1. **Purpose and Aims**
* A neutron detector replacement for the shortcoming supply of 3He gas is needed. 3He is commonly used in neutron detectors. Today there is a definite deficiency of supply and new detectors have to be developed.
* An integrated pixellated E/E detector telescope, which suppresses the influence of gamma background, is proposed for counting of neutrons. This detector will have applications where background suppression is needed and high spatial resolution is required. Typically performance of such detectors for neutron scattering is better defined as signal to background performance rather than raw efficiency; such enhanced gamma rejection capability addresses exactly that.
* Scientists working at spallation sources need this new developed solid state detector, especially in the instruments for MacroMolecular Crystallography, Reflectometry, Small Angle Neutron Scattering (SANS) and also in neutron imaging experiments. The new Spallation Source in Lund (ESS) is one center where we see the need of this new detector, with unmatched spacial resolution qualities.
* The detector will also be of interest in neutron dose measurements where gamma background suppression is needed. The detector will also be of interest in surveillance and security applications as well as in industrial production.

In material research using thermal or cold neutron beams, a gamma background is present by interaction of the neutrons in the beam tube, mechanical shutters etc. For a long time the “golden” detector for neutrons has been the 3He based gas detector, which has a very high efficiency and low gamma sensitivity. But now, with the shortage of 3He, new detectors have to be developed within the neutron science community.

The proposed structure will suppress the gamma background by a coincidence measurement! The structure consists of an integrated E/E detector telescope. A layer of neutron converter is deposited on the detector telescope to generate charged energetic particles. The particle passes through the thin E detector into the E detector and by coincidence measurement the event is recorded. A Gamma photon gives, if absorbed, only interaction in either the E or E-detector and is therefore not recorded, i.e. a non-coincidence event. To improve the sensitivity to neutrons, the surface can be textured to increase the area [1] or the detector can be at an inclined angle to incident neutrons. A schematic sketch is seen in fig.1. We will also investigate an alternative where the converter layer is deposited between the two detectors, in this case taken advantage of the two opposite directed particles that are emitted, an alpha (2.05 MeV) and Triton (2.75 MeV) (Li converter) and a 7Li (0.83 MeV) and an alpha(1.47 MeV) (Boron converter). In this case the coincidence is caused by two particles emitted at the same time but 180 degrees apart.

E-detector, 300 m

Neutron converter

E-detector, 3-10 m

nnN+-doping

MEDIPIX-readout chip

Indium bump

N+-doping

P+-doping

Figure 1, A schematic sketch of a pixellated neutron detector with MEDIPIX readout chip (not in scale).

Moreover, the E-detector is proposed to be pixilated, and with a pixel size of 55 m by 55 m, a neutron imaging system can then be built. Together with the MEDIPIX readout chip [2], a complete system is formed. The system is developed to be used at existing neutron sources and also at the proposed *European Spallation Source* to be located in Lund. Future instrumentation would benefit from using a detector system with high rate capability, improved spatial resolution and suppression of the gamma background [3]. Questions like the following statements have to be investigated and answered during the project: Does the neutron converter induce serious stress in the structure which can increase the leakage current and density of recombination centers? Is the sensitivity satisfied with one layer of converter or is it necessary to stack several detector systems to achieve an efficiency of about 30%? Can we increase the sensitivity, without changing the thickness of the converter layer by altering the composition of the converter? Do we need to segment the E detector into a strip detector in order to decrease the capacitance and lower the noise in the detector system?

1. **Survey of the field**

The neutron is a neutral particle, which in order to be detected, must undergo nuclear reactions, which generate charged particles and/or gamma rays. The charged particle and/or gamma photons can then be detected in a sensor for ionizing irradiation [4]. In most cases the charged particle is easiest to detect, caused by its higher stopping in the solid state detector. A material which produce charged energetic particles when irradiated by neutrons can therefore be used as a converter layer in a detector system. However, gamma rays are present in abundance, originated from the neutron source itself or by interaction with matter i.e. beam tube, mechanical shutters etc., a gamma background is generated in the spectrum measured by the solid state detector. I want to remind that all semiconductor detectors are also sensitive to high energy photons. The gamma background thus interferes with the spectral peak from the charged particle. Therefore the resulting number of neutron counts is imprecise [5].

The use of neutrons in material research has many advantages as neutrons interact with material with light atoms such as hydrogen compared to gamma rays which interact more efficiently with material consisting of heavier atoms. Moreover, the particle´s wave properties at low energies makes it possible to investigate materials on an atomic scale i.e. ~Å- dimensions. The interaction of neutrons with matter is weak. The absorption in most material is therefore also small. This means that thicknesses of several centimeters can be investigated. The low energy used (less than 0.025 eV) makes the neutron irradiation gentle, when studying sensitive samples. Carbon-Carbon bond energy is as small as 4 eV and can therefore be investigated using neutrons i.e. biological material. This property of neutrons makes it suitable for use in techniques based on “small angle neutron scattering”, SANS, [6]. The detector systems for SANS instruments have generally been equipped with 3He gas detectors or scintillation neutron detectors. The spatial resolution is in the order of a few mm for these detectors [7]. A GSO scintillating layer of 500 um gives a spatial resolution of about 1.3 mm, while a thickness of about 20 um is predicted to give a spatial resolution of 100 um. However, an imaging intensifier with a multiplication factor of 109 has to be used for efficient detection using a CCD camera [8]. The scintillation structure is also sensitive to gamma background. A solution with a CCD readout detector system has also the drawback that it is too slow for timing experiments. The 3He gas detector has the drawback caused by the fact that the access of 3He is limited, which will definitely stop the use of these detectors.

Detectors for large area detection are developed by ESS in collaboration with ILL, Grenoble and the Thin Film Physics Division, University of Linköping, where B4C is used as converter and this layer is deposited on Aluminum foils and stacked to increase efficiency. The basis for the detector is a gas discharge, caused by the particles emitted from the B converter, which is read out by strips and the resolution is in the mm range. The advantage is that large areas, several square meters can be covered. Other similar development projects can be found in some other laboratories in Europe like the work at the Helmholz-Zentrum Geesthacht. For details, see ref. [20 and 21 and 22]

A technology to be developed is detectors based on semiconductor materials. This is a promising area for limited area detectors and detectors that can show high spatial resolution, in the range of micron or better, as well as timing and high count rate performance. By stacking detectors large areas can be obtained and right now we are involved in a 15x15 cm detector project. Such detectors will be game-changing for neutron scattering applications.

Solid state detectors have been used for several decades for ionized particles and photon detections. The use of planar processing utilizing ion implantation and thermal silicon dioxide was adapted relatively lately for manufacturing of radiation detectors made of silicon [9]. One example of planar processing of detectors is the work we have done in UV-Detectors, where critical issues regarding processing and termination of interface recombination centers is discussed and verified experimentally [10]. Long time stability in detectors for radiation therapy is described in ref [11]. Detectors with spatial resolution began to be developed in early 80s. The demand was to achieve a spatial resolution for 3-10 um for short-living particles. Strip detectors and charge coupled devices (CCD) were developed during that time. Furthermore, at the end of the 1990s pixellated detectors began successfully to be implemented in the experimental work [12]. Moreover, specially designed detectors to minimize the effect of charge sharing between the pixels have been developed and manufactured in our own processing clean-room at Mid Sweden university [13].These detectors were connected via bump bonding to the MEDIPIX readout chip developed by the MEDIPIX collaboration [4]. Integrated E-E Detectors for coincidence measurements in nuclear physics have been developed and fabricated using wafer bonding, described in ref [14]. An alternative way to form the buried contact is by using high energy implantation [15]. Another possible method is by epitaxial growth of layers. The E-E detector used in nuclear physics has the advantage to be able to identify an ionized particles identity (mass) and energy. For neutron detection we use the coincidence from a detected charged particle in the E/ E detector to record the event.

1. **Project Description**

***Theory:***

The basis of this proposal is that, in some applications, solid state detectors will replace the 3He filled gas detector now in use, caused by the low production of 3He gas.

The solid state detector will replace existing detectors where high spatial resolution is needed and the detector area is limited. This replacement will also lead to detectors with improved performance in above aspects. In some applications the detector area can be decreased by changing the geometry of the experiment. This is possible when detectors have high spatial resolution and can handle high count rates.

This project is focused on the development of the stacked detector built up of two semiconducting layers bonded together by a metal layer. This enables suppression of gamma background counts by coincidence counting and thus excluding pulses generated by gamma photon absorption in the detector structure. The detector can either be developed for dose measurements with a single pad area or as a pixellated detector for 2d-imaging.

Two areas have to be studied and integrated when it comes to thermal budget and other constrains in the detector processing technology.

**The first** is the bonding of the two detectors, the thin detector and the thick detector that can act as carrier. This will be discussed later in the project description.

**The second** is the integration of a converter layer. The structure of the neutron converter must be made so that an efficiency of about 30% is reached and without any serious stress induced in the detector. The stress can result in a high leakage current and increased density of recombination centers, which increase the noise and lower the charge collection efficiency. Moreover, the neutron converter used must be a stable layer on the detector surface, without any tendency to react or diffuse into the detector.

We will also as an alternative put the converter layer together with the glue layer, this will give coincidence from the two particles ejected 180 degrees apart. TiB2, B4C or Li compounds will be investigated. The suppression of the gamma background improves the accuracy in the neutron counts; therefore the amount of suppression is an important parameter to investigate.

***Method:***

Designed and fabricated detectors will be experimentally tested. Simulation and theoretical calculations will support the experimental work.

* + Simulation and theoretical calculations will give us guidance how the final detector structure should be defined.
	+ Some critical issues like induced stress motivate that some parameters need to be split up in the processing. The etched groove in the E detector, which increases the area of converter, can have different ratio between etched trenches or pores and unetched areas. Different ratios can easily be implemented in the mask set.
	+ The neutron converter must be stable and not react with the detector structure. Measurements and investigations have to be done to detect possible reactions or in-diffusion in the detector surface. Four-point probing can be used, if the in-diffusion alters the resistivity, X-ray diffraction, scanning electron microscopy with energy dispersive spectroscopy etc is other methods used in the material analysis.
	+ The used thickness of the E detector depends of the energy of the detected charge particle, which in turn is depending of used neutron converter. Some adjustment of the thickness of E-detector can therefore be necessary.

***Implementation:***

* Simulation and detector design, which includes converter layer, used ratio of pores, if these can be used, and thickness of E detector, is done at Mid Sweden University.
* Mask set design using Clewin and ordering of mask sets. (Mid Sweden University)
* Ordering of neutron converter material (Mid Sweden University)
* Test of stability and measurement of in-diffusion of critical diffusers, i.e. Lithium etc. This is performed using monitor wafers. (Mid Sweden University)
* Ordering of wafers with two grown epitaxial layers. (Mid Sweden University)
* Critical processing steps and processing strategies are tested, i.e. passivation of pores walls, connection of buried layers in between the E and E detector, measurement of leakage current in non pixilated test samples, measurement of particle response with an alpha source. (Mid Sweden University)
* Processing of pixilated detectors in the clean room of Mid Sweden Universities, deep etching is done by ACREO in Kista.
* The pixilated detector is bump bonded to the MEDIPIX-electronic chip, at Mid Sweden University.
* The System is tested in terms of sensitivity and gamma background by using an AmBe source with paraffin moderator (Mid Sweden University).
* Evaluation is done regarding suppression of gamma background and neutron sensitivity. Efficiency can be improved if needed by stacking detectors in a telescope configuration. (Mid Sweden University, together with IEAP at CTU in Prague).
* The system is tested in a neutron beam line in terms of sensitivity, gamma background and spatial resolution. In cooperation with IEAP or at other places.

***Preliminary timeplan:***

|  |  |  |
| --- | --- | --- |
| **Year** | **Activity** | **Milestone Deliverable** |
| **1** | Simulation and detector designDifferent composition of neutron converterMaskset design | * Define ratio of pores
* Define thickness of E det.
* Prediction of neutron sensitivity and suppression of gamma background by different composition of neutron converter. Converter on top or as a glue layer in between the detectors.
* Investigate a porous structure in the delta E detector; use only one thin detector, no coincidence, but low gamma absorption
 |
| **2** | Ordering of neutron converter for depositionStability evaluation of neutron converterOrdering of epi-waferProcessing of detector | * Stability test of converter using monitor wafers, evaluation is done using four point probe, x-ray diffraction, SEM- with EDS
* Critical processing steps and processing strategies is defined, non pixilated test samples is finished
* Measurement of leakage current
* Measurement using alpha particle, energy deposition , energy resolution
* Measurement of neutron sensitivity and suppression of gamma background
* Submission of publication at IWORID conference
 |
| **3** | Processing of detector, continuedPreliminary testing | * Processing of pixilated detector
* Measurement of neutron detector bonded to a MEDIPIX-readout chip
* Submission of publication at Nuclear science symposium
 |
| **4** | Final test in a beam line | * Measurement of spatial resolution in a neutron beam line, small angle neutron scattering, using detector bonded to a MEDIPIX-readout chip
* Submission of publication at IWORID conference
 |

1. ***Preliminary results:***

We have, in the research group at MIUN, a specially designed clean room including ion-implantation for detector fabrication, bump bonding for indium and laboratory resources for characterization of fabricated detectors. Planar and pixellated detectors have been fabricated in the clean-room at Mid Sweden University and results are published.(16 to 19)

***Evaporation of TiB2 as a neutron converter:***

TiB2 was deposited by electron evaporation on a planar silicon detector to investigate the possibility to use it as a neutron converter layer. Figure 3 shows a schematic sketch of the structure and in figure 4 is the simulated response of the generated alpha particles shown for two different thicknesses. [16] From figure 4 it is clear that a thicker layer does not improve the sensitivity with respect to the count rate for a defined spectral peak. Instead the peak is broadened caused by the stopping of the alpha particles in the converter layer. This is problematic in the presence of a gamma background.

 

Figure 3, Simulated structure of a detector with neutron converter

Figure 4, Comparison of two alpha spectra simulated with 2000 Å and 10000 Å TiB2 layer thicknesses energy

Detector response of the produced alpha particles and 7Li nuclei from a converter layer with thicknesses of 2000Å, se figure 5 from ref [17].

 

Figure 5, Energy calibrated P/H spectra measured on a detector with converter layer using the CMI’s neutron source.

Figure 6, Simulated detection efficiency of structures with square pores as a function of pore size and 6LiF neutron converter density.

***3D-structures:***

To improve the sensitivity of the detector, the surface can be structured. This can be done by electrochemical etching of silicon or by using deep reactive ion etching. In figure 6 it can be seen that an efficiency of about 30% or more can be achieved by a proper pore size and the pores filled with enriched 6LiF as neutron converter [18] and [19]. This will be studied in the case we need coincidence measurements and this will need special designs of the detector stack.

1. **Significance**

This project regarding imaging of neutrons is of importance for the development of new detector structures that can replace 3He gas detectors. The improved spatial resolution is needed, as well as the suppression of gamma background and rate capability address exactly the detector limitations presently encountered for macromolecular crystallography, reflectometry and SANS instrument classes. The European Spallation Source to be located in Lund, gives us new, unique possibilities to improve and verify experimentally the performance of neutron imaging detectors, which we will develop in our laboratory.

The need of high spatial resolution detectors is growing with the development of improved techniques for high resolution neutron imaging. One interesting area is phase contrast imaging where high resolution detectors are needed.

One should also remember that together with the need of 2D detectors for research , there is also a need for detectors for neutron dose monitoring. These detectors have to be portable in many cases and should be cheap and low power operated, which makes the solid state semiconductor detector the ultimate choice. The growing field of detectors for surveillance and security needs also detectors with gamma rejection counting and with similar performance requirements as the research community is asking for.

1. **Equipment**

***Laboratory resources***

We have in house a 250 m2 clean-room class 1000, equipped with in general all necessary equipment and processes to fabricate radiation detectors in silicon, an overview of the clean-room is found in figure 7. Deep ion etching of silicon to form pores or trenches is at this moment done at ACREO in Kista. The close cooperation with ACREO gives us access to advanced processing, when needed. We have also an in-house electrochemical etch installed that will be used in some of the detector manufacturing processes.

A new X-ray laboratory has been built at MIUN. In this laboratory essentially all software and auxiliary equipment is available for reading the MEDIPIX readout circuit.

Measurement systems for particles detectors are available in our characterization area, including different radiation sources i.e. alpha, beta and gamma as well as thermal neutron sources.

The close cooperation with IEAP in Prague and SURO gives us access to calibration equipment and neutron beam analysis facilities.

Through ESS, calibrated testing facilities for neutrons and backgrounds and access to neutron beamlines is possible. Additionally expertise in simulation and in measuring performance comparative to existing detector classes is available.



Figure 7, Clean-room for processing of semiconductor and micromechanical sensors at Mid Sweden University

1. **International and National collaboration**
* The European Spallation Source, ESS, Richard Hall-Wilton, head of detector group (www.esss.eu) Experience with detector and imaging instrumentation, end user. Knowledge of overall demands on neutron detector parameters for ESS experiments. Expertise in neutron imaging in general and best knowledge of detector requirements for neutron imaging at a Spallation source like ESS. ESS will be involved in the testing of the detectors. Richard H-W is in the final stage in the faculty evaluation process for becoming an adjunct professor at Mid Sweden University.(April 2013)
* MEDIPIX collaboration at Cern ([www.cern.ch/medipix](http://www.cern.ch/medipix)) As the project is based on MEDIPIX/TIMEPIX chip technology developed within Medipix collaboration coordinated through CERN, it is expected that close cooperation will be established with CERN. MIUN is a member of the MEDIPIX collaboration and one of us Christer Fröjdh is elected spokesperson for the Medipix2 consortium. One student from Mid Sweden University is on a grant position at Cern for three years to finish his Ph D thesis and working in the Medipix group headed by Michael Campbell. Christer Fröjdh has also supervised three students working at Cern and financed by Cern to their Ph D at Mid Sweden University.
* Cooperation with Desy in Hamburg, Heinz Grafsmaa, which is adjunct professor at Mid Sweden University.
* Institute of experimental and applied physics, IEAP at CTU in Prague, prof. Stanislav Pospisil ([www.utef.cvut.cz](http://www.utef.cvut.cz)) Access to and know-how of Medipix and Timepix technology, R/O hardware, software to control detector and signal evaluation. IEAP detector team has a broad experience with a development of Medipix/Timepix detecting systems and their use. We cooperate in two ongoing Vinnova projects in detector technology. One of us, S.P. is ordinary staff member at the institute, working 10%. Students from IEAP have done part of their thesis work at Mid Sweden University, supported by IEAP.
* Sintef in Norway. We collaborate in 3D structure detectors and pyramidal detectors with TiB2 as converter. (Thor-Erik Hansen and Angela Kok)
* Acreo in Kista. We cooperate in two projects on x-ray scintillating and neutron detectors for imaging. Projects are financed by Vinnova and industrial partners. Acreo has developed the dry etching process for deep trenches.
* Cooperation in Vinnova and KK foundation financed projects with industry. Ongoing project with Scint-X, MidDec, RTI and Studsvik as well as closed projects with Bjerkings and SURO in Prague. The ongoing Vinnova projects are MIXRAY a European project within the MNT-ERA NET platform, 4.5 Mkr, coordinated by S.P., and a Scintillator project of about 2 Mkr also coordinated by S.P. Both projects are industrial and are neutron detector and x-ray counting detector developments, i.e. not the same project as the project described in this application, which is a research project and which maybe later can become a product. We are also cooperating with Sitek in position sensitive detectors and especially looking into UV beam position detection.
* SURO the National Radiation Protection Institute, NRPI, in Czech Republic. ( http://www.suro.cz/en) We work together on Radon detector development financed by Vinnova and a company in radon radiation control by ventilation, Radovac. This detector project is close to the end and detector systems are at the moment placed at customers for testing. A pre study was finished before this project started, financed by Vinnova and Bjerking. Partners were IEAP in Prague, SURO and Bjerking as well as Mid Sweden University and MidDec. Our group is responsible for the development of the radon detector system, which is based on a particle detector similar to the E detector in this application.

**Final Comment:**

This application is based on the competence at Mid Sweden University when it comes to solid state detector research. No other University or research group in Sweden is active in this field and our competence is unique, with a track record back to 1968, when the first publication was made on surface barrier detectors (S.P.).

The research group with members doc. Göran Thungström, Prof. Christer Fröjdh and Prof. Sture Petersson with support from adjunct professors, Jan Andersson Acreo and doc. Richard Hall-Wilton ESS and Professor Stanislav Pospisil at IEAP, is in our opinion well suited to carry out this project.

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