

Abstract—In this work we present the results of the experimental characterization of Silicon Drift Detectors (SDDs) readout by CUBE preamplifiers for X-ray spectroscopy measurements. One specific goal of the work was to characterize SDDs of different sizes cooled at low temperature in view of their use in the upgrade of the SIDDHARTA nuclear physics experiment. Beside the target application, the results of this work are also of interest for a more extended use of the SDDs in other X-ray spectroscopy applications. The SDDs have been designed as single units with square shape of different areas, 64 mm^2 ($8 \text{ mm} \times 8 \text{ mm}$) and 144 mm^2 ($12 \text{ mm} \times 12 \text{ mm}$), and also as monolithic array of 3×3 elements of the $8 \text{ mm} \times 8 \text{ mm}$ unit (total area $26 \text{ mm} \times 26 \text{ mm}$). The read-out of the SDDs is based on a CMOS (Complementary Metal Oxide Semiconductor) preamplifier (CUBE) both for the single unit and for the 3×3 array. For the readout of the array, an Application Specific Integrated Circuit (ASIC) has been used. An energy resolution better than 124 eV at the Mn – $K\alpha$ line has been measured with a 64 mm^2 SDD cooled at the temperature of 50 K. The energy resolution remains good ($< 130 \text{ eV}$) also at short shaping time (250 ns) thanks to the noise feature of the CUBE preamplifier. Results of measurements on SDDs of different format and also on arrays of SDDs are presented in this work.

Index Terms—Charge preamplifier, silicon drift detectors, X-ray spectroscopy.

I. INTRODUCTION

THE development of Silicon Drift Detectors (SDDs) for high-resolution X-ray spectroscopy is still a domain of intense research work [1]–[4]. This work deals specifically with the use of SDDs in the SIDDHARTA experiment for nuclear physics studies, although conclusions may be of interest for a more extended use of these devices in other X-ray spectroscopy applications (e.g. with synchrotron light).

In the SIDDHARTA experiment, high precision X-ray spectroscopy measurements of the transitions in kaonic atoms are

performed to determine the transition yields and the strong interaction induced shift and width of the lowest experimentally accessible level [5]. The kaonic atoms are formed whenever a beam of negatively charged kaons, originating from a particle accelerator (in SIDDHARTA the DAΦNE $e^- - e^+$ collider in Frascati, Italy) enters a gaseous target: the kaons lose their kinetic energy via interactions with the matter atoms, up to when they are captured by one of the target atoms replacing an electron and thus forming the kaonic atom. The kaon mass is about 1000 times bigger than the electron mass. The orbit in which the kaon, replacing the electron, is captured is a highly excited one. It follows then a series of de-excitation processes of the kaonic atom. In the last transition (from the level $n = 2$ to $n = 1$, the fundamental level) X-rays are generated and measured in the SIDDHARTA apparatus.

The interaction between kaon and nucleus does not depend only on the electromagnetic (EM) interaction (as the electron) but also on the strong interaction. This results in a shift in the measured X-ray spectrum with respect to the one depending on the EM interaction only, allowing us to study the strong force between the kaon and the nucleus at very low energies [6].

In the first SIDDHARTA-1 apparatus, the SDDs were manufactured at the Semiconductor Laboratories of the Max Planck Institut of Munich (Germany) and they were characterized by a readout based on a JFET (Junction Field Effect Transistor) integrated in the detector [7]. Those detectors were assembled in monolithic modules with three $1 - \text{cm}^2$ active area SDDs, for a total area of 144 cm^2 (and therefore 144 channels). For the future upgrade of the experimental set-up, called SIDDHARTA-2 [8], a new SDD development is ongoing. It is based on SDDs recently designed and manufactured by the Fondazione Bruno Kessler (FBK). A first production run of devices with different sizes, both individual elements and monolithic arrays of more units, was made in the framework of a project supported by the European Space Agency (ESA), aimed to evaluate SDDs as photodetectors of large LaBr_3 scintillator crystals. The performance of single SDDs of this production used for gamma ray spectroscopy has already been reported [9].

In this work we report about the performance of both single units of these new SDDs, with different sizes, as well as of arrays of SDDs, in X-ray spectroscopy measurements at cryogenic temperatures. Low temperature operation is needed in SIDDHARTA-2 to speed-up the drift time of the charge inside the SDD (due to the increase of the electron mobility at low temperature). A short drift time, in fact, minimizes the timing uncertainty due to the random position of the X-ray interaction in the SDD, allowing the shortening of the coincidence window

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R. Quaglia, P. Busca, C. Fiorini, and M. Occhipinti are with the Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria and with INFN Sezione di Milano, Milan, Italy (e-mail: carlo.fiorini@polimi.it).

L. Bombelli is with XGLab s.r.l., Milan, Italy.

G. Giacomini, F. Ficorella, A. Picciotto, and C. Piemonte are with Fondazione Bruno Kessler (FBK), Trento, Italy.

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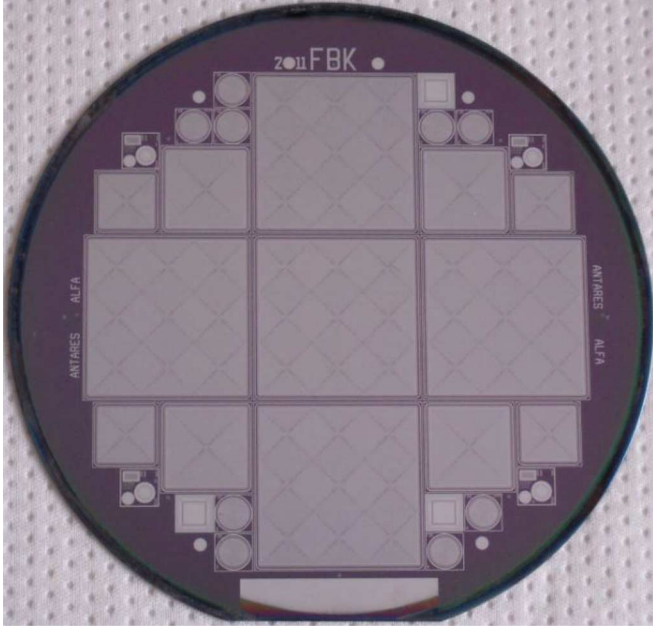


Fig. 1. 4" wafer produced by the FBK Semiconductor Laboratories. Different structures can be identified: round shaped 10 mm^2 , square shaped $8 \times 8 \text{ mm}^2$, $12 \times 12 \text{ mm}^2$ single anode SDD and a monolithic array of nine SDDs in a 3×3 format ($8 \times 8 \text{ mm}^2$ active area each, for a total $26 \times 26 \text{ mm}^2$ including dead areas).

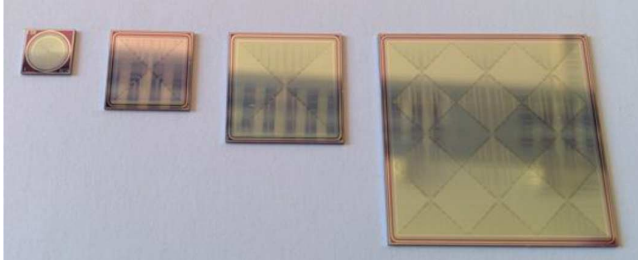


Fig. 2. Different SDDs chips, from left to right: 10 mm^2 round-shaped, 64 mm^2 and 144 mm^2 square-shaped and the 3×3 array of 64 mm^2 units.

with a kaon trigger which is used to reject the radiation background.

Fig. 1 shows a picture of a 4" wafer produced by FBK (now the production process has been upgraded to 6" wafers). The single square shaped SDDs are designed with two different active areas: 64 mm^2 ($8 \times 8 \text{ mm}^2$) and 144 mm^2 ($12 \times 12 \text{ mm}^2$). The monolithic array is composed by 9 SDDs, $8 \times 8 \text{ mm}^2$ each, in a 3×3 square format (total area $26 \times 26 \text{ mm}^2$). Also 10 mm^2 circular SDDs are visible in the wafer layout, and they have been used for the characterization of the noise performances of the CUBE preamplifiers. Fig. 2 shows a picture of the three chip structures described above, after wafer cutting. The chip detectors are produced on $450 \mu\text{m}$ thick wafers in a process with an average leakage current of 2 nA/cm^2 (value at depletion voltage) at room temperature.

The back entrance window of the devices in this production has been optimized with a shallow entrance window with a further implementation of an ARC (Anti-Reflective-Coating) layer in order to optimize the quantum efficiency ($> 80\%$) at the emission wavelength of the $\text{LaBr}_3:\text{Ce}$ scintillator (380 nm)

foreseen for the γ -ray application. Such shallow entrance window is considered to be suitable also for soft X-rays measurements.

All the detectors are mounted on a custom ceramic carrier which provides all the bias signals and allows also the direct connection of each SDD to the custom CMOS (Complementary Metal Oxide Semiconductor) preamplifier, placed in the near proximity with respect to the SDD anode. The readout of the SDDs is based on the CMOS preamplifier CUBE [10] developed at Politecnico di Milano. This circuit provides similar or even superior performances in terms of electronics noise with respect to the more conventional JFET readout, in particular at short shaping times. Such performances are based on the high transconductance of the input PMOSFET (P-type Metal Oxide Semiconductor Field Effect Transistor) which compensates for the larger capacitance introduced by the connection of the SDD to an external FET.

To readout monolithic arrays of SDDs, an ASIC (Application Specific Integrated Circuit), originally developed for γ -ray applications [11], has been used for the acquisition of the nine channels in parallel. The experimental set-up is completed by a custom data acquisition (DAQ) system which allows the simultaneous collection of the X-ray spectra from the SDDs of the array. The DAQ system is also described in ref. [11].

The paper is organized in the following way. In the second section, the best performances measured with the CUBE preamplifier connected to circular SDDs of 10 mm^2 active area are reported. In the third section, the results of the experimental characterization at low temperatures of the square SDDs with 64 mm^2 and 144 mm^2 area are reported. In the fourth section, preliminary results of the measurements with the monolithic arrays are presented. Conclusions and future work are discussed in the last section of the paper.

II. X-RAY SPECTROSCOPY WITH CUBE PREAMPLIFIER

CUBE is a monolithic charge preamplifier equipped with a PMOSFET input transistor optimized to reach the best noise performances [10], [12]. The small CUBE die (1 mm^2) includes the whole preamplifier and not only the input FET. This feature allows to provide already at the output of the detection module the output waveform of the preamplifier without additional stages and to drive the signal at relatively long distance (tens of cm) up to the following processing unit (analog or digital processor). This feature is of particular interest when arrays of SDDs have to be connected to the readout electronics because it relaxes the distance constraints between detector and readout ASICs. This solution only requires a placement of the preamplifier die very close to the detector, similar to the conventional mounting used for an external JFET. Compared to the SDD with a JFET integrated directly on the detector chip [13], this solution is compatible with a simpler detector manufacturing technology, i.e. characterized by a smaller number of processing steps. With regard to noise performance, the CUBE preamplifier used with an SDD has already demonstrated very good results, in particular at short shaping times. In fact, the high transconductance of the input PMOSFET compensates for the parasitic capacitance introduced by the connection between SDD and preamplifier input, which is larger in comparison to the solution with the

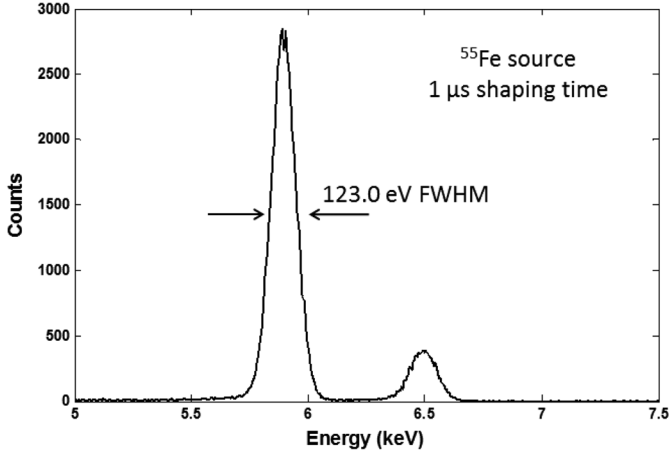


Fig. 3. Energy spectrum of the ^{55}Fe calibration source measured with a round shaped detector cooled to 233 K. The shaping time of the filter is $1\ \mu\text{s}$. The corresponding Equivalent Noise Charge (ENC) is $3.7\ e^-_{\text{rms}}$.

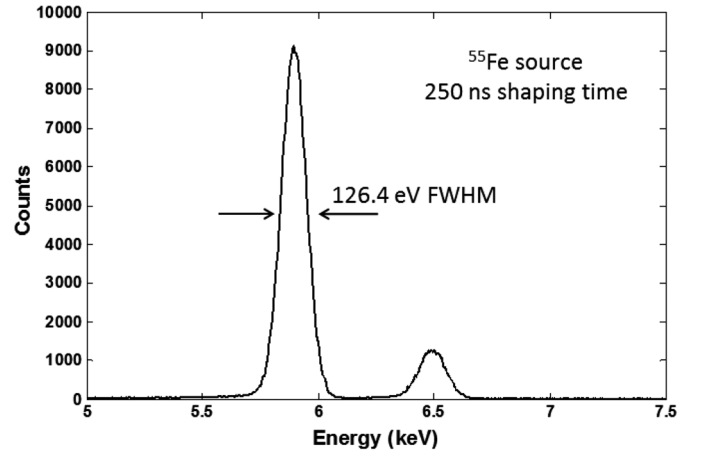


Fig. 4. Energy spectrum of the ^{55}Fe calibration source measured with the shortest shaping time available of 250 ns, also at 233 K. ENC is equal to $5.0\ e^-_{\text{rms}}$.

JFET integrated on the SDD chip. Moreover, an input MOSFET in the preamplifier can be considered more suitable than a JFET in operations at cryogenic temperatures [14], [15], like the ones foreseen for the SIDDHARTA experiment ($< 50\ \text{K}$).

CUBE operates in a pulsed reset regime with a MOS transistor periodically resetting the charge accumulated on the feedback capacitance due to leakage current and signals. The reset may be applied periodically or can be triggered when the output ramp overcomes a given threshold voltage. Upon application of the reset, the dead time of the preamplifier to recover normal operations becomes less than $1\ \mu\text{s}$.

A new version of CUBE has been designed for this project, with the noise of the input PMOSFET further minimized and with a number of pads reduced to the minimum necessary to further simplify interconnections in the mounting of SDD arrays. The only CUBE pads are: input, output, reset, bias, and ground. The power consumption of the circuit is 6 mW.

X-ray spectroscopy characterizations with the new version of the CUBE preamplifier have been made using a round-shaped SDD with $10\ \text{mm}^2$ active area from the same wafer shown in Fig. 1. For this test, the SDD has been cooled with a Peltier cell (Laird, model MS-11) to a temperature of 233 K. The output of CUBE has been connected to a Tennelec TC244 spectroscopy amplifier.

Fig. 3 reports the spectrum of the ^{55}Fe calibration source measured with the optimum shaping time of $1\ \mu\text{s}$. The measured energy resolution at the 5.9 keV peak is $123.0 \pm 0.1\ \text{eV}$ (the uncertainty is given by the Matlab Gaussian fitting tool). Fig. 4 reports an energy resolution measured with 250 ns shaping time, the shortest available in the filter. The energy resolution is $126.4 \pm 0.1\ \text{eV}$ which is, to the best of our knowledge, the best result for an SDD for such a short shaping time. All the measurements are obtained with an uncollimated source.

III. SINGLE SQUARE-SHAPED SDDS

Square shaped SDDs of different active areas have been tested with the CUBE preamplifier. These detectors have been tested in a vacuum chamber with a cryostat which allowed to reach temperatures down to 50 K. The used cryostat is a

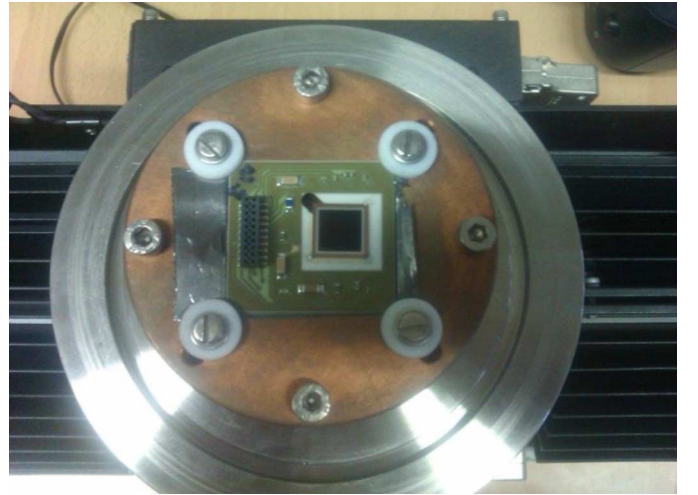


Fig. 5. Photograph of the SDD mounted in the set-up for measurements at low temperatures. The ceramic carrier hosting the SDD is fixed on the cool finger of the cryostat which is mounted into a flange of the vacuum chamber.

twin piston linear integral stirling cryocooler (RICOR, model K535). The temperature is stabilized by a controller integrated in the cryostat. In Fig. 5, a photograph of the SDD mounted on the ceramic board and connected to the copper cool finger of the cryostat is shown.

Fig. 6 shows the FWHM energy resolution measured at the Mn- $K\alpha$ line with the $64\ \text{mm}^2$ detector cooled at different temperatures, from 240 K down to 50 K. The SDD and the CUBE preamplifier were still perfectly operational when cooled to the minimum temperature of 50 K achievable by the cryostat. From the figure, it can be noted that the contribution of the leakage current to the electronic noise can be considered practically negligible at temperatures below 200 K. The quite steep worsening of energy resolution at short peaking times for temperature above 160 K is mainly due to the effect of the ballistic deficit occurring in this quite large detector. In fact, during the drift of the charge, the width of the electrons packet enlarges and only part of the charge is integrated at short shaping times. At lower temperatures, the drift time of the charge in the SDD

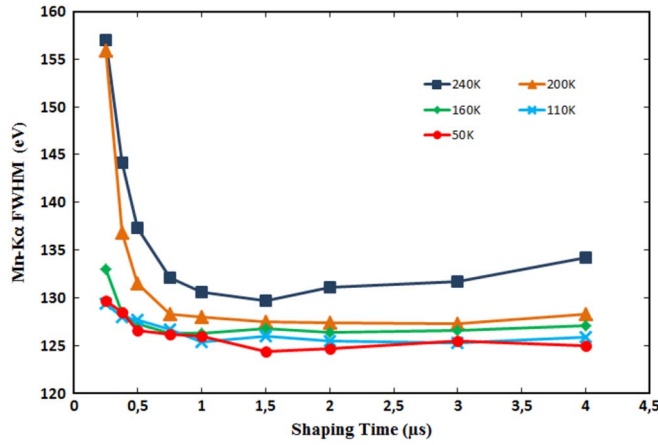


Fig. 6. Energy resolution measured at different shaping times of the filter with the 64 mm² SDD cooled at different temperatures between 240 K and 50 K. ⁵⁵Fe uncollimated source has been used.

is reduced due to the increase of the electron mobility in the silicon and the effect of the ballistic deficit is reduced, leading to better spectroscopy performances at short shaping times.

We have also compared the performances of the SDD when biased in two different modalities: with the direct application of the voltage to the back electrode by means of a bonding wire, or by biasing the detector with the punch-through technique [16]. In this latter case, the biasing of the back electrode can be made without a dedicated bonding on the back side but by creating an electrical connection between the last ring of the front side (which is biased at the most negative voltage) and the back electrode. The punch-through between these two electrodes is obtained when the last ring is biased over the depletion voltage of the wafer. This alternative method, thanks to the avoidance of the bonding on the back side of the detector, allows to reduce the dead area in the hybrid, which is of particular importance when monolithic arrays are assembled side by side.

Fig. 7 shows the comparison of the energy resolution measured at the temperature of 160 K with the same SDD biased with one or the other of the two different methods. No relevant differences are noticeable using one method or the other (this has been further verified at lower temperatures). In both cases, the resolution is very good, with only 6 eV of difference from 0.5 to 12 μs shaping time. The spectrum with the best energy resolution of 123.8 ± 0.5 eV measured at 12 μs shaping time is shown in Fig. 8.

Also the 12 × 12 mm² (144 mm² active area) SDD has been successfully tested at low temperatures with an energy resolution similar to the one measured with the 8 × 8 mm² prototype. At a temperature of 60 K, 124.7 ± 0.1 eV and 130.4 ± 0.2 eV have been measured with shaping times of, respectively, 4 μs and 500 ns.

Despite the fact that the larger SDD shows similar energy resolution to the smaller one, for the SIDDHARTA experiment most probably the 8 × 8 mm² size will be adopted as the maximum drift time is about a factor 2 smaller than in the 12 × 12 mm² format. The maximum drift time, in fact, rises approximately with the square of the side of the device [9]. A lower drift time is preferable to improve the timing capability of the

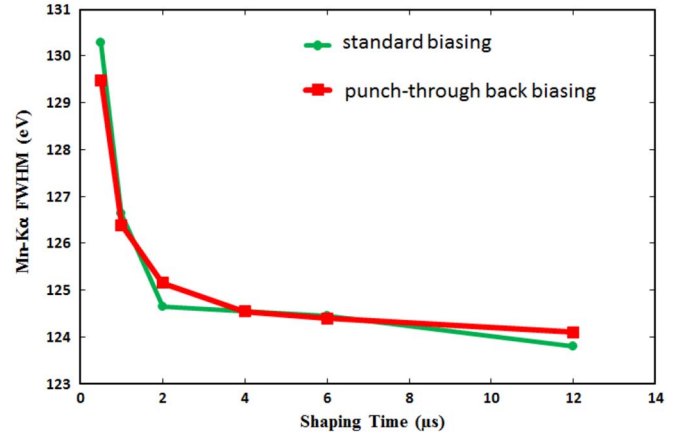


Fig. 7. Energy resolution vs. shaping time of the filter with the same 64 mm² SDD back biased with two methods: standard (with bonding) and by punch-through mechanism (without bonding). ⁵⁵Fe uncollimated source.

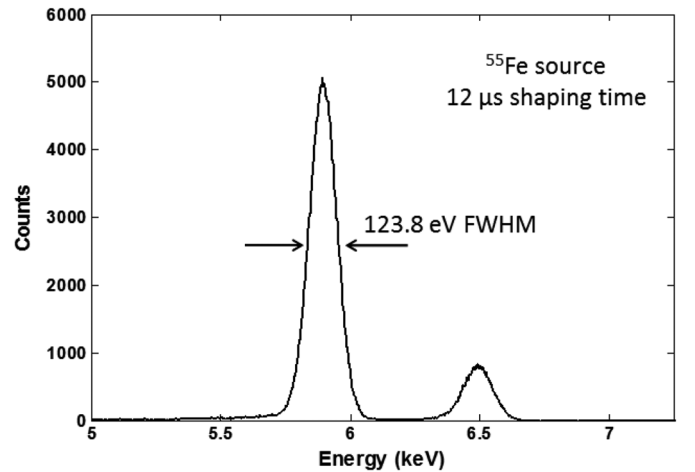


Fig. 8. ⁵⁵Fe spectrum measured with the 64 mm² SDD at 160 K and with a shaping time of 12 μs. $T = 160$ K.

detector used for background rejection, as already mentioned in the first paragraph.

The SIDDHARTA experiment requires a high precision in the spectroscopy measurements (e.g. less than 0.1% in the shift of the peak position) for long time periods, as the count rate of the useful events is very low and the data taking to record one spectrum can last some weeks. For this reason, stability measurements of the SDD coupled to the CUBE preamplifier have been performed.

The measurements consist of two different data acquisition of six days each using the same SDD (in this case the squared 144 mm² area) and preamplifier and keeping them in operation inside the vacuum chamber at the temperature of 100 K. The detector was acquiring ⁵⁵Fe spectra continuously with each independent spectrum acquisition lasting 30 minutes. Fig. 9 reports the position of the fitted Mn-Kα peak of the ⁵⁵Fe spectrum during the two acquisition periods while Fig. 10 shows the corresponding energy resolution FWHM of the peak. In both acquisitions, recorded with some days of difference and after switching off and on the detector, the vacuum system and the cooling, the variation of the peak position was in the order of 1

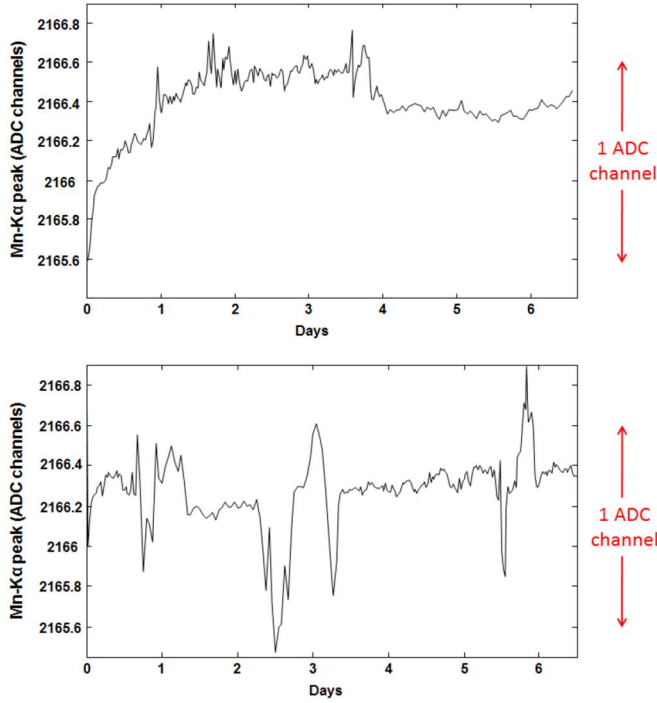


Fig. 9. Peak position (in ADC channels) of the Mn-K α line for two long acquisitions (reported separately in the upper and lower graphs). The SDD is the square-shaped device of 144 mm² active area.

ADC channel, i.e. below 0.1%. Also the energy resolution did not change significantly during the measurements.

IV. SDD ARRAY

In this section, the preliminary results of the experimental characterization of one prototype of the 3×3 SDD monolithic array, as the one shown on the right side of Fig. 2, are reported. Due to the number of processing channels to be adopted for parallel acquisition of all SDD units, we have used an analog processing ASIC and a DAQ system originally designed for a γ -ray application [11].

The ASIC includes 27 analog channels each one with a 7-complex-pole semi-Gaussian shaper, a baseline holder and a peak stretcher circuit. The relatively high order complex-poles shaper amplifier is necessary to guarantee both low noise and to reduce the dependence to ballistic deficit (which could be relevant in γ -ray detection, the original application of the electronics) with respect to more conventional CR-RCⁿ filters [17]. The circuit includes a 160 bits internal register completely programmable in order to choose between 4 different peaking times (2, 3, 4 and 6 μ s), 3 gain settings and other functionalities. A blocks diagram of the ASIC is shown in Fig. 11. The unused 18 channels with the 9-SDDs array were excluded during the acquisition. In view of a possible use of several SDD arrays, up to 3 arrays can be readout by a single ASIC and 9 arrays (about 52 cm² of total detector area) connected to 3 ASICs (81 channels) can be readout by the same DAQ system.

The array is mounted on a ceramic carrier which is then connected to a copper block in order to cool the detector by a Peltier stage, and thus, to reduce the leakage current. A photograph of

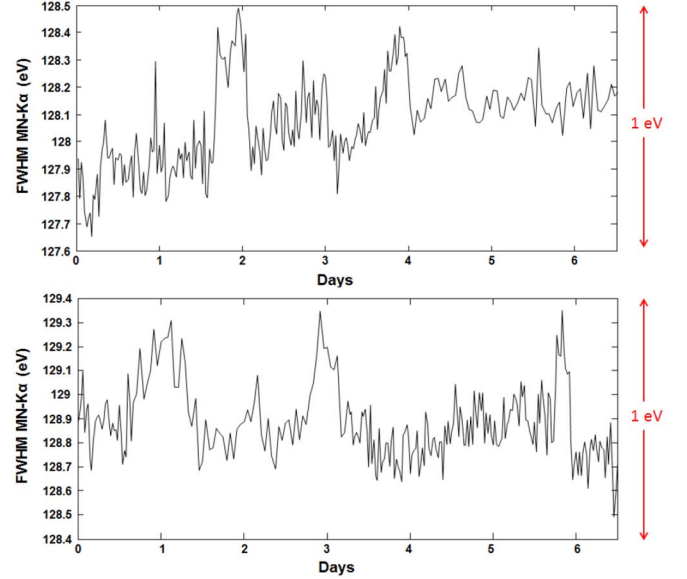


Fig. 10. Energy resolution of the Mn-K α peak for the two long acquisitions. The energy resolution is stable within 1 eV for all the measurements.

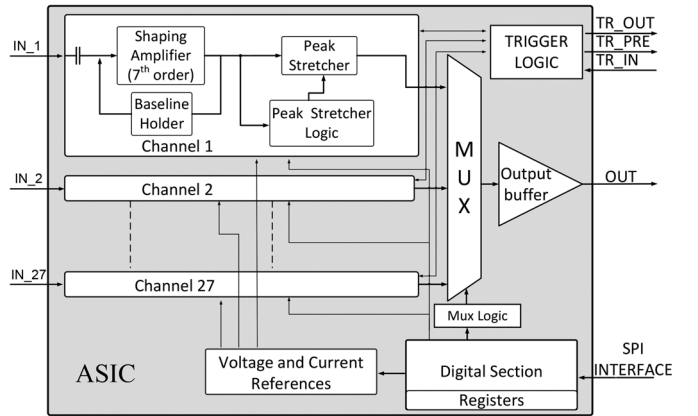


Fig. 11. ASIC diagram with the main blocks of the analog channel: shaping amplifier, baseline holder, peak detector. The circuit is completed with an analog multiplexer, an output buffer a digital section with SPI interface. The ASIC was produced in a standard CMOS 0.35 μ m by AustriaMicroSystem.

a module with copper block is shown in Fig. 12. It can be observed that the mounting concept allows to have the cross-section of the detector module limited by the area of the silicon area only and not by the extension of the ceramic carrier. The dead area of the module is therefore rather small (about 15%) and it allows a compact tiling of several modules to cover larger detection areas. This efficient assembly is achieved also by the use of the punch-through bias mechanism. This technique avoids the presence of the bonding on the back electrode of the detector, which is in common to all 9 units.

In the present experimental set-up developed for the characterization of the SDD array, the Peltier stage (Multicomp, model MCPF-161-12-10-E) was able to cool the detector to a minimum temperature of 243 K. At this temperature, the contribution to the electronics noise of the leakage current is still significant. Despite the expected non optimal resolution, a test of the array in this condition was considered still worth to do in order to evaluate the operation and initial performances of the array.

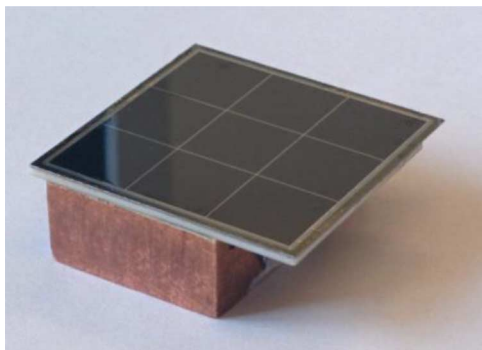


Fig. 12. Photograph of the detection module based on the monolithic array of 3×3 SDDs mounted on a ceramic carrier and on a metal block for connection to a Peltier stage.

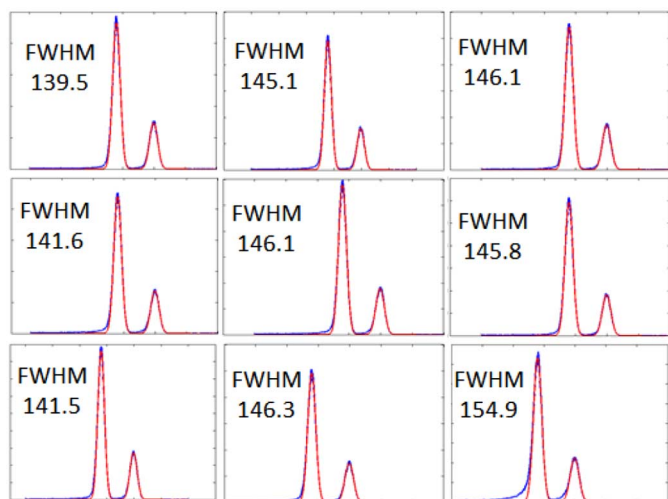


Fig. 13. ^{99}Fe spectra of all the nine channels of the SDD array acquired in parallel with the ASIC configured with $3 \mu\text{s}$ peaking time of the shaping filter. In all spectra, horizontal scale is energy and vertical scale is counts. The difference in energy resolution between channels is due to the different value of leakage current.

Fig. 13 shows the spectra acquired with a parallel acquisition of all the channels using $3 \mu\text{s}$ peaking time for the ASIC shapers. The average energy resolution for the 9 units is 145.2 eV FWHM and it is consistent with the resolution of a single 64 mm^2 detector with the same leakage current at the same temperature. The common biasing of all 9 SDDs seems not to produce penalties in the performances of each single unit, with the exception of the unit on the bottom-right corner of Fig. 13. The spectrum of this unit exhibits a tailing in the spectrum, most probably due to a non optimum biasing of such unit. Additional tests on more samples will be necessary to further investigate this issue.

V. CONCLUSION

In this work, we have presented the results of the experimental characterization of SDDs recently produced at FBK in view of their possible use in X-ray spectroscopy applications. One application of these devices is the upgrade of the SIDDHARTA experiment. For this purpose, square shaped SDDs of different size, 64 mm^2 and 144 mm^2 , with a front-end readout

based on CUBE preamplifier, have been successfully tested in the range of cryogenic temperatures foreseen in the experiment, with a minimum temperature of 50 K .

The measured energy resolution with the 64 mm^2 detector was about 124 eV at 160 K , which is also a satisfactory performance for the experiment. The behavior of the energy resolution at different temperatures and shaping times has been reported in the work. The expected benefit of cooling for reduction of the drift time has been observed through the improvement of the energy resolution at short shaping times, where the effect of the ballistic deficit is more important. Also stability of the spectroscopy peak has been verified in continuous measurements lasting several days.

A monolithic array based on 3×3 SDDs of 64 mm^2 each has been tested with the moderate cooling allowed by the present set-up. At 243 K , an average energy resolution of 145 eV among the nine channels has been measured and it is consistent with the leakage current contribution which is still relevant at this temperature. This result shows that arrays of SDDs, although not yet operated at cryogenic temperatures, do not show significant difference in performances with respect to the single units. Further tests of the array will be done with a new set-up under preparation which will allow operation of the arrays inside a vacuum chamber at cryogenic temperatures. Future work will also include the design of a multichannel readout ASIC optimized for X-ray spectroscopy using the SDD arrays.

This work has allowed also to explore the performances of new versions of CUBE preamplifier which has been tested with round shaped SDDs at 233 K . An optimum energy resolution of 123 eV at $1 \mu\text{s}$ shaping time has been obtained. A resolution of 126.4 eV has been measured at 250 ns shaping time, to the best of our knowledge, the best resolution achieved at such a short shaping time with an SDD. This last result shows the potential capability of this SDD in combination with CUBE to operate at high counting rates still with good energy resolution. This feature can be of interest in X-ray spectroscopy applications with high photon fluxes, e.g. at synchrotron light sources.

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