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Silicon Drift Detectors for high count rate X-ray spectroscopy at room temperature

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Abstract

Silicon Drift Detectors (SDDs) combine a large sensitive area with a small value of the output capacitance and are therefore well suited for high resolution, high count rate X-ray spectroscopy. The low leakage current level obtained by the elaborated process technology makes it possible to operate them at room temperature or with moderate cooling.

A brief description of the device principle is followed by the presentation of first results of a new production of large area SDDs with external electronics. Performance and applications of the already established SDDs with on-chip amplification are summarised. Various shapes of Multichannel Drift Detectors are introduced as well as their use in new experiments like X-ray holography and in new systems like an Anger camera for γ-ray imaging.

Key words: silicon drift detector, X-ray spectroscopy, X-ray detector, γ-camera

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Introduction

Silicon Drift Detectors (SDDs) are based on the principle of sideward depletion introduced by Gatti and Rehak in 1984 [1]: a large volume of a high resistivity semiconductor, in our case n-type silicon, is depleted by a small sized n^+ ohmic substrate contact reverse biased with respect to rectifying p^+ junctions covering both surfaces of the structure. In a SDD the p^+ junctions are strip-like segmented and biased in such a way that an electric field parallel to the surface exists. Electrons released within the depleted volume by the absorption of ionising radiation or by thermal generation drift in the field towards the n^+ substrate contact, which acts as collecting anode and is connected to an amplifier. The generated holes are taken away by the p^+ junctions.

Originally SDDs have been designed and used as position sensitive detectors in particle physics where the measurement of the signal electrons' drift time allows to reconstruct one coordinate of the particle's interaction point. The second coordinate is given by an appropriate segmentation of the collecting anode(s). The SDD concept is of great flexibility in the choice of anode arrangements and drift directions. For instance two-dimensional (x, y)-position sensors with an active area of 4.2 x 3.6 cm^2 have been fabricated [2] as well as cylindrical (r, φ)-detectors with a diameter of 10 cm and an angular resolution of 1°, realised by a radial drift field and 360 anodes placed along the edge of a 4-inch wafer [3].

Silicon Drift Detectors for X-ray spectroscopy

In an advanced SDD design optimised for applications in X-ray spectroscopy the concentric ring-shaped p^+ strip system for the generation of the drift field and the collecting anode in their center are placed on one side of the structure, while the opposite surface is covered by a non-structured p^+ junction acting as homogeneous radiation entrance window (fig. 1) [4, 5]. The calculated electron potential of a biased SDD is shown in fig. 2 in a section through the anode perpendicular to the surface. In the back there is the equipotential of the entrance window, the field strips with their step-like increasing negative potential are shown in the front. The voltage of the field strips is defined by an integrated voltage divider, only the first and the last ring must be biased externally. There is no field-free region in the device, i.e. the whole volume is sensitive for the absorption of ionising radiation and each generated electron has to fall down to the point of lowest potential energy, which is the anode in the center of the front side. SDDs of this type are not used as position sensors, but as energy dispersive detectors for X-rays and charged particles, taking advantage of the small value of the anode capacitance, which is almost independent of the detector area. For a given number of collected electrons this quality translates to a large amplitude and a short rise time of the output signal. Compared to a conventional photodiode of equal size and operated under the same conditions (e.g. temperature, noise of readout electronics) the SDD can be operated at higher count rates and it yields a substantially better energy resolution, because the signal is less sensitive to the noise contribution of the subsequent amplifying electronics.

At the semiconductor laboratory of Max Planck Institut für Physik and Max Planck Institut für extraterrestrische Physik (MPI-HLL) in Munich SDDs for X-ray spectroscopy with different readout concepts have been designed, fabricated, and tested:

a.) SDDs with a 'traditional' external amplifier connected to the anode by a bond wire,

b.) SDDs with the amplifier's input stage integrated on the detector chip.

The following sections present the relevant results.

Silicon Drift Detectors with external amplifier

SDDs with external electronics have been designed and fabricated in four sizes: 5 mm^2 and 10 mm^2 in cicular geometry, and 30 mm^2 and 100 mm^2 with the shape of squares with tilted corners. The production of these devices has only recently been finished, therefore only the preliminary first results of a laboratory test of the 10 mm^2 and the 30 mm^2 SDD can be given here. Both have been tested in a climatic chamber at temperatures between 25 °C and -50 °C with a radioactive ^{55}Fe source, the count rate on the detectors was 1 to 2 kcps. Figure 3 shows the obtained values of FWHM of the Mn-Kα line at 5.895 keV as a function of temperature for both sizes. In addition the values of the corresponding optimum shaping time constant are specified. From the experimentally obtained FWHM numbers a dark current density less than 1 nA/cm^2 for the fully biased and operating detector at 20 °C and a total capacitance of the detector-amplfier-system of 500 fF have been deduced.

At high temperature the energy resolution is limited by the statistically fluctuating current of thermally generated carriers adding to the signal charge packets. Despite the large area of the tested SDDs the elaborated process technology of MPI-HLL is capable of getting leakage current levels low enough for room temperature operation with an energy resolution better than 300 eV and 400 eV FWHM for the SDDs with 10 mm^2 and 30 mm^2. At -20 °C, a temperature within the range of Peltier coolers, the energy resolution is already as good as 190 eV for the 10 mm^2 SDD and 250 eV for 30 mm^2 at shaping times of 2 and 1 μsec respectively. The comparison with a conventional Peltier-cooled silicon PIN diode of only 7 mm^2 demonstrates the gain in speed and resolution by the SDD's small capacitance: the diode's specified FWHM value is 220 eV at a shaping time of 12 μsec [6].

The limit of the energy resolution at low temperature and short shaping time is set by the 1/f noise contribution of the amplifier's input transistor. In the first test a transistor with a considerably high 1/f noise floor has been used. Replacing it by a state-of-the-art spectroscopy FET further improvement on the shown FWHM values is to be expected.

As incomplete charge collection at the radiation entrance window is limiting the detector response at low X-ray energies and the SDD's ability to identify low intensity lines special emphasis has been put in the minimisation of the effective silicon 'dead layer' [7, 8]. Figure 4 demonstrates the quality of the entrance window by the example of a ^{55}Fe spectrum recorded with the 10 mm^2 SDD at -20 °C. Besides the well known Si escape peaks the low energy background of the Mn-K lines contains the M-lines of Pb above 2 keV, because the source was fixed in a lead holder, and the K-lines of Ar around 3 keV, because the experimental setup was in an atmosphere of dry air. Comparing the height of the Mn-Kα line with the undisturbed continuum around 1 keV a peak-to-background ratio of 11000 can be deduced, which is comparable with the best reported values of Si(Li) detectors.

On-chip amplification

The detector share of the total output capacitance is already optimised by the SDD topology with the small dimension of the collecting anode. A further reduction of capacitance and consequently an additional gain in signal rise time and energy resolution can only be achieved by minimising the remaining contributions: the amplifier's input capacitance and the stray capacitance of the connection between detector and amplifier. Both goals are achieved simultaneously by integrating the first transistor of the amplifying electronics on the SDD chip: the integrated transistor can be designed with minimum input capacitance, which is unusual for discrete devices, and the bond wire connecting detector and amplifier in the traditional setup is replaced by a short metal strip on the chip. That way the system also gets more robust for applications in non-laboratory environment, because noise by microphony, i.e. mechanical vibrations, is excluded and electrical pickup is significantly reduced.

SDDs with integrated transistor have also been developed, produced, and qualified in large quantities by MPI-HLL. Their sensitive area is 5 mm^2, the total output capacitance is 250 fF. The integrated transistor is a single-sided n-channel JFET [9]. It has an internal, self-adapting discharging mechanism [10], so that there is no need for an externally clocked reset pulse, and the whole system is operating with dc-voltages only. Figure 5 shows the statistical spread of measured Mn-Kα FWHM numbers of more than 300 samples coming from two productions as a function of temperature. With Peltier cooling, i.e. at temperatures between –10 °C and -20 °C, the typical resolution is in the range 170 eV to 145 eV FWHM of the Mn-Kα line. Due to the minimised overall capacitance the best resolution is obtained at extremely short shaping times of maximum 1 μsec. The count rate capability of SDDs with integrated FET is demonstrated in fig. 6: the FWHM of Zn-Kα fluorescence radiation (8.6 keV) excited by synchrotron radiation at HASYLAB in Hamburg is almost constant up to 10^5 cps input count rate. Even at 10^6 incoming photons per second the detector is able to deliver spectroscopic information with a resolution that is far beyond the capability of other systems and still satisfactory for fast counting applications with energy discrimination like EXAFS or X-ray holography.

SDDs of this type cooled by a single-stage Peltier element and mounted in a standard TO8 package are used in industrial scale for fast elemental mapping in scanning electron microscopes [11] and for material analysis in table-top and portable XRF-spectrometers, for instance in archeometry, i.e. the investigation of works of art [12].

Multichannel Silicon Drift Detectors

To combine a larger sensitive area with the extraordinary properties of the 5 mm^2 SDD with integrated FET we introduced the concept of McDrift (**M**ulti**c**hannel **Drift** Detector). McDrift is a continuous, gapless arrangement of a number of SDDs with individual readout, but with common voltage supply, entrance window, and guard ring structure (fig. 7). It allows not only to fill any large area (fig. 7a) without losing the energy resolution and count rate capability of the single SDD cell, but it also implies the choice of any two-dimensional shape according to the requirements of the experiment like a linear chain for diffractometry (fig. 7b) or a closed ring (fig. 7c). The ring structure is the basic component of a compact XRF spectrometer: a sample is excited by an X-ray beam through a laser-cut hole in the center of the detector chip, and the SDD-ring receives the fluorescence photons covering a large fraction of the solid angle around the sample.

In a laboratory test the sum spectrum of the individual cells of a 7 channel McDrift with a total area of 35 mm^2 yielded a Mn-Kα FWHM of 160 eV at -20 °C. The development of a compact Peltier cooled detector module of that size is almost complete.

Multichannel SDDs have already been used at synchrotron light facilities as they are able to cope with the extremely high photon rates in fast counting applications like EXAFS [13] and X-ray holography [14, 15]. For the latter experiment a detector system based on McDrift is currently in production. In the final configuration a total number of 1000 SDDs grouped in 61 channel McDrift chips will cover almost the complete sphere around the sample. For the readout of this system the amplifier chip ROTOR (**ro**tational **t**rapez**o**idal **r**eadout) based on JFET-CMOS technology has been developed [16, 17]. ROTOR is able to handle the random asynchronous event occurence of a large number of SDDs with low read noise at count rates exceeding 10^5 cps per channel. A ROTOR prototype connected to a single cell SDD yielded a Mn-Kα FWHM of 190 eV to be compared with 162 eV obtained by conventional electronics.

A γ-ray camera using Silicon Drift Detectors

The use of SDDs for the detection and spectroscopy of photons is on the high energy end restricted to 20 to 30 keV, limited by the low atomic number of silicon and the detector thickness, which is 300 µm. For hard X-rays and γ-rays either direct converting detectors of high-Z materials like Cd(Zn)Te have to be used or indirect converting systems like scintillators coupled to photomultiplier tubes (PMTs). Recently the scintillation detectors experienced a step forward in performance by replacing the PMT by a SDD used as low-capacitance photon detector for the scintillation light. That way not only the known practical problems of PMTs like requirement of space, incompatibility with magnetic fields, and the necessity of a high voltage are avoided, but also the quantum efficiency and energy resolution of the system are improved [17]. The transmittance of the SDD entrance window can be tuned by deposition of anti-reflective coatings to the emitted wavelengths of a wide range of scintillators [8].

The existence of pixellated large area detectors like SDDs of the McDrift type makes it now possible to realise γ-ray cameras as proposed by Anger [18]. In this application a single non-structured scintillator is mounted on a Multichannel Drift Detector. The scintillation light generated by the absorption of an energetic photon is seen by at least a number of detector cells. The position of the γ-ray interaction is calculated by the centroid method and the γ-energy is obtained by summing the detector cell signals. By the combination of a CsI(Tl)-scintillator with the linear chain McDrift of fig. 7b a one-dimensional position resolution of 0.36 mm FWHM can be achieved [19]. Measurements with two-dimensional systems are on the way. Compared to direct converting pixellated Cd(Zn)Te detectors with equal position resolution the scintillator-SDD combination requires a considerably lower number of readout channels. In addition it has the advantages of comprehensive material experience, existing technologies, proved long term stability, and practically unlimited availability of high quality material.

Conclusions

Silicon Drift Detectors (SDDs) for X-ray spectroscopy are unequalled in the combination of their properties. They are working at room or moderately low temperature, don’t require liquid nitrogen cooling or vacuum environment, exist in a compact and easy-to-use setup, and are at least a factor ten faster than conventional systems based on PIN diodes or Si(Li) detectors. With respect to energy resolution SDDs are principally better than PIN diodes, they already come close to Si(Li) detectors, which are significantly higher in costs.

In a number of scientific and industrial applications, where high count rates appear or relaxed operating conditions are required, SDDs have become well established. Multichannel Drift Detectors (McDrift) led to the proposal and realisation of new experiments and systems, like X-ray holography and Anger-type scintillation cameras.

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Figure captions

Figure 1

Cross section of a cylindrical Silicon Drift Detector (SDD) for X-ray spectroscopy. Electrons are guided by an electric field to the collecting anode in the center.

Figure 2

Calculated potential energy for electrons in the SDD shown in fig. 1. The entire volume is depleted and sensitive to ionising radiation. Electrons drift to the collecting anode, which is the point of lowest potential energy.

Figure 3

Measured energy resolution of SDDs with external amplifier. The μsec-numbers are the optimum shaping time constants at the given temperatures.

Figure 4

^{55}Fe spectrum recorded with a 10 mm^2 SDD with external amplifier at –20 °C. The FWHM of the Mn-Kα line is 190 eV, the peak-to-background ratio is 11000.

Figure 5

Measured energy resolution values of more than 300 SDDs with integrated FET. The μsec-numbers are the optimum shaping time constants at the given temperatures.

Figure 6

Dependence of the energy resolution of a SDD with integrated FET on the rate of incoming photons.

Figure 7

Different shapes of McDrift (Multichannel Drift Detector):

a.) hexagon, 19 cells, 1 cm^2; b.) linear chain, 6 cells, 30 mm^2; c.) ring, 12 cells, 60 mm^2

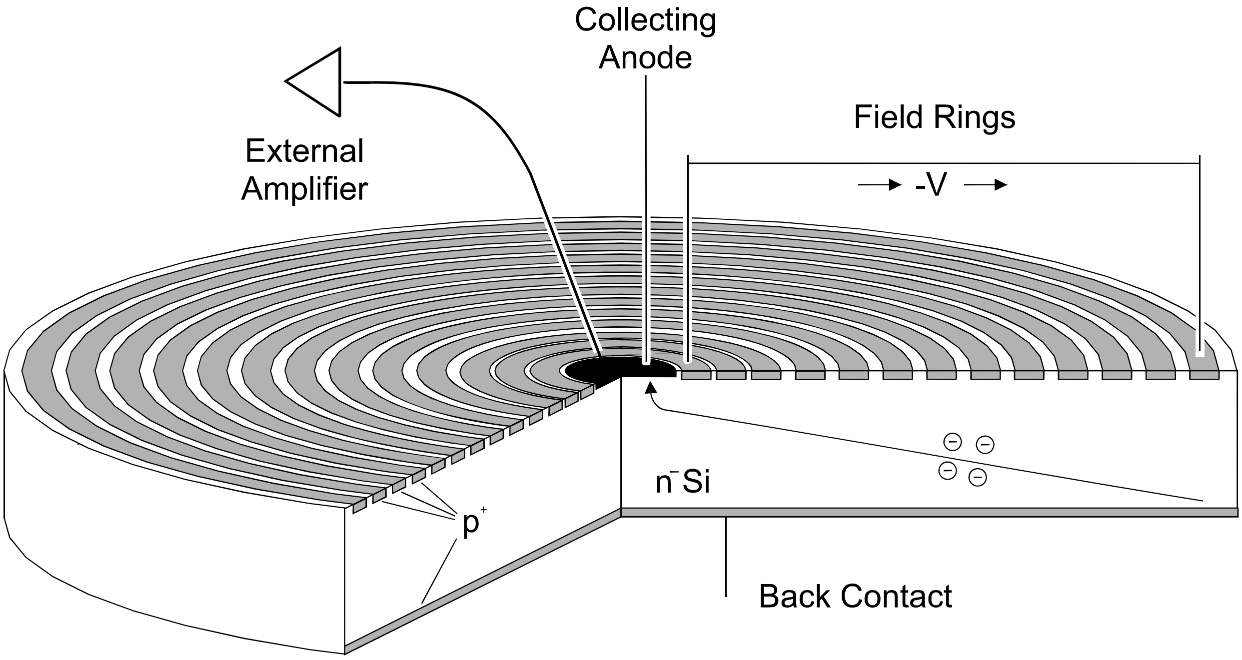
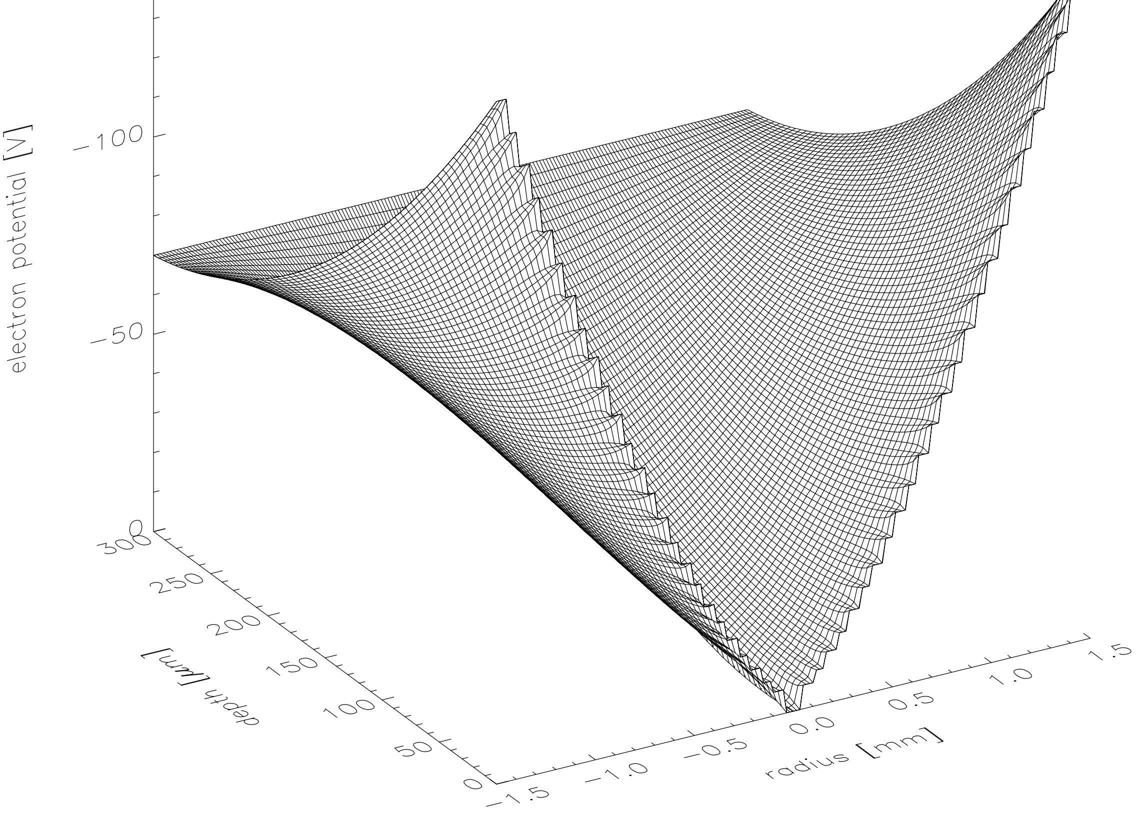
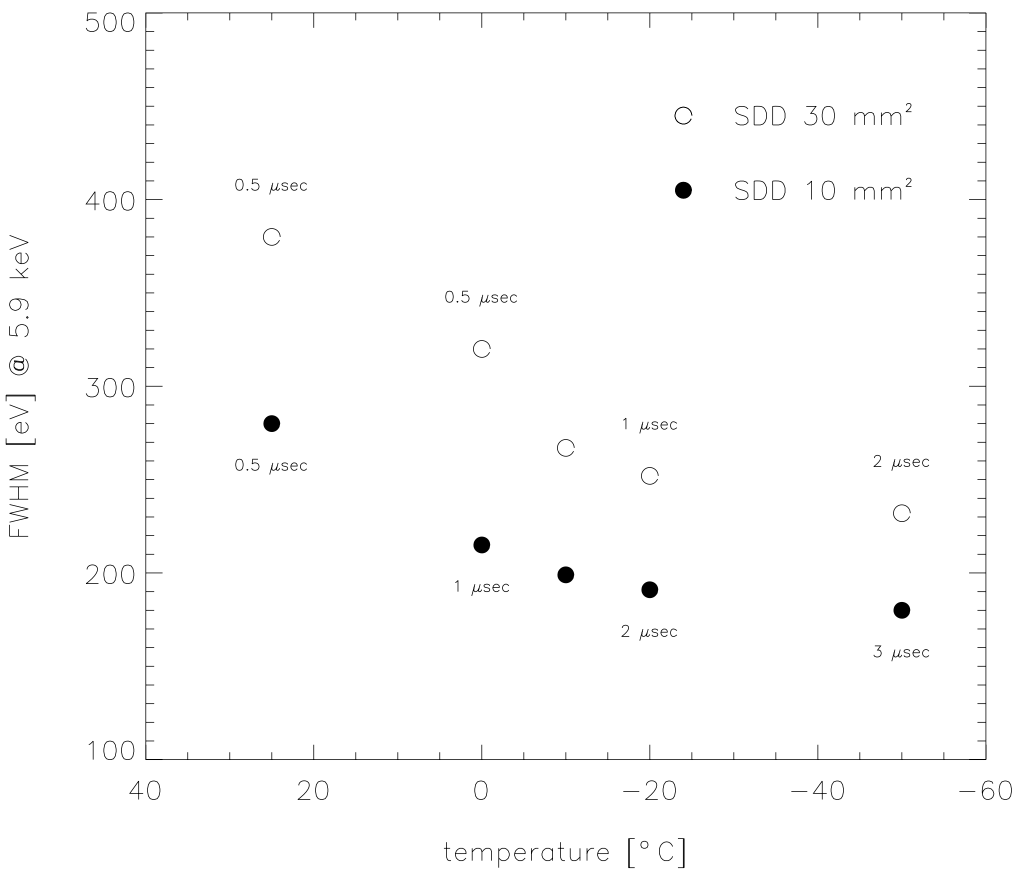

Collecting
Anode
Field Rings
External
Amplifier
-V
n⁻Si
p⁺
Back Contact

Fig. 1



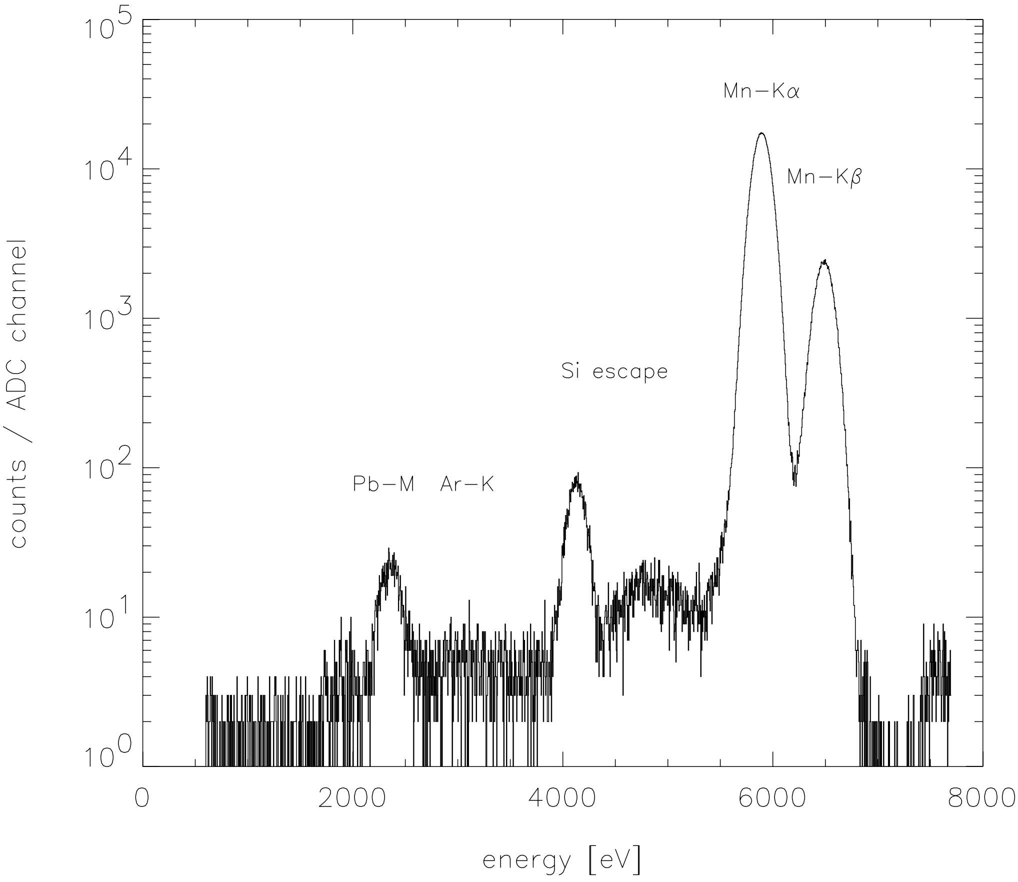
electron potential [V]
−150
−100
−50
0
depth [μm]
300
250
200
150
100
50
0
radius [mm]
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5

Fig. 2



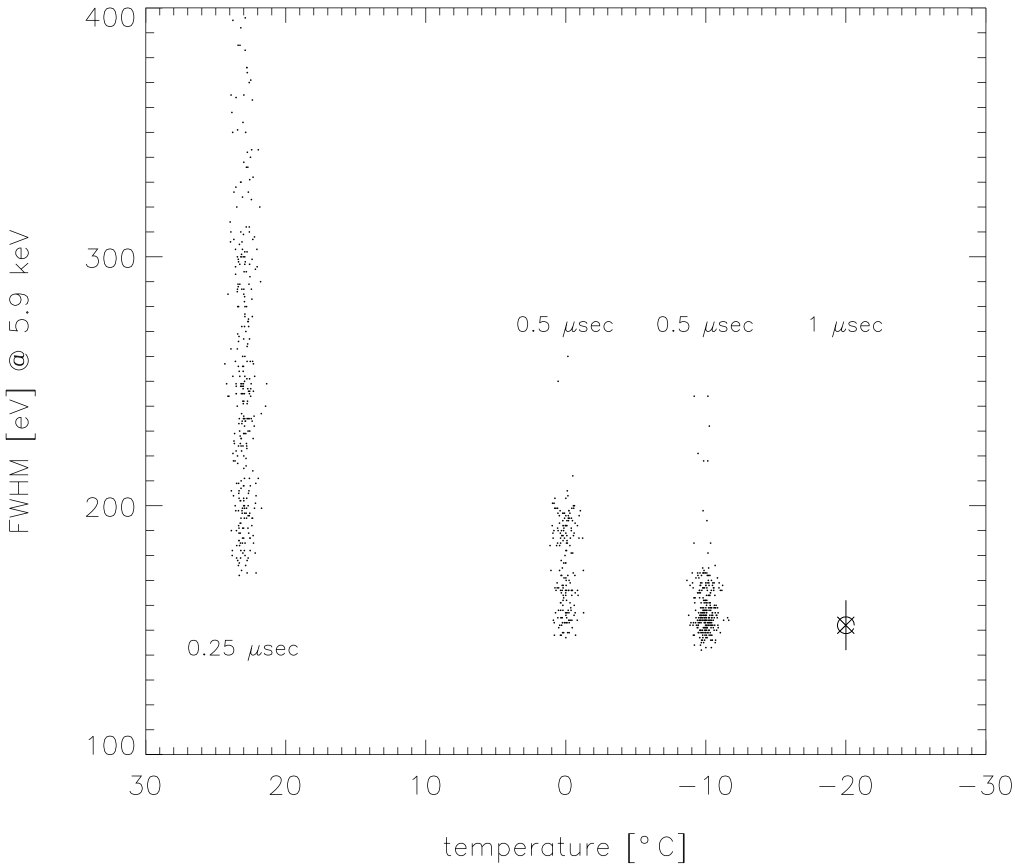
500
400
300
200
100
40
20
0
−20
−40
−60
FWHM [eV] @ 5.9 keV
temperature [°C]
SDD 30 mm²
SDD 10 mm²
0.5 μsec
0.5 μsec
0.5 μsec
1 μsec
2 μsec
1 μsec
2 μsec
3 μsec

Fig. 3



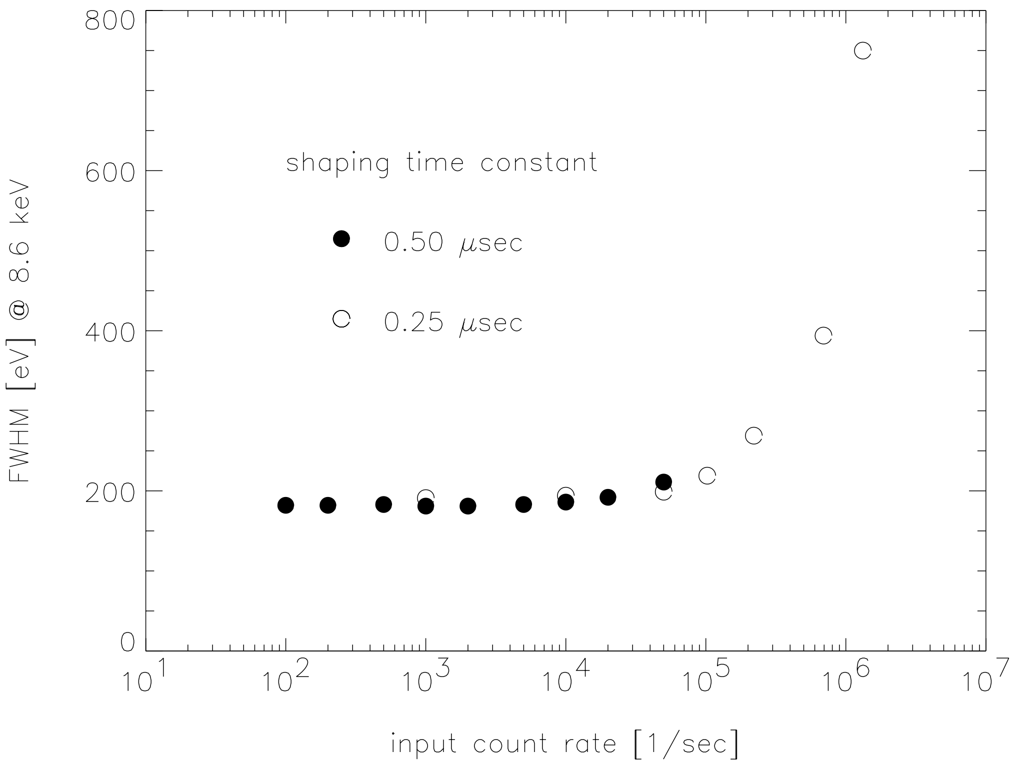
Mn−Kα
Mn−Kβ
Si escape
Pb−M
Ar−K
counts / ADC channel
energy [eV]
10^5
10^4
10^3
10^2
10^1
10^0
0
2000
4000
6000
8000

Fig. 4



400
300
200
100
30
20
10
0
−10
−20
−30
FWHM [eV] @ 5.9 keV
temperature [°C]
0.25 μsec
0.5 μsec
0.5 μsec
1 μsec

Fig. 5



800
600
400
200
0
FWHM [eV] @ 8.6 keV
shaping time constant
0.50 μsec
0.25 μsec
10^1
10^2
10^3
10^4
10^5
10^6
10^7
input count rate [1/sec]

Fig. 6

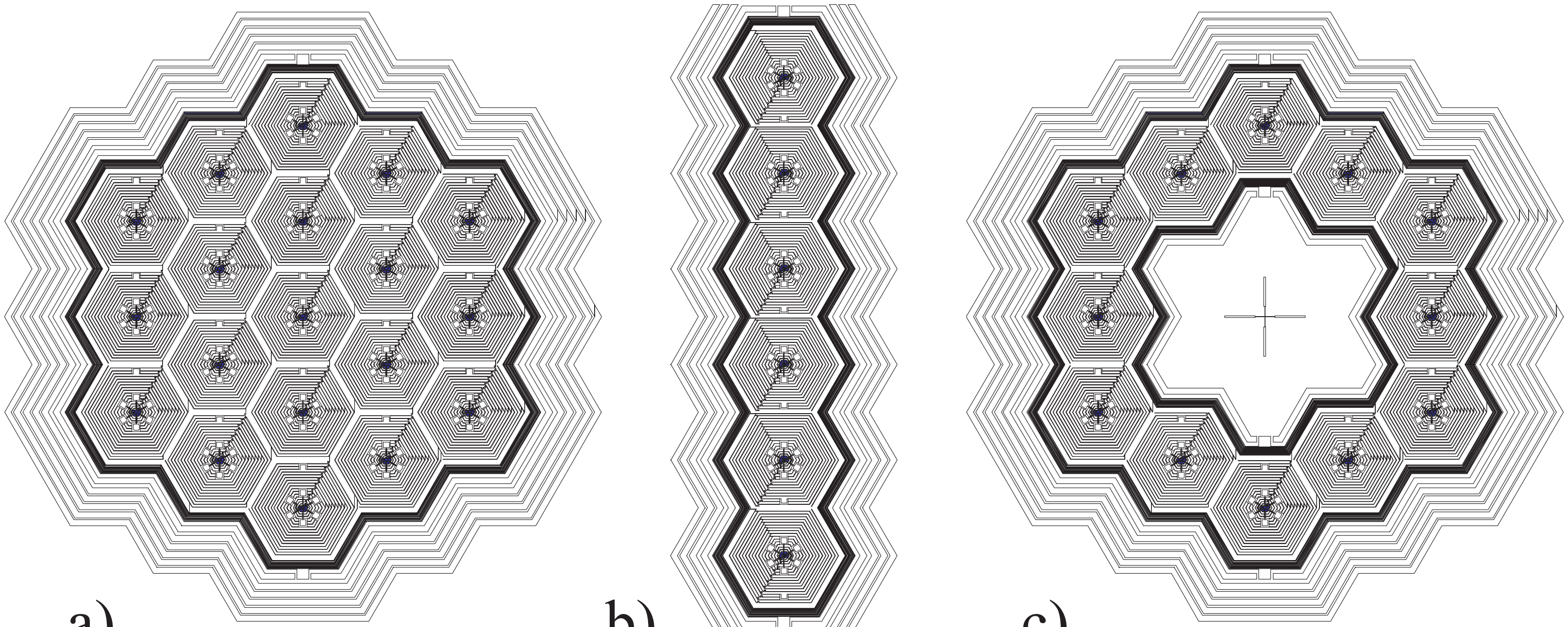

a) b) c)

Fig. 7