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# Characterization of 3D thermal neutron semiconductor detectors

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## Abstract

Neutron semiconductor detectors for neutron counting and neutron radiography have an increasing importance. Simple silicon neutron detectors are combination of a planar diode with a layer of an appropriate neutron converter such as $^6$LiF. These devices have limited detection efficiency of not more than 5%. The detection efficiency can be increased by creating a 3D microstructure of dips, trenches or pores in the detector and filling it with a neutron converter. The first results related to the development of such devices are presented. Silicon detectors were fabricated with pyramidal dips on the surface covered with $^6$LiF and then irradiated by thermal neutrons. Pulse height spectra of the energy deposited in the sensitive volume were compared with simulations. The detection efficiency of these devices was about 6.3%. Samples with different column sizes were fabricated to study the electrical properties of 3D structures. Charge collection efficiencies in silicon columns from 10 to 800 μm wide and 80–200 μm high were measured with alpha particles.

The neutron detection efficiency of a full 3D structure was simulated. The results indicate an increase in detection efficiency by a factor of 6 in comparison with a standard planar neutron detector.

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## 1. Introduction and goals

Silicon detectors cannot be used for thermal neutron detection directly. A material that "converts" neutrons into detectable radiation must be present. There are many possible candidates among which compounds of $^6$Li seem to be the best [1,2]. The neutron capture reaction on $^6$Li

$$^6\mathrm{Li} + \mathrm{n} \rightarrow \alpha(2.05\,\mathrm{MeV}) + {}^3\mathrm{H}(2.73\,\mathrm{MeV})$$

has a cross-section $\sigma = 942\,\mathrm{b}$ at a neutron energy of 0.0253 eV.

$^6$Li-based converters offer a sufficiently high neutron capture cross-section together with high enough reaction product energies and ranges for their efficient detection. The final objective of the detector R&D described here is a neutron imaging sensor with high sensitivity and good spatial resolution. We have already successfully tested the Medipix-2 chip with a planar sensor chip covered with the $^6$LiF neutron converter [3]. The spatial resolution of such a device of ~65 μm (in terms of FWHM of the line spread function) can compete very well with common neutron imaging devices. The signal to noise ratio (SNR) of silicon detectors is also superior to common neutron imaging devices. However, the detection efficiency of such planar semiconductor detectors (ratio of the number of detected to the number of incident neutrons) is limited to about 5%. The detection efficiency can be increased by creating dips or pores ("3D" structures) in the silicon detector body and filling them with a neutron converter.

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## 2. Detection efficiency of planar neutron detectors

A Monte-Carlo simulation package was used to predict the detection efficiency of the planar structure. The package combines MCNP-4C (neutron transport simulation) [4] with SRIM/TRIM (stopping power) [5] and our own C++ Monte Carlo code (simulation of energy deposition, pulse height spectra, detection efficiency, etc.).

Fig. 1 shows the detection efficiency versus the $^6$LiF (enriched in $^6$Li to 89%) converter thickness, first for frontal irradiation where the curve exhibits a maximum of 4.48% at 7 mg/cm$^2$. The detection efficiency starts to decrease above this converter thickness, because alphas and tritons created at more distant levels of LiF from the Si–LiF boundary can no longer reach the sensitive volume. Moreover, a higher number of neutrons is absorbed close to the converter outer surface (see Fig. 2a). The second curve shown in Fig. 1 is for the detector irradiated from the backside. Above a converter thickness of about 7 mg/cm$^2$, the detection efficiency remains constant at 4.90%. Neutrons are preferentially captured close to the converter–semiconductor boundary (see Fig. 2b) and the detection efficiency becomes saturated and independent of the converter thickness [6].

Pulse height spectra of energy deposited in the simple planar detector were measured (Fig. 3). The sample was a 5 × 5 mm$^2$, 300-μm-thick Si detector. The resistivity of the n-type bulk was ~5 kΩ cm. The sample was partially covered[1] with a layer of $^6$LiF (~20 mg/cm$^2$) enriched in $^6$Li to 89%. The measured spectrum was compared with results of the Monte-Carlo simulation. The simulation is in good agreement with the measured spectrum. The sample was irradiated from the backside with a beam of thermal neutrons. The measurements were performed at the horizontal channel (neutron guide) of the LVR-15 nuclear research reactor at the Nuclear Physics Institute of the Czech Academy of Sciences at Rez near Prague. The neutron flux was about $10^6\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at reactor power of 8 MW.

Alphas and tritons from the thermal neutron capture reaction always fly in opposite directions (Fig. 4). The simple planar detector can detect either alpha or triton particle, but never both. Therefore, the spectrum of deposited energy does not contain any events above an energy of 2.73 MeV which corresponds to tritons.

## 3. Detection efficiency of detectors with pyramidal dips

The second test sample contains an array of inverted pyramidal dips created by anisotropic etching of silicon with KOH. The base of the pyramids is 60 × 60 μm$^2$ and they are 28 μm deep. The gap between pyramids is 23 μm. The chip size was again 5 × 5 mm$^2$, thickness 300 μm and resistivity about 5 kΩ cm.

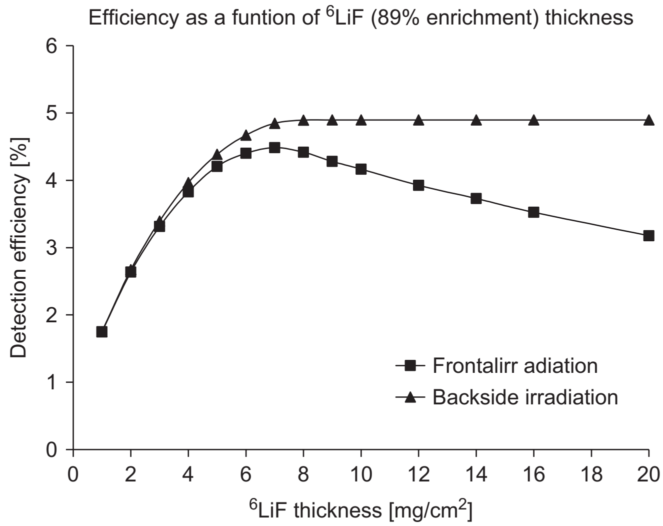

Fig. 1. Simulated dependency of detection efficiency as a function of $^6$LiF neutron converter thickness.

The dips double the surface between the neutron converter and the detector. Contrary to the planar detector case the spectrum (Fig. 5) now contains events above 2.73 MeV, because both particles (alpha and triton) can be detected simultaneously if the reaction takes place in the region close to the pyramid tip (Fig. 6).

A simulation was also used to predict the thermal neutron detection efficiency of the detector with inverse pyramidal dips on its surface. The plot in Fig. 7 contains simulated dependencies of the detection efficiency on $^6$LiF thickness for the detector without dips and with pyramidal dips.

The detectors were irradiated from the backside in both cases. The pyramidal dips increase the overall detection efficiency from 4.90% to 6.30%, which means a relative increase by ~28%. One can also see in Fig. 7 that for the thin converter the increase of the detection efficiency corresponds to the increase of the detector surface.

## 4. Detection efficiency of 3D neutron detectors

### 4.1. Simulations of porous structures

Contemporary semiconductor technologies allow the creation of 3D structures in semiconductors that can further increase significantly the surface between the neutron converter and the detector sensitive volume. Such geometries allow a larger volume of the neutron converter while keeping a high probability of secondary particle detection, giving a higher thermal neutron detection efficiency in comparison with the planar detector or the detector with pyramidal dips.

Two types of structures were simulated—with square (Fig. 8) and cylindrical pores (Fig. 9). The pore depth was 230 μm in both cases. The plots show simulated dependencies of the thermal neutron detection efficiency on pore

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[1] To leave an empty space which allows an energy calibration with alpha particles from a calibration source.