SILICON DRIFT DETECTORS FOR HIGH RESOLUTION, HIGH COUNT RATE X-RAY SPECTROSCOPY AT ROOM TEMPERATURE

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ABSTRACT

An advanced Silicon Drift Detector (SDD) for X-ray spectroscopy designed and fabricated at the MPI semiconductor laboratory has the input transistor of the amplifying electronics integrated on the detector chip. That way the total capacitance of the detector/amplifier system is very small (200 fF) guaranteeing excellent energy resolution (147 eV FWHM at 5.9 keV, 10 mm², -10 °C) and extreme count rate capability (up to 10^6 incoming photons per sec). The elaborate process technology stands for a low leakage current level allowing operation at or close to room temperature. The new design of the Silicon Drift Detector Droplet (SD^3) offers an energy resolution of 128 eV (FWHM at 5.9 keV, 5 mm², -10 °C) that conventional detectors only obtain at liquid nitrogen cooling. The concept of Multichannel SDDs provides large sensitive areas up to cm² without losing the energy resolution and count rate properties of the single SDD cells.

INTRODUCTION

The Silicon Drift Detector (SDD) is derived from the principle of sideward depletion [1, 2]. A volume of high-resistivity n-type silicon is fully depleted by reverse biased p⁺ junctions covering both surfaces. Electrons generated within the depleted volume by thermal processes or by the absorption of ionizing radiation are forced to drift to a small-sized n⁺ anode by an electric field with a strong component parallel to the wafer surface. In the original SDD design the electric field is achieved by segmentation of the p⁺ regions on both surfaces to patterns of parallel strips and superposition of a voltage gradient [1]. The direction of the voltage gradient is such that the n⁺ readout anode has the most positive potential and collects all electrons released within the depleted volume by the absorption of ionizing radiation or thermal generation.

Originally SDDs have been designed and used as position sensitive detectors in particle physics where the measurement of the signal electrons’ drift time allows the reconstruction of 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 cm² have been fabricated [3] as well as cylindrical (r, ϕ)-detectors with a diameter of 10 cm and an angular resolution of 1°, realized by a radial drift field and 360 anodes placed along the edge of a 4-inch wafer [4].
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To optimize the SDD principle for X-ray spectroscopy the strip system on both surfaces is replaced by a large area p⁺ junction on the side opposite to the n⁺ anode. This non-structured p⁺ junction is used as a homogeneous, thin radiation entrance window [5]. In addition backside illumination has a self-shielding effect: the radiation sensitive components, e.g. the readout structure, are placed on the non-irradiated surface and can only be hit by hard X-rays (> 10 keV), whose intensity is reduced by the absorption of the silicon bulk. A further improvement is the design of circular, concentric drift electrodes driving signal electrons to the small sized n⁺ anode in the center of the device. The potential values of the drift rings are defined by an integrated voltage divider, i.e. only the inmost and the outmost rings must be biased externally [6].

With the SDD topology and the collecting anode’s small physical size the detector contribution to the total readout capacitance is already minimized. An additional reduction is achieved by the integration of the first transistor of the amplifying electronics on the detector chip [7]. The integrated transistor is a single-sided n-JFET [8, 9] designed to operate on a fully depleted n-type bulk. It is placed in the center of the ring shaped collecting anode (figure 1). The anode is connected to the floating FET gate by a narrow metal strip, so that the change of the anode voltage caused by signal electrons can be easily measured as a modulation of the transistor current. The on-chip FET 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 working with dc-voltages only. The integration of the first FET not only minimizes the overall capacitance recommending the SDD for high-resolution, high-rate spectroscopy, but also makes it insensitive to a great extent against electronic pickup and microphony, i.e. noise induced by mechanical vibration.

Figure 1
Circular SDD with uniform radiation entrance window. The entire thickness of the device is sensitive to radiation. The first FET of the amplifying electronics is integrated in the center of the ring-shaped anode.

Figure 2
Calculated distribution of the potential energy in an SDD. The simulation applies to the cross section of a detector as shown in figure 1. The arrow lines indicate the signal electrons’ drift directions.
Figure 3

Measured count rate dependent energy resolution of an SDD with analog pulse processing system [11] at a temperature of -15 °C (5 °F). With the shortest shaping time of 70 nsec the system is still able to operate at $10^6$ incoming photons per sec with a throughput of $4 \cdot 10^5$ processed counts per sec.

Figure 1 shows the topology of an SDD with cylindrical geometry, uniform entrance window, and integrated FET. Figure 2 shows the corresponding calculated potential energy distribution. SDDs of the type shown in figure 1 have been fabricated and qualified at the semiconductor lab of Max-Planck-Institute in Munich/Germany in large quantities in different shapes and sizes. Due to the advanced process technology used in the SDD fabrication the leakage current level is so low, typically 100 pA/cm$^2$ at full depletion of the 300 µm thick wafer, that the devices can be operated at room temperature or with moderate cooling by a single-stage thermoelectric cooler. The numbers quoted in the following reflect the typical performance of an SDD with a sensitive area of 10 mm$^2$ operated at a temperature of -10 °C (14 °F).

The energy resolution in terms of full-width-at-half-maximum (FWHM) at the Mn-K$_\alpha$ line (5.9 keV) is 147 eV. Because of the small value of the total output capacitance of about 200 fF the SDD is operated at pulse shaping time constants of the order of 100 nsec (figure 3), whereas conventional systems with comparable spectroscopic quality require longer shaping times by about a factor of 100. This means that the SDD can be used at extremely high count rates far beyond the ability of other systems. Figure 3 demonstrates the count rate capability obtained with an analog pulse processing system with variable shaping time constant [11]. With a shaping time of 70 nsec the energy resolution is still 250 eV (FWHM at 5.9 keV) at $10^6$ incoming photons per sec and a throughput of $4 \cdot 10^5$ processed counts per sec. For high energy resolution at lower count rates longer shaping time constants up to 450 nsec are selected.

To prove their radiation hardness SDDs have been irradiated with a high flux of Mo-K$_\alpha$ photons (17.5 keV). Photons of this energy have a maximum probability of transmission through the 300 µm thick silicon bulk and absorption in the radiation sensitive components (readout structure, integrated voltage divider) on the opposite surface. Irradiated devices reveal no change in energy resolution up to $10^{13}$ absorbed photons [12]. At higher doses an increase of the leakage current is observed. That means that the SDD can be operated under worst case conditions for 30 continuous years at a constant rate of $10^4$ photons per sec without any radiation damage effect. The radiation entrance window has been optimized for the detection of soft X-rays [13, 14]. The quantum efficiency is above 90% in the energy range from 300 eV up to 10 keV. On the low energy end the quantum efficiency is a function of the entrance window technology, on the high energy end it is given by the full depletion of the 300 µm thick silicon bulk. The quality of the entrance window is also reflected in the low energy background of SDD spectra (figure 5).
peak/background ratio defined as amplitude ratio of the Mn-Kα line relative to the average background at 1 keV is 3000.

SDDs are found in a variety of scientific experiments and commercial systems. With their count rate capability they set new boundary conditions for electron microprobe analysis [15]. The fact that SDDs don’t require expensive and inconvenient cooling by liquid nitrogen initiated new applications in X-ray spectroscopy. In combination with a micro-focus X-ray tube the SDD makes up a compact, portable spectrometer for XRF measurements in the field, i.e. independent of laboratory infrastructure, developed for the use in archeometry [16]. The ESA comet lander mission ROSETTA as well as NASA’s 2003 Mars Exploration Rovers are equipped with an Alpha-Proton-X-ray-Spectrometer (APXS) including an SDD for PIXE analysis [17].

**SD³ - A NEW SDD LAYOUT**

In the new Silicon Drift Detector Droplet (SD³) the readout structure, i.e. the collecting anode and the integrated FET, is no more placed in the center but at the edge of the sensitive area, where it can be easily shielded from direct irradiation by a circular collimator. The electric field that drives electrons towards the anode is generated by bow-shaped drift electrodes (figure 4). Compared to the standard circular device the SD³ layout is of great benefit in two respects [12]:

- Direct irradiation of the readout structure results in a partial loss of signal electrons to the integrated FET. Although the FET is small in area the effect is a significant contribution to the low energy background in SDD spectra. Therefore, with the SD³ geometry the peak/background ratio is increased from 3000 to 5000 using a collimator with $\varnothing = 2$ mm (figure 5).
- The fact that in the SD³ geometry the signal electrons approach the anode from a given direction instead from all sides allows one to design the anode with different shape and size resulting in a reduction of the total output capacitance from 200 fF to 120 fF. The measured energy resolution of a 5 mm² SD³ is 128 eV (FWHM at 5.9 keV) at a detector temperature of -10 °C (14 °F) and 124 eV at -20 °C (-4 °F). So the SD³ cooled by a thermoelectric Peltier element has a resolution superior to the best values reported for liquid nitrogen cooled Si(Li) detectors.

**Figure 4**

Topology of the Silicon Drift Detector Droplet (SD³) with a sensitive area of 5 mm². The readout structure (black region) is placed at the edge of the device where it can be shielded from direct irradiation by a circular collimator. The arrow lines indicate the signal electrons’ drift directions.
MULTICHANNEL DRIFT DETECTORS

To provide a large sensitive area without losing the energy resolution and count rate capability of the single SDD cell the concept of Multichannel Drift Detectors has been introduced [18]. A Multichannel SDD is a continuous, gapless arrangement of a number of SDDs with individual readout, but with common voltage supply, entrance window, and guard ring structure (figure 6). It allows not only to fill any large area (figure 6a), but it also implies the choice of any two-dimensional shape according to the requirements of the experiment like a linear chain for diffractometry (figure 6b) or a closed ring (figure 6c).

Multichannel SDDs are used at synchrotron light facilities as they are able to cope with the extremely high photon rates in fast counting applications like EXAFS [19] and X-ray holography [20]. The ring structure is the basic component of a compact XRF spectrometer: a sample is excited through an X-ray polycapillary fiber inserted 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 (figure 7). For the readout of Multichannel SDDs the amplifier chip ROTOR (rotational trapezoidal readout) based on JFET-CMOS technology has been developed [21]. ROTOR is able to handle the random asynchronous event occurrence of a large number of SDDs with low read noise at count rates exceeding $10^5$ counts per sec per channel.
Figure 7
Principle of a compact XRF-spectrometer using the SDD ring structure of figure 6. The sample is excited through an X-ray polycapillary fiber inserted through a laser-cut hole in the center of the detector chip. The SDD-ring receives the fluorescence photons covering a large fraction of the solid angle around the sample.

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