A pixelised detector for thermal neutrons

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Since its advent Neutron Scattering has become a critical analytical tool for materials science leading to new scientific fundaments and the development of scientific, industrial and consumer products worldwide. The increasing demand for more and 'better' neutrons resulted in the planned European Spallation Source (ESS), which entered its construction phase in 2014, in Lund, Sweden. The optimum use of the advanced instrumentation of the ESS, and of the existing neutron facilities such as the European High flux reactor at the Institute Laue Langevin (ILL, France) or the spallation source ISIS (UK) require neutron detectors that outperform the state-of-the-art. We aim to realize a leap forward in this direction and develop a neutron detector with unprecedented performance in terms of (2D) spatial resolution, time resolution, rate capability and radiation hardness. We propose to develop a new detector based on a pixel chip, covered with a Boron-based neutron absorber/convertor. Our first choice material is Boron Nitride (BN) because of its known semiconductor properties.

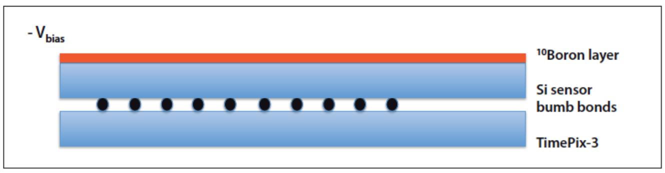

Figure 1. The TimePix-3 pixel chip with a bumb-bonded Si sensor covered with a 1μm thick layer of pure Boron, possibly enriched ^{10}B. Instead of pure B, BN or B_4C could be applied, having practical advantages.

The starting point for the pixelised detector will be the TimePix-3 pixel chip [1], which is the latest incarnation of a generic chip widely used in radiation detectors (see Figure 1 & 2) and was developed at CERN. In order to be used as a charged particle detector, the TimePix-3 chip must be covered by a bump-bonded pixelized Si layer. If the passage of an ionising radiation creates electron-hole pairs in the (depleted) Si layer, a charge pulse activates the TimePix pixel circuitry and the time and amplitude of the pulse are registered.

On top of the Si we will apply a 1 μm thick layer of ^{10}B. This will absorb thermal neutrons the following nuclear reaction:

$$^{10}B + n \rightarrow {}^{7}Li + \alpha + \gamma_{0.48MeV}$$

where the energy of the ^{7}Li recoil nucleus is 0.84 MeV, and the energy of the α particle 1.47 MeV. The ^{7}Li and α particle will strongly ionise the ^{10}B in which they will be created, and with a very high probability the Si layer as well, leading to recordable charge pulses. Besides the realization of a the ^{10}B-covered Si pixel detector, Task 1.2 includes:

the realisation of an operational readout system for the TimePix-3 chip (using the available SPIDRE readout system and the FitPix TPX-3 readout system), including DAQ and chip control software;

test of the performance in terms of efficiency, noise, spatial resolution, time resolution by comparing with (Monte Carlo) simulations

determination of the sensitivity for background γ's.

investigation of ageing effects induced by radiation.

Apart from its low efficiency (4–20 %, for λ = 1.8–10 Å), the performance of the detector is expected to be excellent in terms of 2D spatial and time resolution and rate capability. This part of the work is of low risk, and uses only known and available technology. The resulting detector will nonetheless generate key knowledge and experience, relevant and necessary for the addressing the next step, namely the high-risk, high-impact neutron detector of Tasks 1.4 – 1.7

Based on the results above, the next step will be to cover the TimePix-3 chip with a 120 μm thick layer of ^{10}BN (preferred, but possibly another B containing compound can be envisaged). In this layer, 94% of neutrons with a wavelength of 0.2 nm will be absorbed and the efficiency will approach 100 % for longer wavelengths. The resulting total ionisation energy of the ^{7}Li and α's of 2.31 MeV will be deposited in a small volume (~10 μm^3) in the bulk ^{10}BN. An added conducting layer on top of the ^{10}BN will allow the application of a bias electric field, under the influence of which, ~300 k electrons and holes will move in opposite direction towards and away from the pixel input pads of the TimePix-3 chip. With a charge separation of 1.2 μm, an induced charge pulse of 6 k e– will appear on the pixel input pad, comfortably larger than the equivalent input noise (100 e–), although the initial positive and negative charge clouds will be reduced due to recombination. With an assumed electron mobility of cubic-BN of 200 cm^2/Vs and a bias electric field of 10 kV/cm, this charge pulse will be theoretically created within 5 ns. In reality, however, electrons and holes are trapped by vacancies, and crystal boundaries, which effectively slows down and limits the charge signal. Therefore the following properties of the ^{10}BN containing layer need to be taken into account to determine the detector response: band gap, determining the number of electron-hole pairs; lifetimes of electrons and holes in the conduction band; bias current as a function of bias voltage (noise); charge transport properties related to the crystal quality of the material.

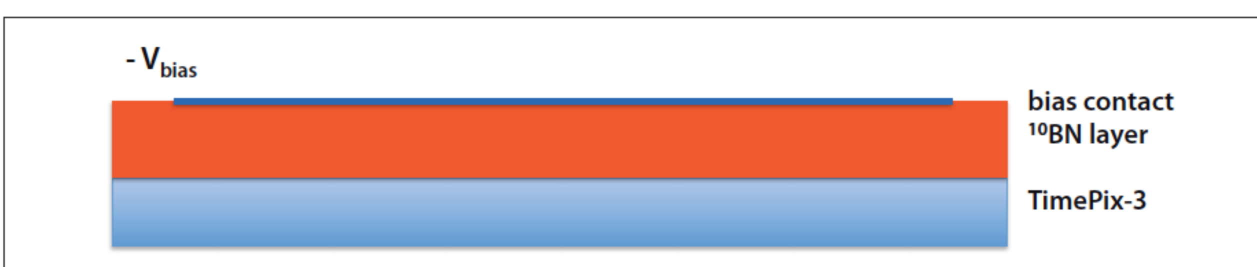

Figure 3. The TimePix-3 pixel chip covered with a 120 μm layer of ^{10}BoronNitride. The BN layer is covered with a thin conductor put at a bias potential.