Silicon drift detector – the key to new experiments

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Originally designed as position-sensitive detectors for particle tracking, silicon drift detectors are nowadays used for high-count-rate X-ray spectroscopy, operating close to room temperature. Due to their low-capacitance read-node concept, they are among the fastest high-resolution detector systems. They have opened a new spectrum of experiments in the wide field of X-ray spectroscopy: fluorescent analysis, diffractometry, material analysis, synchrotron experiments and X-ray holography. In addition, the detection of visible light, near-infrared light and UV light is measured with high efficiency. The low-noise readout of the light of scintillation crystals extends the spectrum of possiblities to the hard X- and gamma-ray spectrum. The fact that the detector system can be used at room temperature with good spectroscopic performance, and at –10°C with excellent energy resolution, avoiding liquid nitrogen for cooling and high-quality vacuum, guarantees a large variety of new applications, independent of the laboratory environment. A brief description of the device principles is followed by basics on low-noise amplification. The performance figures of a complete detector system are presented along with some already realized dedicated applications, with emphasis on a recently operated "mini-spectrometer" for the analysis of works of art.

The silicon drift detector principle

In 1983, Gatti and Rehak [1] proposed a new detector scheme based on sideward depletion. The idea is that a large semiconductor wafer of high resistivity, e.g. n-type silicon, can be fully depleted by a small n^+ ohmic contact positively biased with respect to the p^+ contacts covering both surfaces of the silicon wafer.

In the standard configuration, the depletion zones will expand from all rectifying junctions simultaneously as long as the ohmic access from the n^+ anode to the entire (non-depleted) bulk is not interrupted. At a given voltage, the depletion zones propagating from the p^+ areas touch each other. Under this condition, the former conducting electron channel symmetrically located in the middle of the substrate between the p^+ implants will abruptly disappear. At this moment, the depletion of the whole wafer is completed at a voltage which is four times lower than the voltage needed to deplete a simple diode of the same thickness. Under the above-described condition, the electron potential energy in a section perpendicular to the wafer surface has a parabolic shape, with an electron potential minimum in the middle of the wafer.

The silicon drift detector (SDD) is derived from this principle of sideward depletion by adding an electrical field parallel to the surface. This is simply achieved by a segmentation of both or one of the p^+ areas to form a strip pattern and superimposing a voltage gradient on the strip system. The direction of the voltage gradient is such that the n^+ readout anode is the point of minimum potential energy for electrons therefore collecting all signal electrons generated in the depleted volume.

The main advantage of the SDD compared to a standard diode of equal size is the small value of the anode capacitance which is practically inde-

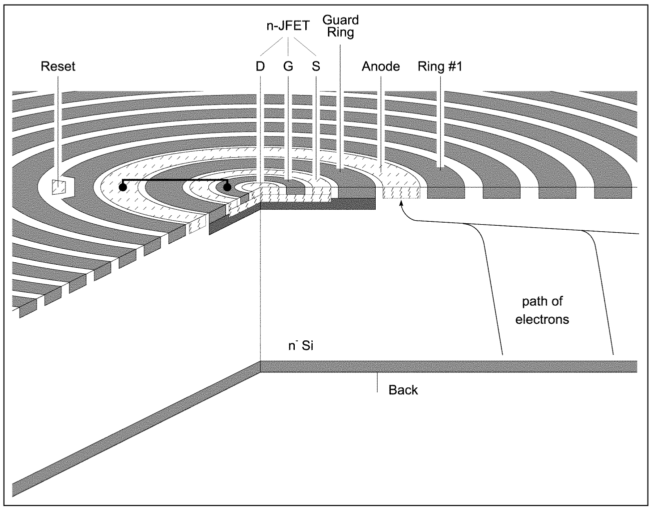

Fig. 1. Central area of a cylindrical silicon drift detector with an integrated amplifier for spectroscopic applications. The entire silicon wafer is sensitive to radiation

pendent of the total area of the device. This feature translates in a shorter rise time and bigger amplitude of the output signal for a given amount of collected electrons, i.e. the signal is less subject to noise of subsequent electronic components.

With the SDD principle, the designer has great flexibility in the choice of anode configurations and drift directions. For instance, at the semiconductor laboratory of the Max Planck Institutes (MPI-HLL), large SDDs have been fabricated with linear drift geometry, i.e. parallel strips [2], up to 4.2×3.6 cm^2 and a 55-cm^2 cylindrical geometry on 4-inch wafers, in which electrons drift along the radial direction to one of 360 anodes placed at the wafer edge [3]. Both systems have been used as particle trackers. In this mode of operation, the position of the interacting particle is reconstructed by a measurement of the drift time of the electrons.

Silicon drift detectors for X-ray spectroscopy

In an advanced design, optimised for applications in X-ray spectroscopy and also realised by MPI-HLL, the strip system at one side has been replaced by a large area pn-junction, which is used as a homogeneous, very thin entrance window for the radiation [4, 5]. The electric field is generated by concentric cylindrical drift electrodes on the opposite side of the wafer forcing the signal electrons to a small-sized anode in the centre of

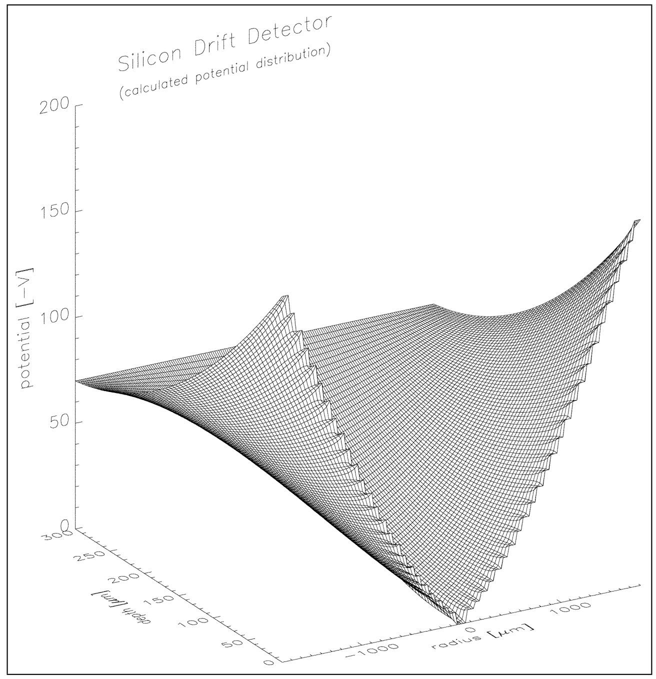

Fig. 2. Potential energy distribution in a silicon drift detector. The simulation applies to the whole detector shown in Fig. 1 including the electron-collecting readout node

the device. The potentials of the individual drift electrodes are defined by an integrated voltage divider, i.e. only the first and last p^+ ring must be contacted and biased externally (Fig. 1).

The electron potential of the cylindrical SDD is shown in Fig. 2 in a section perpendicular to the surface through the silicon wafer. It shows the potential energy for electrons of the device of Fig. 1 in operating condition, including all field strips and the central electron-collecting anode. The equipotential of the homogeneously doped radiation entrance window can be seen on the back, the field strips with their decreasing (negative) potential on the front side. There is no field-free region in the device, and all electrons in the sensitive area are guided within less than 100 ns towards the readout node.

The anode not only collects signal electrons generated by the absorption of radiation but also electrons which have been thermally generated within the depleted volume. The latter electrons make up a statistically varying leakage current and spoil the signals. Due to the elaborated process technology at MPI-HLL, the rate of thermal generation of charge carriers is so small that the device can be operated at moderate low temperature or without any cooling.

On-chip Amplification

The anode is connected to an amplifying field effect transistor (FET) integrated directly on the detector chip (see Fig. 1). This way, the capacitance of the detector-amplifier system is minimized by eliminating bond wires between detector and amplifier, thus avoiding all kinds of stray capacitances between the readout node and ground, making the system even faster and less noisy. Further advantages are evident, as the effect of electrical pick-up is significantly reduced and problems of microphony, i.e. noise by mechanical vibration, are excluded.
With the help of Fig. 1, the basics of the amplification process of the integrated FET can be easily understood. In the centre of the schematic drawing, a single-sided JFET is shown. Let us assume that electrons, generated by the ionising radiation, drift towards the readout anode. The voltage generated at the readout node is directly coupled to the p^+ gate of the n-channel transistor (source and drain are n^+ implants, the transistor channel is a deep n implant). The negative voltage on the p^+ gate reversely biases the junction, thus depleting the transistor channel, resulting in a current drop through the transistor. This change of current can be precisely measured.
As it collects more and more electrons, the FET gate gets increasingly reverse biased relative to the transistor channel. At a given potential difference, the gate is discharged by a breakdown of the gate-channel junction at the drain end of the channel. During detector operation, the gate adjusts its potential in a way that all signal and leakage current electrons are compensated by the breakdown mechanism. In other words, the integrated FET resets itself, there is no need for an externally clocked reset pulse, and the SDD is operated with d.c. voltages only.

SDD systems

A short summary of the SDD characteristics will lead us to new applications which have been initiated and made possible by this detector type. We have designed, fabricated and tested cylindrical drift detectors with integrated FET as shown in Fig. 1 [6]. They have an active area of 5 mm^2 and a thickness of 300 μm. At room temperature, the intrinsic noise figures are in the order of 15 e^- translating in a width of the ^{55}Fe Mn K_α line (5.9 keV) of 180 eV at a shaping time of 0.25 μs. The bulk leakage current at 300 K contributing to the system noise is less than 1 nA/cm^2. At 263 K, a temperature that can be gained by a single-stage Peltier cooler, the equivalent noise charge is reduced to about 9 e^- rms, i.e. 150 eV FWHM at the Mn K_α line. At 243 K, the SDD is already as good as conventional Si(Li) or HPGe detectors requiring a cooling around 100 K.
On the other hand, the SDD is operated at shaping times in the order of 100 ns, while conventional systems with comparable spectroscopic quality need longer time constants by a factor of at least 100. That means that the SDD can be operated at extremly high-count-rates which are beyond the potentialities of other systems: up to 10^5 cps incoming counts can be detected without a significant increase in the equivalent noise charge, that means without a broadening of the e.g. Mn K_α line of the ^{55}Fe spectrum. At 6×10^5 cps, the resolution is still as good as 230 eV FWHM at the Mn K_α line.
The radiation entrance window has been optimised for the detection of soft X-rays: the quantum efficiency is 80% at 0.5 keV and above 90% between 1 keV and 10 keV [4, 7]. All other detector-relevant parameters are satisfactory: complete charge collection, spatially homogeneous response, reproducibility and long-term stability.
These figures recommend the use of SDDs in two categories of applications.
(1) High-count-rate applications. Silicon drift detectors have been installed as radiation monitors in our satellite test facility PANTER, and they have been operated in EXAFS and atomic holography at various synchroton light sources [8]. These experiments take advantage of the SDDs high rate capability, still with simultaneous good energy resolution, thus reducing necessary beam time and related costs by orders of magnitudes.
For synchrotron applications, we also designed and produced detector arrays by combining several SDDs to a multi-cell drift detector. This way,

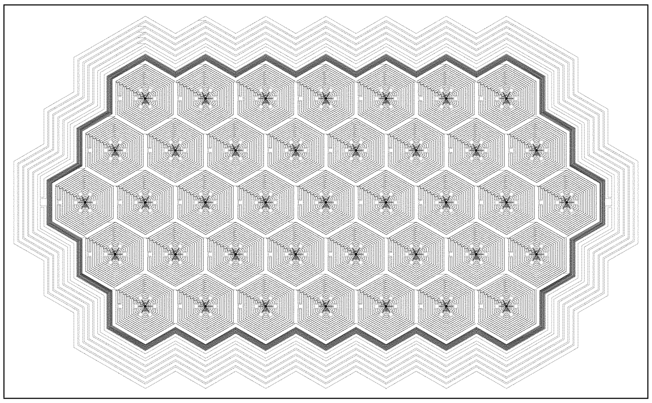

Fig. 3. Layout of the 39 cell silicon drift detector array with 39 integrated on-chip amplifiers. The total active size of the system is 195 mm^2

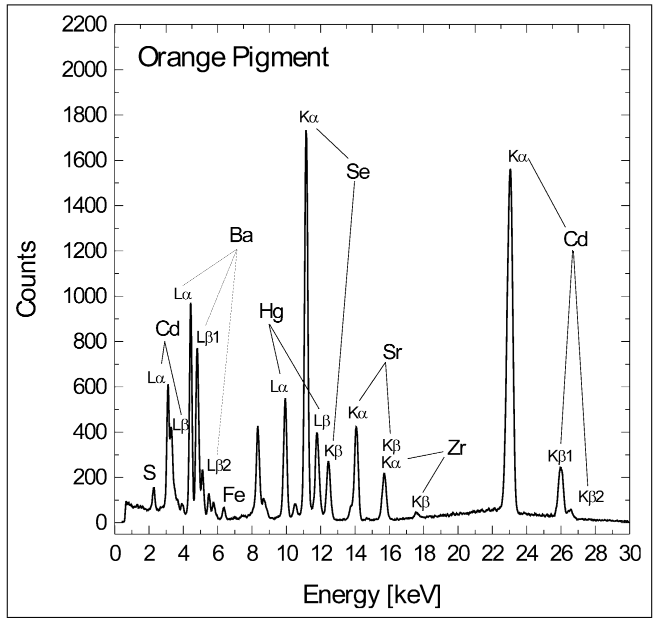

Fig. 4. Spectrum of an orange pigment acquired with the X-ray flourescence-spectrometer based on a silicon drift detector

deliberately large sensitive areas can be achieved without losing the high-count-rate capability and the low noise level of the individual 5-mm^2 large subsystems. The largest device has 39 readout nodes corresponding to an area of 195 mm^2 area (Fig. 3). Multiplexing VLSI amplifiers are actually being developed to keep the complexity of the readout electronics for the user at a reasonable level.

(2) Compact, easy-to-use set-up. That fact that SDDs do not require cooling by liquid nitrogen or cryogenic systems allows the integration of detector, Peltier cooler, and Be entrance window in a small-sized package. This compact, inexpensive module is well suited for a number of commercial applications and in-the-field measurements.

SDDs have already been used as X-ray detectors for electron microbeam analysis in scanning electron microscopes [9]. In this set-up, the electron beam is used not only to produce a surface image of the sample but also as a generator of characteristic X-rays which are detected by the SDD and yield information of the chemical consistence of the sample.

The SDD module in combination with a commercial microfocus X-ray tube makes up a compact, portable spectrometer for X-ray fluorescence (XRF) measurements, also in the field, i.e. independent of laboratory infrastructure. This feature has already led to the use of such a spectrometer in archeometry. In this context, it is now possible to perform a fast element analysis of works of art in galleries and museums without transportation of the precious objects to scientific laboratories.

Investigations of works of art with SDDs

In archeometry, different kinds of investigations are used for the characterisation of artistic objects. In particular, XRF spectroscopy is a nondestructive technique widely used for the identification of chemical elements in pigments, metal alloys, and other materials. The classical high-resolution cryogenic detectors, like Si(Li) and HP(Ge) detectors (whose energy resolution is of the order of 140 eV FWHM at the Mn K_α line), are not completely suitable as portable instruments because they need liquid nitrogen in the cooling system.

Recently, new silicon PIN diodes simply cooled by a Peltier element have been introduced. Their energy resolution (of the order of 250 eV FWHM at the Mn K_α line) sometimes yields unsatisfactory results (especially for the analysis of light chemical elements). At low energy, the main contribution to the FWHM is due to the electronic noise of the detector, which is associated with the detector-capacitance, directly dependent from the detection area.

The possibility of operating the SDD at non-cryogenic temperatures and the excellent energy resolution (of the order of 150 eV FWHM at 6 keV) makes these detectors suitable as high-resolution portable instruments. Recently, a portable high-resolution X-ray spectrometer – based on the SDD cooled by a Peltier element – was manufactured at the research laboratories of Politecnico di Milano. A commercial miniaturised X-ray tube was utilised as an excitation source. Measurements of different kinds of artistic objects confirmed the ease of use combined with high-class performance, in particular the high energy resolution. Figure 4 shows the spectrum of an orange pigment recorded with the above-described system. The almost background-free detection of the individual chemical elements helps to identify the composition of complex materials directly at the location of the work of art. A transfer of the objects to the laboratory is no longer needed.

Conclusions

We have demonstrated the performance of high-resolution spectrometers, which can be operated at or close to room temperature avoiding liquid nitrogen for cooling and vacuum environment. The spectrometers are compact and have count rate capabilities which are ten times higher than conventional systems. The cost of the spectrometer is significantly lower than comparable conventional Si(Li) or high-purity-germanium systems.

SDD-based spectrometers have been used as fast detectors in synchrotron experiments, as XRF devices for investigations in archeometry, in the field of microbeam analysis in scanning electron microscopes and for the scintillation light readout when coupled to anorganic scintillators. New scientific and industrial applications have already been proposed.

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