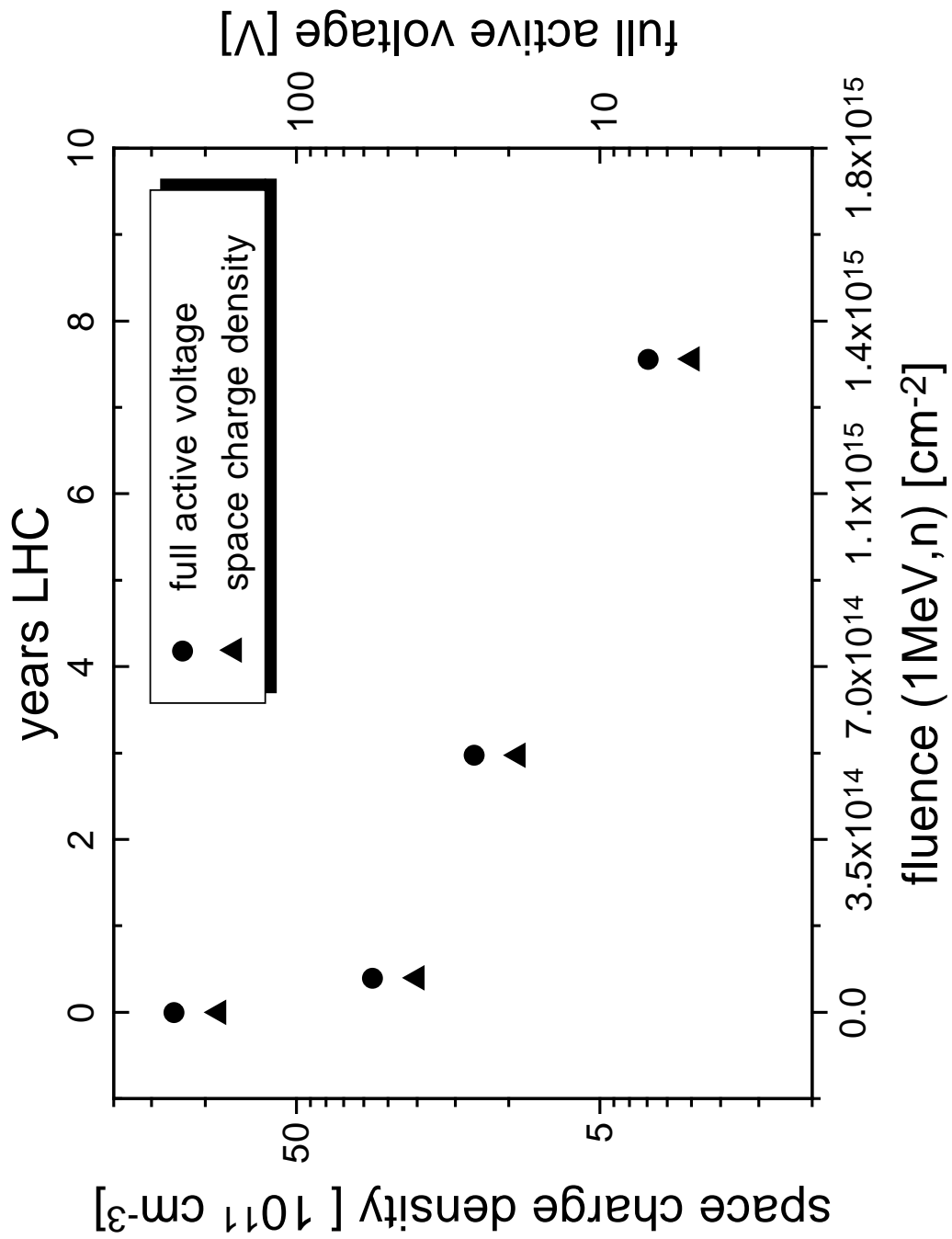


Fig. 6. The space charge density and full active voltage obtained by CV-measurements versus the irradiation level.