Directional Response of Microstructure Solid State Thermal Neutron Detectors

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INTRODUCTION

Recent advances in the design and fabrication of solid-state thermal neutron detectors[1,2,3] aim at improving device efficiency, such as the inclusion of micron and sub-micron scale structures[4,5] and the development of solar-cell type devices with continuous p-n junctions[6]. Previous research has focused on the optimization of single detector designs, where simulated and experimental results have assumed all of the incident neutrons are normal to the device surface[4,7]. The work presented here investigates the angular response of single and multiple detector configurations to a fast neutron source.

THEORY

The basic design of most solid state thermal neutron detectors currently under development consist of a semiconductor (e.g., Si, GaAs) etched with structures such as holes, pillars, or parallel trenches, which are then filled with a thermal neutron converter, typically ^{10}B or ^{6}LiF. For these devices, one of the main factors affecting detector efficiency is neutron interaction probability. As mentioned previously, almost all work done to increase device efficiency assumes a parallel incident neutron beam; for a given absorber, neglecting the small scattering cross section and assuming thermal (0.0253 eV) neutrons, a first order approximation is

$$P(x) = \left(1 - e^{-\Sigma_a \cdot x}\right) \cdot F_g \qquad (1)$$

where Σ_a is the thermal macroscopic absorption cross section, x is the neutron path length in the absorber, and F_g is the absorber area fraction. By neglecting scattering in the semiconductor, the neutron path length is a consequence of incident trajectory.

Consider a neutron dosimeter, a possible application of these devices; the detector (or detector stack) would need to be covered by or encapsulated within a moderating material, such as high density polyethylene (HDPE) to detect fast neutrons. As scattering of neutrons from hydrogen is virtually isotropic in center of mass, thermal neutrons would be incident on the detector with a wide angular distribution. This would result in varying path lengths in the absorber, making the parallel beam approximation invalid for a single detector. With proper alignment, however, a stack of multiple detectors would be less affected by this. Although there is some research on the effect of detector angular response on efficiency[8], it is only a 2-D approach.

DESCRIPTION OF THE ACTUAL WORK

Monte Carlo Simulation

The GEANT4 simulation toolkit [9] was used to model both single and multiple detector configurations in three different scenarios as shown in figure 1.

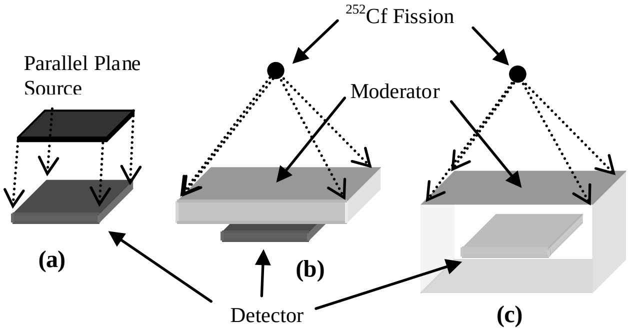

Fig.1. Simulated detector-source configurations of: (a) parallel plane thermal neutron source, and a fission neutron source with (b) a moderator covered detector and (c) a detector embedded in the moderator

Simulated detector parameters, obtained from previous work[7], were as follows: 50 μm deep hexagonal holes, possessing a diameter of 1.4 μm and separation of 1.0 μm, were etched into a 100 μm thick block of monocrystalline silicon and filled with 99% ^{10}B. The moderator utilized was HDPE with a density of 0.94 g/cm^3. The multiple detector configurations consisted of repeated single detectors, each copy rotated 90 degrees about the z-axis from the previous. Each simulation was run until 10^6 thermal neutrons were incident on each detector/stack, with no distinction made between the absorption layer and silicon base. The lower level of discrimination (LLD) was set at 200 keV.

RESULTS

The efficiencies shown in figure 2 were calculated by dividing the number of incident thermal neutrons by the number that deposited energy in excess of the LLD.

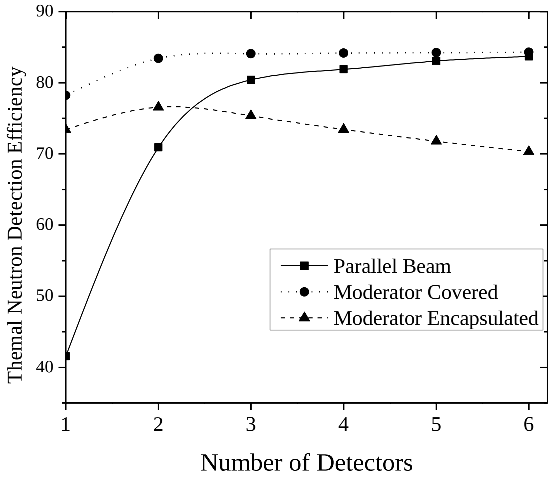

Fig. 2. Thermal neutron intrinsic detection efficiency as a function of moderator configuration and number of coupled detectors

As seen above, there is a large difference in the response of a single detector. For the geometry in figure 1a, neutrons streaming through the silicon walls surrounding the ^{10}B do not interact. This neutron streaming is significantly reduced by the offset stacking of additional detectors, increasing efficiency by ~30% and 8% for stacks of two and three detectors, respectively.

The geometry of figure 1b improved efficiency by 35% and 13% over the single and double detector stacks of geometry in figure 1a, respectively, while the response with additional detectors demonstrated convergence of geometries 1a and 1b.

The encapsulated device exhibits a maximum efficiency of ~76% with two detectors, but decreases with additional detectors. Similar to the parallel beam geometry, this effect is caused by neutrons streaming through the device; since half of each detector volume is pure silicon, neutrons incident to this area on trajectories near parallel to the device face will not interact.

CONCLUSIONS

As expected, the incident angular distribution of a moderated source minimized neutron streaming, greatly improving the intrinsic efficiency of a single device. Surprisingly, the appropriate stacking of two detectors resulted in a maximum efficiency of ~80%, comparable to that of a ^{3}He filled gas detector. Although exhibiting lower efficiency, the application of a moderated solid state detector similar to that seen in figure 1c would be insensitive to source location.

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REFERENCES

1. D Mcgregor, M Hammig, Y Yang, and H Gersch, "Design considerations for thin film coated semiconductor thermal neutron detectors---I: basics regarding alpha particle emitting neutron reactive films," *Nuclear Instruments and Methods in Physics Research A*, vol. 500, no. 1-3, pp. 272-308, 2003.
2. D Emin and T Aselage, "A proposed boron-carbide-based solid-state neutron detector," *Journal of Applied Physics*, 2005.
3. R Nikolic et al., "Fabrication of Pillar-structured thermal neutron detectors," *Nuclear Science Symposium Conference Record, 2007. NSS '07. IEEE*, vol. 2, pp. 1577-1580, 2007.
4. J Shultis and D Mcgregor, "Efficiencies of coated and perforated semiconductor neutron detectors," *Nuclear Science, IEEE Transactions on*, vol. 53, no. 3, Part 3, pp. 1659-1665, 2006.
5. Rebecca J Nikolic et al., "Pillar structured thermal neutron detector," *Solid-State and Integrated-Circuit Technology, 2008. ICSICT 2008. 9th International Conference on*, pp. 2361-2364, 2008.
6. N LiCausi, J Dingley, Y Danon, J Lu, and I Bhat, "A novel solid state self-powered neutron detector," *Proceedings of SPIE*, **7079**, (2008)
7. J Dingley, N Licausi, Y Danon, I Bhat, and J Lu, "Optimization of a Novel Self-Powered Solid State Neutron Detector," *International Conference on Mathematics, Computational Methods & Reactor Physics* , Saratoga Springs, NY, 2009.
8. S Bellinger, W Mcneil, T Unruh, and D Mcgregor, "Angular response of perforated silicon diode high efficiency neutron detectors," *Nuclear Science Symposium Conference Record, 2007. NSS '07. IEEE*, vol. 3, pp. 1904-1907, 2007.
9. S Agostinelli, J Allison, K Amako, and J Apostolakis, "Geant4---a simulation toolkit," *Nuclear Inst. and Methods in Physics Research*, **506**, pp. 250-303, (2003).