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Application of Si-strip technology to X-ray diffraction instrumentation

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ABSTRACT

We describe the successful technology transfer of High Energy Physics (HEP) silicon-strip detectors for tracking of minimum ionising particles (MIPS) to industrial X-ray diffraction instruments. In our application the detector is used to measure 1-D intensity profiles of low-energy photons. The challenges of such an application are low noise because of the relatively low energy of X-ray photons, from 5 to 22 keV, and high count rate capability. The technical implementation, with a focus on custom designed front-end electronics and optimisation of strip geometry taking into account the charge division effects, is shown and the achieved performance is summarized. The detector was launched several years ago and we report on the in-field experience. Lastly, we describe several scientific applications.

1. Introduction

The combined technologies of silicon strip detectors and Application Specific Integrated Circuits (ASICS) have enabled 1-D position sensitive X-ray detectors to be designed to fulfil specific requirements. This combined technology is widely used in HEP experiments for building high precision tracking detectors. As a mature technology, it is a suitable one for building a detector for in-house commercial instruments used for X-ray diffraction, X-ray reflection, and X-ray scattering measurements.

One-dimensional X-ray diffraction (XRD) detectors were quite popular in academics and research for a long time. They enabled special X-ray diffraction investigations also in a laboratory. One example is the kinetic study of materials under non-ambient conditions. However, due to their limited count rate capabilities, the quality of the data in terms of measured intensity and of peak position stability was considerably low. An overview of XRD detectors, the specific requirements, and relative performance can be found in Ref. [1]. With the introduction of silicon strip detectors this limitation was removed. Furthermore, due to the enormous count rate capability, robustness, and ease of use, new applications in X-ray diffraction were opened. In its first instance, the novel instrument consists of an X-ray source, primary beam modifying optics, e.g. focussing or monochromating optics, a sample, and the 1-D detector with optical components suppressing scattered radiation. The whole set-up is arranged in Bragg–Brentano geometry obeying the θ–2θ condition during the entire measurement. The 1-D detector replaces the 0-D detector in the classical set-up. This set-up allows powder diffraction measurements for qualitative and quantitative crystalline phase identification. Results for this type of X-ray diffraction, in addition to more elaborate measurements using different set-ups, are shown in Section 5 of this paper.

The performance of a new technology like the silicon strip detector can easily be checked by using standard reference material (SRM) provided by the National Institute of Standard and Technology (NIST, USA). Various certified solid or loose powder samples are available for comparison measurements. An important quality criterion of a detector is its angular resolution measured as full width at half maximum (FWHM) for given reflections. Fig. 1 shows a measurement recorded on an LaB_6 powder sample (SRM 660a) using the developed silicon strip detector. The FWHM of 0.042° matches very well the value, which can be expected from the instrument set-up. There is no loss in angular resolution when compared to a point detector. This shows even though the silicon strip detector acts as 192 point detectors, recording data at the same time at slightly different diffraction angles, the data quality is equivalent to a single point detector, but measured 192 times faster.

It is worth mentioning that the ideas to build a 1-D detector for powder diffraction, based on silicon strip detector technology, have been presented many years ago [2,3]. However, to our knowledge, none of these projects has materialised as a useful instrument addressing properly the requirements of the diffraction technique. Performance and measurement capability of both prototype detectors reported in the above mentioned papers were severely limited by the performance and quality of the readout electronics. While the silicon strip detector technologies, as

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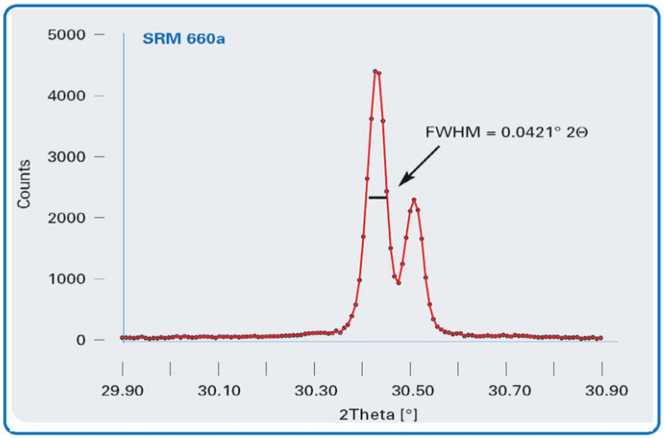

Fig. 1. Measurement of the angular resolution using the standard reference material 660a (LaB_6). The resolution achieved is equivalent to a point detector (0-D detector) with a 0.1 mm receiving slit (diffractometer D2 Phaser with 1.5° Soller slit[1] and 0.1 mm divergence slit).

developed for high energy particle physics experiments, can be applied directly to measurement of X-rays, one needs a readout ASIC of different readout architecture and much better performance to build a useful instrument. The basic requirements for the ASIC are as follows:

- counting mode with an energy window discriminator
- low equivalent noise charge (ENC), below 150 electrons rms, at room temperature for a detector capacitance of 2.4 pF, allowing for discrimination between noise and signal of 1500 electrons corresponding to X-ray energy of 5.4 keV
- linear front-end circuitry up to an input charge of 6200 electrons (22.2 keV in Si)
- count rate capability significantly higher than 10^6 cps
- storage data buffers on the chip and multiplexed data readout
- possibility of simultaneous data taking and data readout
- low power dissipation of 3 mW per channel allowing operation without active cooling.

2. Silicon strip detector

We have selected a conventional single-sided silicon strip detector structure with AC-coupled p^+ strips in high resistivity n-type silicon bulk as the sensor for our detector. Such a choice was driven, firstly, by the requirement to use a mature sensor technology and, secondly, by specific technical requirements discussed below. The strip length of ~16 mm is determined by the geometry of the X-ray beam in the diffraction instruments. This allows us to maximise the use of the beam, although shorter strips would result in lower noise and better energy resolution. However, since the intention was to use the detector in pre-existing instruments with a given geometry it was decided to use the full possible length. Also, the strip pitch was chosen due to the available instrumentation for which the detector was designed. Due to the commonly achieved focal spot dimensions of sealed X-ray tubes, a pitch width of much less than 100 μm would no lead to better spatial resolution of the system.

2.1. *Detection efficiency*

The considered range of X-ray energy is from 5.4 up to 22 keV, while the majority of applications uses 8 keV copper X-ray tubes. The typical wafer thickness of 300 μm used in silicon strip detectors for HEP experiments appear to match well our requirement as it provides 98% absorption for 8 keV X-rays. Using a thicker detector would provide higher efficiency for X-ray energies above 8 keV; however, this would result in larger charge sharing between the neighbouring strips and compromising the single strip energy resolution due to diffusion of charge generated in the detector volume. These effects are related directly to the strip geometry and will be discussed later. Therefore, we have decided to develop an optimised design for typical applications based on 300 μm thick silicon wafers and an optional design for higher X-ray energies based on 500 μm thick wafers.

2.2. *Bias voltage and leakage current*

The typical full depletion voltage of 300 μm thick sensors is about 60 V. This parameter is not very critical as we want the sensor to be biased with much higher voltages, up to 250 V, in order to ensure a short charge collection time and to minimise division of charge between neighbouring strips. No active cooling is foreseen for the detector. Given that the detector is operated in the diffraction instrument at temperatures typically about 10 °C above room temperature, we have assumed a maximum leakage current of up to 1 nA per strip. This upper level of the strip leakage current is set by the requirement that the parallel current noise generated by the detector leakage current should not contribute significantly to the equivalent noise charge (ENC) of the overall system. For a given voltage noise of the preamplifier and detector capacitance this limits the peaking time of the front-end electronics to be below 300 ns.

2.3. *Bias resistance*

Because the noise contribution of the strip leakage current cannot be made completely negligible we have used the structure with AC-coupled strips. Using DC-coupling would require an additional circuitry in the front-end electronics to compensate the DC voltage shifts in the preamplifier circuit. Such a circuitry would be an additional source of current noise. In first approximation, this circuitry would double the noise due to the detector leakage current. For the AC-coupled strip, the bias resistance becomes another critical parameter as an additional source of parallel current noise at the preamplifier input. The assumed maximum leakage current of 1 nA corresponds to an equivalent noise resistance of 50 MΩ. In order to avoid additional noise contribution from the bias resistor, it should be made at least an order of magnitude higher, i.e. 500 MΩ. Such high values are achievable only with FOXFET structures [4].

2.4. *Spatial resolution*

Primarily, the silicon strip detector should replace the 0-D detectors used in scanning mode so that the strip pitch should be of the same order of magnitude as the slit used with the 0-D detector. It is worth noting a different approach to the spatial resolution of silicon strip detectors used for X-ray detection compared to the common approach used for tracking relativistic charged particles in HEP experiments. In tracking detectors of charged particles one can take advantage of charge division effects between the strips and improve the spatial resolution by estimating the centre of gravity of signal amplitudes measured for

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[1] A so called Soller slit consists of parallel plates limiting beam divergence in one direction. It is typically defined by its opening angle.