Silicon-based, pillar-structured thermal-neutron detectors

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A microscale, solid-state system can be fabricated to produce a radiation detector that promises to achieve an efficiency of 50%.

Ensuring that our country remains safe from chemical, biological, nuclear, or radiological attack is the main motivation behind the search for new sensor technologies. These efforts have steadily increased since 11 September 2001, because concerns have mounted about dangerous materials potentially falling into the wrong hands. One important area of research is detection of illicit possession of special nuclear materials. Because these materials release gamma ($\gamma$) rays and neutrons, work at Lawrence Livermore National Laboratory to develop detectors for both types of radiation is ongoing.

Neutron detectors used in the field typically operate with tubes filled with Helium-3 ($^3$He) gas. These devices are large, require high operating voltage, and are sensitive to vibrations. In addition, $^3$He is in much shorter supply at present than it was when our nuclear-weapons stock was built. Current supplies of $^3$He are declining rapidly. They come, in part, from dismantling of nuclear weapons, where it accumulates as tritium decays.

A typical $^3$He tube employs a 50mm-diameter vacuum tube and operates at approximately 1000V. Such a device can achieve thermal-neutron-detection efficiency of greater than 70% in the laboratory. However, its efficiency is reduced to approximately 20% because of adjustments that are usually made to achieve long-term stability. Advances in micro- and nanotechnology can enable a new $^3$He-tube replacement technology. Our recently developed ‘pillar detector’ relies on a carefully constructed platform of 3D etched microscale silicon pillars that are interspersed with $^{10}$Boron ($^{10}$B). The $^{10}$B converts incoming neutrons to $\alpha$ and $^7$Lithium ($^7$Li) particles that interact with the semiconductor and create the current that provides the electronic signal. Figure 1 shows a comparison of both devices. Our team recently demonstrated a thermal-neutron-detection efficiency of 20% (for 2$\mu$m-wide pillars with a 4$\mu$m pitch and a height of 26$\mu$m). This is the highest efficiency reported to date for a semiconductor-based thermal-neutron detector using $^{10}$B as converter material. The device’s $\gamma$ discrimination is $10^5$. Figure 2 shows the corresponding radiation spectra.

A key challenge in fabricating the pillar detector is associated with the deposition of the $^{10}$B material. We are collaborating with Barry Cheung (University of Nebraska at Lincoln), who uses chemical vapor deposition (CVD) to fill the pillars with $^{10}$B. We developed conformal filling of high-aspect-ratio silicon micropillar structures with $^{10}$B using low-pressure CVD with decaborane. However, the $^{10}$B needs to decompose on the surface of the pillar array rather than in the gas phase. If decomposition occurs in the gas phase, the boron coating will reside at

Figure 1. Comparison of primary figures of merit for a commercial Helium-3 ($^3$He) tube and our pillar-structured thermal-neutron detector. HV: High voltage. Si: Silicon. $^{10}$B: Boron-10.

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Radiation spectra exhibiting low detector noise, neutron events, and low \( \gamma \) counts based on measurements of the device without a radiation source, and with moderated Californium-252 (\(^{252}\text{Cf}\)) and Cesium-137 (\(^{137}\text{Cs}\)) sources, respectively.

the top of the pillars and a poor fill factor will result. A high volume of \(^{10}\text{B}\) is needed to efficiently capture the thermal neutrons. We found that preferential decomposition of decaborane on the substrate surface favors conformal coating of the pillar structure at a low process temperature of 425°C. A low process pressure (<50mTorr) is necessary to ensure uniform delivery of decaborane to all substrate surfaces because of the resulting very-long mean-free path of the precursor molecules.

We have now acquired funding to scale up the device by increasing the pillar height to ‘build up’ a larger volume of \(^{10}\text{B}\), which will enable us to achieve high efficiency. We estimate that fabrication of a 50%-efficiency device will be possible with a pillar height of approximately 50µm. In addition, we are combining our device with readout electronics to develop a system-level solution. We are making progress in this area by integrating a nine-channel system (that will include nine pillar detectors, each covering a 4 \times 4\text{mm}^2 area) with a custom design using off-the-shelf-components. The readout chain includes a charge-sensitive preamplifier, a shaping amplifier with 250ns shaping time, a low-level discriminator, and a LED display. It will read out either an electron or a hole signal.

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Rebecca Nikolic received her PhD degree in electrical engineering (specializing in applied physics) from the University of California at San Diego in 2002. Since joining in 2002, she has contributed to and led many projects at LLNL, where she is group leader. She is author or co-author of 50 publications.

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References

This work was performed under the auspices of the US Department of Energy by Lawrence Livermore National Laboratory (contract DE-AC52-07NA27344, LLNL-TR-434794) and supported by the Domestic Nuclear Detection Office in the Department of Homeland Security.