

# Very Large Area Multi-Element Microstructured Semiconductor Neutron Detector Panel Array

Steven L. Bellinger, *Member, IEEE*, Brian W Cooper, Nathaniel R. Crawford, Ryan G. Fronk, *Member, IEEE*, Timothy J. Sobering, *Member, IEEE*, Russell D. Taylor, Douglas S. McGregor, *Member, IEEE*

**Abstract** – Low-power microstructured semiconductor neutron detector (MSND) devices have long been investigated as a high-efficiency replacement for thin-film diodes for solid-state thermal neutron detection. Improvements in detection efficiency were made by integrating two stacked  $1\text{ cm}^2$  devices to function as a single detector, achieving over 42% intrinsic thermal neutron detection efficiency. The need for larger active area devices led to the development of the Arrayed Device which combined seventy-two dual-stacked  $1\text{ cm}^2$  devices to act as a single large-area detector in a  $6\times 6$  configuration, providing an active detector area of  $36\text{ cm}^2$ . A new development in large active area devices has led to high-quality  $4\text{ cm}^2$  individual devices arrayed into a detector array comprised of 16 of individual perforated devices, at  $64\text{ cm}^2$ , providing a 78% increase in active area over the previously reported  $6\times 6$  element. Nine of the  $4\times 4$   $4\text{-cm}^2$  elements are then integrated together into the Very Large Area Panel Array (VLAPA) with total device dimensions of  $11.125''\times 11.125''\times 0.5''$  without moderator. The elements work to function as a single VLAPA with an effective active detection area of  $576\text{ cm}^2$ . The VLAPA has been found to have an intrinsic efficiency of  $2.21\pm 0.02\%$  with 2 inches HDPE on the front and back for an un-moderated  $^{252}\text{Cf}$  source.

## I. INTRODUCTION

THE need for large active-area neutron detectors has become more important in recent years. Previously, the low-power, high-efficiency, microstructured semiconductor neutron detectors (MSND) had proven to be a viable alternative to other common neutron detectors. These devices were initially developed with  $0.25\text{ cm}^2$  in active area as thin-film and perforated devices [1-31] but have since been scaled to  $4\text{ cm}^2$  in active detection area [32]. Current progress in dual-stacking two perforated detectors has yielded a device with 42% intrinsic detection efficiency [33-34]. Further increasing the active area of a single semiconductor device will typically increase the leakage current and capacitance of the device, leading to high noise and low signal strength. It is the ability to discern signal from noise that allows for the MSND devices' ability to discriminate neutron events from incident gamma rays. The leakage current and capacitance issue was

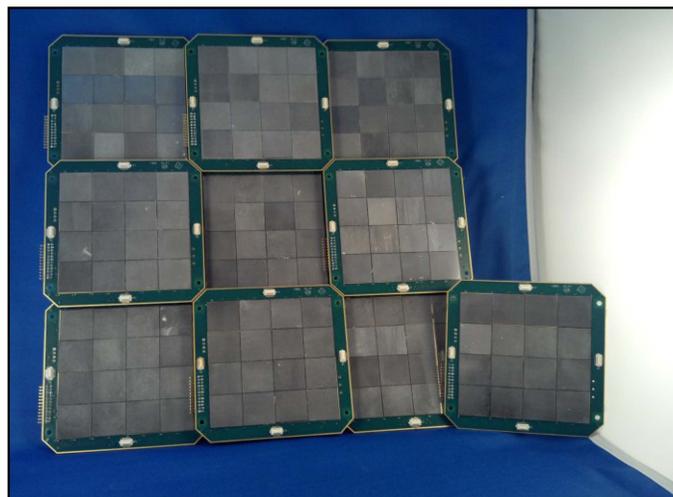


Fig. 1. Pictured is the Very Large Area Panel Array. Nine elements are arranged in a  $3\times 3$  configuration. A tenth element sets beside the array.  $4\text{ cm}^2$  MSND devices are arranged in a  $4\times 4$  layout to form a single element.

circumvented by arraying thirty-six  $1\text{ cm}^2$  devices and integrating them into a single  $36\text{ cm}^2$  device as previously reported [35]. The Very Large Area Panel Array (VLAPA) was developed to further increase the total active area of the MSND devices. Currently, nine  $64\text{ cm}^2$  elements have been arrayed together and integrated to form a single neutron detector with an active area of  $576\text{ cm}^2$ , as shown in Fig. 1. Each of the  $4\times 4$  elements are populated with  $4\text{ cm}^2$  diodes that were fabricated on 4-inch, n-type silicon wafers. Trenches were etched using a wet-etching technique and  $pn$ -junctions were formed with a  $p$ -type dopant. Prior to populating the  $4\times 4$  element, each of the diodes was tested for leakage current and capacitance. I-V and C-V curves of the  $4\text{ cm}^2$  diodes can be found in the sections below. The devices were then back-filled with  $^6\text{LiF}$  and mounted to their electronics.

The entire VLAPA assembly was then sandwiched between varying thicknesses of HDPE and was tested for its thermal neutron response, fast neutron response, and its gamma-ray rejection capability. For the thermal neutron response test, the detector array was compared to a calibrated  $^3\text{He}$  gas-filled thermal neutron detector. The detector's intrinsic detection efficiency was calculated from solid-angle calculations at 2 meters for all other tests.

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Steven L. Bellinger, Ryan G. Fronk, and Douglas S. McGregor are with the Semiconductor Materials and Radiological Technologies (S.M.A.R.T.) Laboratory, Kansas State University, Manhattan, KS 66506 USA (telephone: 1-785-532-7087, e-mail: rfronk@ksu.edu).

Timothy J. Sobering and Russell D. Taylor are with the Electronics Design Laboratory (EDL), Kansas State University, Manhattan, KS 66506 USA.

Nathaniel R. Crawford is with JNT Company, LLC, Manhattan, KS 66506 USA.

## II. DEVICE FABRICATION

The Very Large Area Panel Array assembly was comprised of nine individual 4x4 elements. Each of the elements consisted of an array of sixteen 4 cm<sup>2</sup> MSND devices, shown in Fig. 2. The individual diodes were fabricated on 100mm diameter wafers with a resistivity of 10k $\Omega$ -cm and (110) orientation. A 2.5 $\mu$ m silicon dioxide layer was grown on the surface of the wafers using a wet-O<sub>2</sub> growth process. A straight-trench design was patterned on to the wafer using AZ photoresist. The exposed SiO<sub>2</sub> was etched using a buffered HF solution, revealing the bare silicon that was to be etched into trenches. 225  $\mu$ m-deep, 20  $\mu$ m-wide trenches were etched along the <111> plane with a pitch of 40 $\mu$ m using a potassium hydroxide wet-etching technique. Using this wet-etching technique, 25 wafers were etched simultaneously, allowing for the production of hundreds of 4cm<sup>2</sup> MSND devices via batch processing. Because the devices are batch-processed, uniform neutron sensitivity from diode to diode is obtained. The devices were etched for several hours to obtain the desired trench depth, cleaned, and then diffused with a *p*-type boron dopant to form the rectifying *pn*-junction, with remaining SiO<sub>2</sub> as the barrier material between diodes. A Ti-Au ohmic contact was evaporated onto the backside to form the cathode of the devices. Each diode of the 4x4 elements was tested for its diode properties. At the operational bias of -1V, leakage current and capacitance of the devices were measured as -7.33 nA cm<sup>-2</sup> and 90 pF respectively, as shown in Fig. 3.

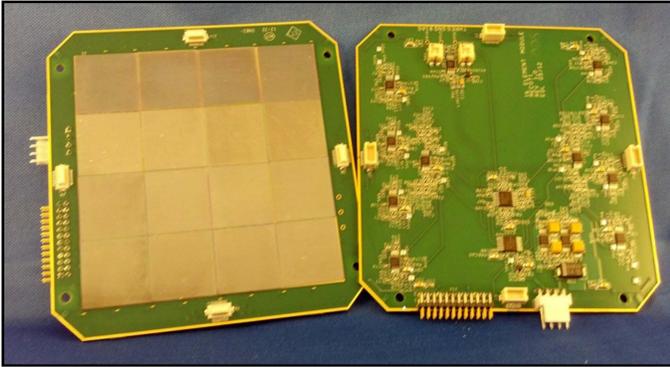


Fig. 2. Two 4x4 elements, each comprised of 4 cm<sup>2</sup> perforated diodes are pictured. One element has been flipped to showcase the back side. Eight pre-amplifiers work to sum all sixteen diodes.

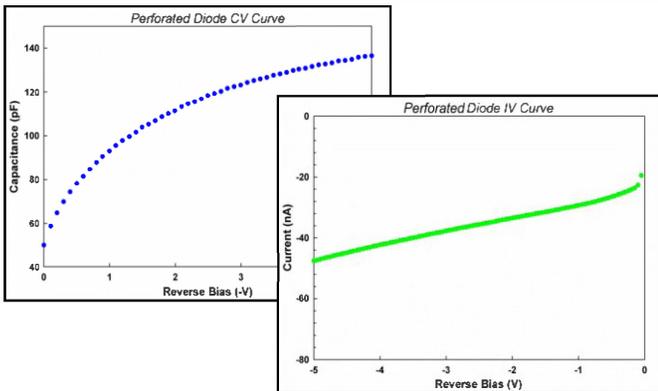


Fig. 3. Capacitance and leakage current of the individual 4 cm<sup>2</sup> diodes has been greatly reduced through new processing techniques using conformal diffusion.

The diodes were then backfilled with in-house nano-sized <sup>6</sup>LiF neutron reactive material and mounted to the electronics boards. The electronics boards house the pre-amplifiers, amplifiers, discriminators, and digital pulsars for the entire detector system. Each diode has an associated pre-amplifier with a gain of 0.33 mV fC<sup>-1</sup> charge amplification. The outputs from four diode-pre-amplifier pairs were coupled with a single amplifier, reducing circuit complexity and power consumption. Amplifiers operate with a 43.3 V V<sup>-1</sup> shaper and 15  $\mu$ s time-constant. In-all, there are sixteen pre-amplifiers and eight amplifiers per 4x4 detector element for an overall gain of 14.3mV fC<sup>-1</sup>. Each diode is biased with -1V, but can be varied by the user from -0V to -5V. The on-board discriminator provides a -3.3V logic level pulse when the analog output from an amplifier is above an user defined LLD, in this case the LLD was set at 350mV. The 4x4 elements were powered by  $\pm$ 8V and have a current draw of 4mA during operation, leading to a total current draw of 36mA for the entire Panel Array during operation.

All nine elements are coupled to a master summing board that combines the digital signal of each of the elements into a single digital output signal. The master summing board also distributes power to the Panel Array. The single digital output is then sent outside of the aluminum housing unit to the

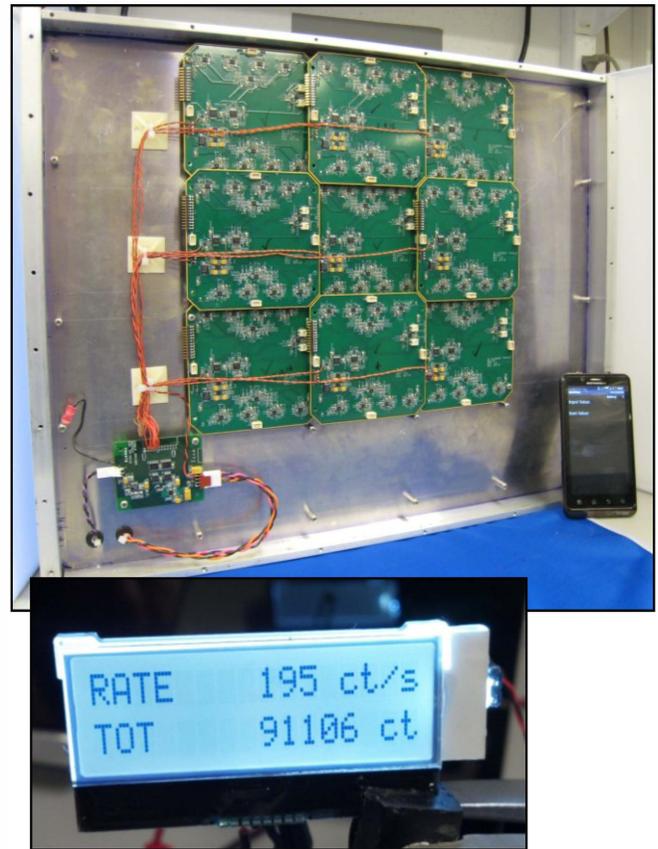


Fig. 5. Reading out information from the Very Large Area Panel Array is performed with both a proprietary Android phone application (top) on a handheld portable device as well as a physical display on the device (bottom).

motherboard where the digital signal is interpreted and read out on a physical display. The motherboard also transmits its signal via Bluetooth which can be read out with any Android phone using a proprietary phone application as shown in Fig. 5. The motherboard also houses a reset function for the measurement.

### III. DEVICE TESTING AND RESULTS

The Very Large Area Panel Array device was tested for neutron and gamma-ray sensitivity using various methods. Thermal neutron detection efficiency of the diodes used to populate the 4x4 elements was determined using the using a mono-energetic 0.0253eV diffraction beam-port located at the TRIGA Mark II nuclear reactor at Kansas State University [34,36]. This thermal neutron beam is 1.25 cm in diameter. The intrinsic efficiency was determined using a direct comparison method with a calibrated Reuter-Stokes  $^3\text{He}$  gas-filled proportional detector [19,27]. Diodes were chosen randomly to be tested. Generally, the efficiency of the diodes was found to be approximately 15% for intrinsic thermal neutrons. The diodes were then used to populate the 4x4 elements, which were in turn tiled to form the VLAPA. The LLD of each of the 4x4 elements were set separately, but were set to approximately 350mV in order to discriminate against gamma-ray background as well as electronic noise.

With thermal neutron sensitivity of the diodes established, the VLAPA was tested for its sensitivity to an un-moderated  $^{252}\text{Cf}$  fast neutron source. Moderator material was placed around the detector in the form of 2-inch HDPE plates on each the front and the back of the detector and 1-inch HDPE plates on the sides and top and bottom of the detector. The cross-sectional area of the HDPE plates was much larger than the detector in order to accommodate the addition of devices in future iterations of the device. Currently, the HDPE cross-sectional dimensions measured at 20"x16" as compared to the devices dimensions of 11.125"x11.125". The measurement was made at a distance of 2 meters for a period of five minutes as shown in Fig. 6. The source was then withdrawn and a background measurement was taken. The intrinsic detection efficiency was found to be  $2.21 \pm 0.02\%$  for the un-moderated  $^{252}\text{Cf}$  source using the larger area of the HDPE as the cross-sectional reference for the detector. Results of the two measurements can be found in Table 1.

The VLAPA device was also tested for its gamma-ray rejection capability using a high-activity  $^{137}\text{Cs}$  662-keV gamma-ray source. At the time of testing, the calibrated source had an activity of 69.84mCi. The device's response was determined at a distance of 55 cm from the source. A five-minute measurement yielded only 57 counts (which yielded a gamma-ray rejection ratio on the order of  $3.36 \times 10^{-9}$ ). The results from this measurement can also be found in Table 1.

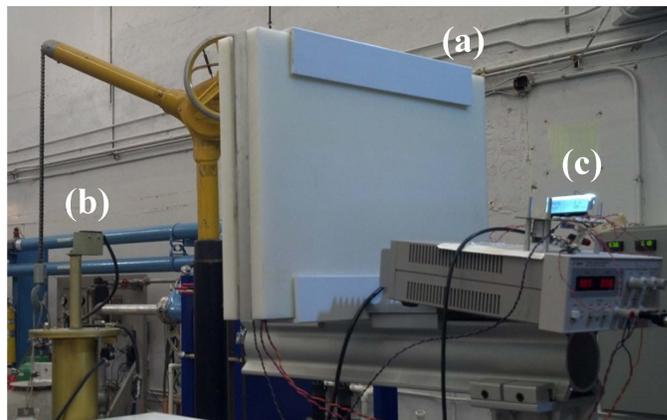


Fig. 6. The VLAPA was tested with an unmodified  $^{252}\text{Cf}$  source at 2 meters. (a) Depicts the VLAPA with 1 inch of HDPE on front and back, (b) is the  $^{252}\text{Cf}$  source location, and (c) is the mother board and power supply.

TABLE I. VLAPA DEVICE TESTING

| Detector                 | Ct. Time  | Counts | Int. Efficiency   |
|--------------------------|-----------|--------|-------------------|
| $^{252}\text{Cf}$ Source | 300 (sec) | 215000 | $2.21 \pm 0.02\%$ |
| $^{137}\text{Cs}$ Source | 300 (sec) | 57     | N/A               |

### IV. CONCLUSION

The Very Large Area Panel Array performed well as a large-area solid-state neutron detector. The device is considered portable because it is light-weight and was capable of being operated entirely without external electronics. Furthermore, with the advent of the Android phone application and Bluetooth capabilities, the device can now be operated with the operator up to 50 feet away, placing the user is far from the irradiated zone. Further investigations must be made to increase the overall detection efficiency of the VLAPA which will include using higher-quality perforated diodes, dual-stacked diodes, and using more 4x4 elements to form a larger active detection area with the near-term plans for the device being to increase the active area up to that of the cross-sectional area of the aforementioned HDPE.

### V. ACKNOWLEDGEMENTS

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### REFERENCES

- [1] D.S. McGregor, M.D. Hammig, H.K. Gersch, Y-H.Yang, and R.T. Klann, "Design Considerations for Thin Film Coated Semiconductor Thermal Neutron Detectors, Part I: Basics Regarding Alpha Particle Emitting Neutron Reactive Films," *Nucl. Instrum. and Meth.*, **A500**, pp. 272-308, 2003.
- [2] D.S. McGregor and J.K. Shultis, "Spectral identification of thin-film-coated and solid-form semiconductor neutron detectors," *Nucl. Instrum. and Meth.*, **A517**, pp. 180-188, 2003.
- [3] C.P. Allier, *Micromachined Si-well Scintillator Pixel Detectors*. Netherlands: DUP Science, 2001.
- [4] D.S. McGregor et al., "New Surface Morphology for Low Stress Thin-Film-Coated Thermal-neutron Detectors," *IEEE Trans. Nucl. Sci.*, **NS-49**, pp. 1999-2004, 2002.

- [5] D.S. McGregor and R.T. Klann, "Pocked Surface Neutron Detector," US-6545281, allowed April 8, 2003.
- [6] J.K. Shultis and D.S. McGregor, "Efficiencies of Coated and Perforated Semiconductor Neutron Detectors," *IEEE Nucl. Sci. Symp. Conf. Rec.*, Rome, Italy, Oct. 16- 22, 2004, pp. 4569-4574.
- [7] J.K. Shultis and D.S. McGregor, "Efficiencies of Coated and Perforated Semiconductor Neutron Detectors," *IEEE Trans. on Nuclear Science*, **NS-53**, pp. 1659-1665, 2006.
- [8] W.J. McNeil et al., "Development of Perforated Si Diodes for Neutron Detection," *IEEE Nucl. Sci. Symp. Conf. Rec.*, San Diego, CA, Oct. 29 – Nov. 5, 2006, pp. 3732-3735.
- [9] D.S. McGregor and R.T. Klann, "High-Efficiency Neutron Detectors and Methods of Making the Same," US-7,164,138, allowed January 16, 2007.
- [10] S.L. Bellinger, W.J. McNeil, T.C. Unruh, and D.S. McGregor, "Angular Response of Perforated Silicon Diode High Efficiency Neutron Detectors," *IEEE Nucl. Sci. Symp. Conf. Rec.*, Honolulu, HI, Oct. 26 – Nov. 3, 2007, pp. 1904-1907.
- [11] D.S. McGregor et al., "Perforated Semiconductor Neutron Detector Modules," *Proc. of 32nd Annual GOMACTech Conf.*, Lake Buena Vista, FL, March 19 - 22, 2007.
- [12] R.J. Nikolic et al., "Fabrication of pillar-structured thermal neutron detectors," *IEEE Nucl. Sci. Symp. Conf. Rec.*, Honolulu, HI, Oct. 26 – Nov. 3, 2007, pp. 1577-1580.
- [13] C.J. Solomon, *Analysis and Characterization of Perforated Neutron Detectors*, Kansas State University, Manhattan, KS, M.S. Thesis, 2007.
- [14] C.J. Solomon, J.K. Shultis, W.J. McNeil, B.B. Rice, and D.S. McGregor, "A Hybrid Method for Coupled Neutron-Ion Transport Calculations for  $^{10}\text{B}$  and  $^6\text{LiF}$  Coated and Perforated Detector Efficiencies," *Nucl. Instrum. and Meth.*, **A580**, pp. 326-330, 2007.
- [15] J. Uher et al., "Characterization of 3D thermal neutron semiconductor detectors," *Nucl. Instrum. and Meth.*, **A576**, pp. 32-37, 2007.
- [16] J.K. Shultis and D.S. McGregor, "Designs for Micro-Structured Semiconductor Neutron Detectors," *Proc. SPIE*, **7079**, pp. 06:1-06:15, 2008.
- [17] D.S. McGregor, S.L. Bellinger, W.J. McNeil, and T.C. Unruh, "Micro-Structured High-Efficiency Semiconductor Neutron Detectors," *2008 IEEE Nucl. Sci. Symp. Conf. Rec.*, Dresden, Germany, Oct. 19 - 25, 2008, pp. 446-448.
- [18] S.L. Bellinger, W.J. McNeil, and D.S. McGregor, "Improved Fabrication Technique for Microstructured Solid-State Neutron Detectors," *Proc. MRS*, **1164**, 2009, pp. 57-65.
- [19] S.L. Bellinger, W.J. McNeil, and D.S. McGregor, "Variant Designs and Characteristics of Improved Microstructured Solid-State Neutron Detectors," *IEEE Nucl. Sci. Symp. Conf. Rec.*, Orlando, FL, Oct. 25 – 31, 2009, pp. 986-989.
- [20] S.L. Bellinger, W.J. McNeil, T.C. Unruh, and D.S. McGregor, "Characteristics of 3D Micro-Structured Semiconductor High Efficiency Neutron Detectors," *IEEE Trans. on Nucl. Sci.*, **56**, 2009, pp. 742-746.
- [21] D.S. McGregor, W.J. McNeil, S.L. Bellinger, T.C. Unruh, and J.K. Shultis, "Microstructured Semiconductor Neutron Detectors," *Nucl. Instrum. and Meth.*, **A608**, pp. 125-131, 2009.
- [22] W.J. McNeil et al., "1-D Array of Perforated Diode Neutron Detectors," *Nucl. Instrum. Meth.*, **A604**, pp. 127-129, 2009.
- [23] W.J. McNeil et al., "1024-Channel Solid State 1-D Pixel Array for Small Angle Neutron Scattering," *IEEE Nucl. Sci. Symp. Conf. Rec.*, Orlando, FL, Oct. 25 – 31, 2009, pp. 2008-2011.
- [24] J.K. Shultis and D.S. McGregor, "Design and Performance Considerations for Perforated Semiconductor Thermal-Neutron Detectors," *Nucl. Instrum. and Meth.*, **A606**, pp. 608-636, 2009.
- [25] Justin Dingley, Yaron Danon, Nicholas LiCausi, Jian-Qiang Lu, and Ishwara B. Bhat, "Directional Response of Microstructure Solid State Thermal Neutron Detectors," *Trans. of the American Nuclear Society and Embedded Topical Meeting Isotopes for Medicine and Industry*, Las Vega, NV, Nov. 7 - 11, 2010, **103**, pp. 1190-1191.
- [26] C.M. Henderson, Q.M. Jahan, W.L. Dunn, J.K. Shultis, and D.S. McGregor, "Characterization of Prototype Perforated Semiconductor Neutron Detectors," *Radiation Physics and Chemistry*, **79**, pp. 144-150, 2010.
- [27] D.S. McGregor and J.K. Shultis, "Reporting Detection Efficiency for Semiconductor Neutron Detectors; a Need for a Standard," *Nuc. Instrum. and Meth.*, 2011, pp. 167-174.
- [28] W.J. McNeil, *Perforated Diode Neutron Sensors*, Kansas State University, Manhattan, KS, Ph.D. Thesis, 2010.
- [29] R.J. Nikolic et al., "Nine Element Si-based Pillar Structured Thermal Neutron Detector," *Proc. SPIE*, **7805**, pp. 78050O, 2010.
- [30] C.J. Solomon, J.K. Shultis, and D.S. McGregor, "Reduced Efficiency Variation in Perforated Neutron Detectors with Sinusoidal Trench Design," *Nucl. Instrum. and Meth.*, **A618**, pp. 260-265, 2010.
- [31] S.L. Bellinger, R.G. Fronk, W.J. McNeil, T.J. Sobering, and D.S. McGregor, "Enhanced Variant Designs and Characteristics of the Microstructured Solid-State Neutron Detector," *Nucl. Instr. and Meth.*, 2010, in Press.
- [32] S.L. Bellinger, R.G. Fronk, D.S. McGregor, and T.J. Sobering, "Characteristics of the large-area stacked microstructured semiconductor neutron detector," *Proceedings of SPIE*, volume: 8373, 2012.
- [33] S.L. Bellinger et al., "Characteristics of the Stacked Microstructured Solid-State Neutron Detector," *SPIE proc.*, **7805**, pp. 78050N, 2010.
- [34] S.L. Bellinger, R.F. Fronk, W.J. McNeil, T.J. Sobering, and D.S. McGregor, "High Efficiency Dual-Integrated Stacked Microstructured Solid-State Neutron Detectors," *IEEE Nucl. Sci. Symp. Conf. Rec.*, Knoxville, TN, Oct. 30 – Nov. 6, 2010.
- [35] S.L. Bellinger, R.G. Fronk, D.S. McGregor, and T.J. Sobering, "Arrayed high efficiency dual-integrated microstructured semiconductor neutron detectors," *IEEE NSS Conference Record*, page(s): 1281-1284, 2011.
- [36] T.C. Unruh, *Development of a Neutron Diffraction System and Neutron Imaging System for Beamport Characterization*, Kansas State University, Manhattan, KS, M.S. Thesis, 2009.