Detection of Low Energy X-rays with High Efficiency and Spectral Resolution

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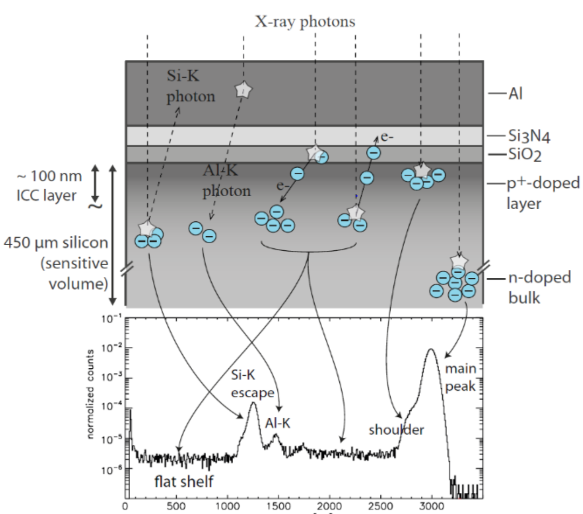
Spectroscopic and imaging information of low energy X-rays in the energy range of 50 eV up to several keV is of great importance for material science and the analysis of biological samples. For example, in material science Li-ion battery research is in the focus of many studies or the analysis of diffraction patterns recorded at synchrotron or Free Electron Laser sources from atomic clusters or viruses. In many of those cases the detection of single X-rays in the above energy band is required as well as intensity distributions with high dynamic range of X-rays with known energy.

The interaction of low energy X-rays with matter – in our case silicon – happens in a very thin layer of the radiation entrance window of the detector. For X-rays of 150 eV the absorption length in silicon is less than 50 nm, at the Carbon edge it is 112 nm and it is still below 3 µm at 1 keV. This fact confronts detector developers with a difficult task: The silicon volume where the incident radiation interacts with the silicon lattice should not affect the collection process of the few signal charges. At 277 eV, the C_Kα energy create only 75 electron-hole pairs and only 14 electron-hole pairs at the Li_K line at 53 eV. The statistical fluctuations during the ionization process, called Fano effect limit the best possible energy resolution of C_Kα radiation to 24 eV (FWHM). Adding an electronic noise of 2.5 electrons (rms) yields an increase of the best achievable energy resolution of 33 eV (FWHM). The measured width of the C_Kα line is 42 eV (FWHM) while the Fano and the noise contribution alone would only yield an energy resolution of 33 eV (FWHM). The increased measured line width in Fig.2 is due to the entrance window effects as highlighted in Fig.1. A variety of interactions of the incident X-rays and the subsequently generated energetic electrons lead to no energy deposition or a partial energy deposition in the sensitive silicon volume also through trapping and recombination. This is responsible for the flat shelf in the spectrum and the escape line. In addition, Al and Si fluorescence is seen in Fig.1. The quality of the entrance window can be described by the incomplete charge collection (ICC) as a function of the penetration depth of the radiation in the silicon. This indicates how the quality of the radiation entrance window limits the performance of the low energy response. In high quality detectors the ICC is about 95% at the Si-SiO_2 interface and goes up to 100% in 200 nm depth in the silicon. The measured spectra are in excellent agreement with the simulations leading to a good understanding of the underlying physics. This knowledge leads to a tailored implementation of the right radiation entrance window and enables the scientist to perform imaging and spectroscopic measurements at the low energy side of the X-ray spectrum.



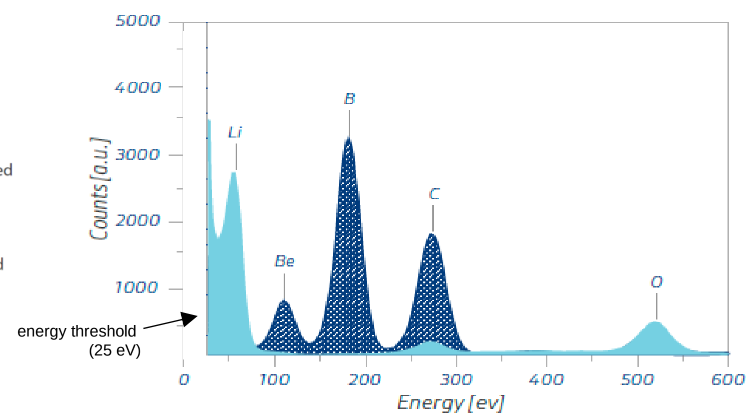


Fig.2 Low energy X-ray spectrum recorded with a silicon drift detector from Li_K up to O_K. At C_K the FWHM is 42 eV.

Figure 1. Model of a high-quality radiation entrance window. The X-rays have to pass through various layers of dielectrics and Aluminum in case a light blocking filter is required before they reach the sensitive volume in Silicon. Those processes lead to a complex response of the incident radiation, in this case to 3 keV X-rays from a synchrotron recorded with a pnCCD.

Silicon drift detectors pnCCDs and the DePFET active pixel sensors are equipped with ultrathin radiation entrance windows designed for their intended use in their instruments. It should be noted that the detectors used for this study (SDDs and pnCCDs) exhibit a Fano limited energy resolution for energies above 2 keV.