Presented at IEEE NSS&MIC Oct. 2003; Submitted to IEEE TNS Vol. 51, 2004

High Efficiency Silicon X-Ray Detectors

C. R. Tull, *Member IEEE*, J. S. Iwanczyk *Senior Member IEEE*, B. E. Patt, *Senior Member IEEE*, S. Barkan, and L. Feng

Abstract-- **Thick silicon multi-cathode detectors (SMCD) for high efficiency x-ray detection have been designed, fabricated and tested. These thick detectors (up to 1.5 mm thick) extend the practical x-ray detection range from the current level of ~20 keV, up to ~40 keV, while still maintaining the low noise and high count rate performance of the thinner (~0.3 mm) SMCD technology. The increase in x-ray detection efficiency at higher energies will have a significant impact on practical uses of these detectors in a wide variety of x-ray fluorescence (XRF) applications. In addition to increasing the detection efficiency for x-rays, the thick silicon detectors will offer improved efficiency for high energy electrons, alphas and other light particles in nuclear physics and astrophysics applications.**

Very high resistivity float zone material was used for the substrates to minimize the operating voltages required. Multi-guard ring structures were designed to prevent the premature breakdown of the devices at the voltages required to fully deplete the thick detectors. We have measured 172 eV and 158 eV FWHM energy resolution at 5.9 keV (at 4 µs and 12 µs peaking time, respectively, -55 ^{o}C) on 1 mm thick prototype detectors. Spectral performance, energy resolution, efficiency and count rate performance are presented.

Index Terms- **x-ray detector, silicon, multi-cathode detector, synchrotron.**

I. INTRODUCTION

Many x-ray fluorescence (XRF) measurements, such as those utilized in bench-top and portable XRF equipment, and synchrotron XRF and XAS (x-ray absorption spectroscopy), experiments which require good energy resolution (2-3% FWHM) utilize silicon or germanium energy dispersive (EDS) detectors [1,2]. Typical lithium-drifted silicon (Si(Li)) or high-purity germanium (HPGe) detectors are fabricated in thicknesses on the order of 5-8 mm, which offer substantial x-ray efficiency for a wide range of x-ray energies. However, these detectors have their drawbacks. They must be cooled with liquid nitrogen, and thus have the mechanical and physical limitations imposed by the LN_2 itself and the large LN_2 dewar. Very often XRF measurements and experiments can greatly benefit by eliminating the LN_2 requirements to yield a more compact, flexible spectrometer system. In addition, the capacitance of these detectors is relatively high, which limits their use at short peaking times and high count rates. An attractive alternative to the traditional Si(Li) and HPGe EDS detectors is the new drift detector technologies, which are now offering very good energy resolution and high count rate capabilities, without cryogenic cooling [3-10]. However, until now, the silicon drift detectors have been designed for, and fabricated on, thin (~0.3 mm) substrates, which limits the practical x-ray detection efficiency to about 20 keV. The x-ray efficiency for 0.3 mm thick Si falls off rapidly above 10 keV, with 50% efficiency at 15 keV and only 9% at 30 keV, as is shown in Figure 1.

We report on the development of thick (1 - 1.5 mm) silicon multi-cathode detectors (SMCD), which are a type of drift detector, for high efficiency x-ray applications. To the best of our knowledge, this is the first time that such thick drift detectors have been made, and their performance rivals that of the thinner detector technology, while offering significantly increased detection efficiency. Currently, there are a large number of XRF measurements that can benefit from the increase in efficiency at higher energies afforded by these new thick devices. For example, the hard x-ray microprobes and nanoprobes currently in use or planned for construction at the Advanced Photon Source at Argonne National Laboratory require fluorescence detectors with a flexible geometry, high count rate capability, large solid active area, high energy resolution and good efficiency up to 40 keV [11-13]. Nuclear physics experiments, electron microscopes and industrial XRF meaurements also can benefit from an x-ray detector that is sensitive up to 40 keV, again without the impediments of cryogenic cooling.

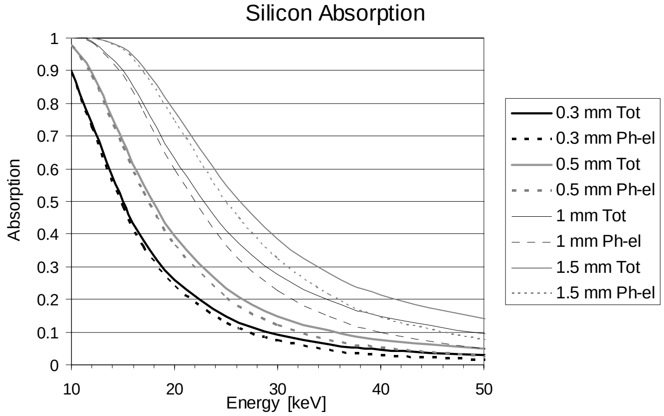

Fig. 1 Calculated x-ray absorption for 0.3 – 1.5 mm thick silicon, showing the total absorption, and the photo-electric component.

Manuscript received October 29, 2003. This work was supported in part by the National Institutes of Health, under grant no. 1R43-RR018113-01, and by the U.S. Department of Energy, under grant no. 70406S02-I.

C.R. Tull, J.S. Iwanczyk, B.E. Patt are with Photon Imaging, Inc. Northridge, CA 91324; (telephone: 818-709-2468, e-mail: ctull@photonimaginginc.com).

L.Feng and S. Barkan are with Radiant Detector Technologies, LLC, Northridge CA 91324.

II. DETECTOR DESIGN AND PROCESSING

A. *Design of multi-guard ring structure*

Photon Imaging's basic SMCD structure consists of multiple concentric cathode rings set in a hexagonal geometry, with a very small central anode structure (~ 80 µm diameter), with active areas 10 - 50 mm^2, and has been described in previous publications [3-6]. The drift detector design results in an extremely small capacitance (~60 femtofarads), independent of detector size, so that large devices (~1 cm^2) are possible without the normal increase in capacitance which increases with detector area for conventional planar devices. The very small capacitance results in very small component of the series noise, and hence the overall inherent electronic noise is very low, resulting in excellent energy resolution. An additional consequence of the low capacitance is that it simultaneously provides for extremely high count rates (>10^6 cps) due to the effect of the small capacitance on placing the optimum signal-to-noise ratio at very short amplifier peaking times.

The thick SMCDs are based on our thin SMCD design, but with structures tailored to accommodate the thicker material. As the detector thickness increases, the depletion voltage increases with the square of the thickness, which can quickly bring the operating voltage into the range where catastrophic breakdown of the device can occur. Thus, the thick SMCDs have a higher resistivity, different operating voltages and improved high voltage termination structures, compared with the thinner design. Multi-guard ring structures were designed and simulated to withstand up to 1000 V bias. The multi-guard ring structure was formed using a boron implant into the substrate, with rings of width ~ 20 microns with ~ 20 micron spacing in between, for a total width of ~ 0.4 mm. The guard rings on the window side and cathode ring side were similar.

The detectors were processed using standard CMOS (complimentary metal oxide semiconductor) processing techniques, which included ion implantation, diffusion, thermal oxidation, and aluminum metallization. N-type (100) silicon substrates of 0.5, 1 and 1.5 mm thickness, ~26,000 ohm-cm resistivity, were used to fabricate the 10 - 20 mm^2 prototype devices.

B. Preliminary Test Measurements

To determine the basic material characteristics, and to test the high voltage performance of the guard ring structures, the dark current as a function of bias was measured on test diodes which ranged in size from 10 – 25 mm^2, and from 0.5 – 1.5 mm thick. The dark current ranged from ~5 – 40 nA/cm^2, depending on the thickness, and the devices depleted at ~ 30, 120 and 250 V for the 0.5, 1 and 1.5 mm thicknesses, respectively. These test diodes could hold voltages much higher than the depletion voltages, which indicated that the guard rings were performing their function properly. Figure 2 shows the I-V performance of some of the test diodes.

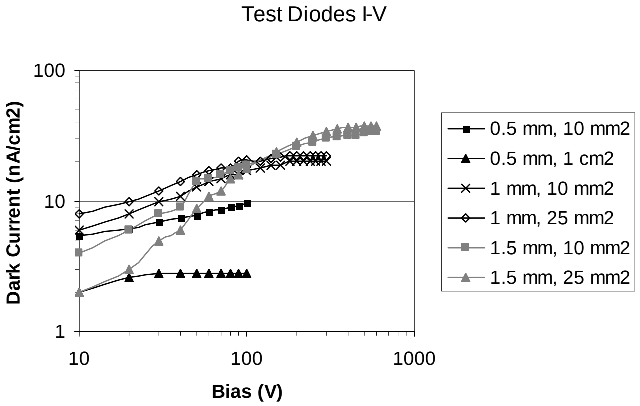

Fig. 2. Dark current as function of applied bias on test diodes of 0.5, 1 and 1.5 mm thickness, 10 – 25 mm^2.

The thick SMCDs were first tested for dark current as a function of applied bias at room temperature on a probe station. The anode dark current was on the order of 10-20 nA/cm^2. The detectors were then mounted on custom-designed ceramic substrates, and wire-bonded to aluminum traces. Low noise field effect transistors were bonded very close to the detector anode, to minimize stray capacitance from the bond wires. The dark current on the detector anode was measured as a function of temperature, with thermoelectric cooling. Figure 3 shows the dark current decreasing as expected with temperature, based on the decrease in bulk intrinsic carrier density. Dark currents on the order of a few picoamperes were necessary for good spectral performance.

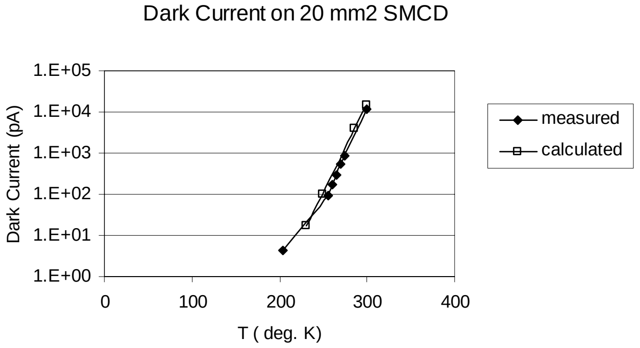

Fig. 3 Dark current as a function of temperature for a typical 1 mm thick, 20 mm^2 SMCD.

III. DETECTOR CHARACTERIZATION

A. X-Ray Response

The x-ray response of 1 mm and 1.5 mm thick SMCDs was measured as a function of amplifier peaking time, using a custom preamplifier, NIM-based amplifier and multi-channel analyzer, with ^{55}Fe, ^{109}Cd and ^{241}Am radioisotope sources. Figures 4 and 5 show the response of a 1 mm thick, 20 mm^2 SMCD to ^{55}Fe and ^{241}Am, respectively. An excellent energy resolution of 158 eV FWHM was achieved (at 5.9 keV, -55 °C, 12 µs peaking time) with the 1 mm thick SMCD. To the best of our knowledge, this is the first time that a drift-type of detector > 0.3 mm thick has been made and the energy resolution is very close to the best performance for the thinner technology.

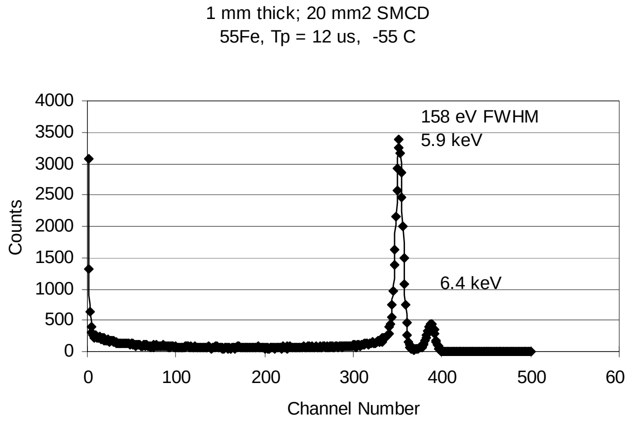

Fig. 4 X-ray response of 20 mm^2, 1 mm thick SMCD to ^{55}Fe; energy resolution is 158 eV FWHM at 5.9 keV (12 µs peaking time, -55 °C).

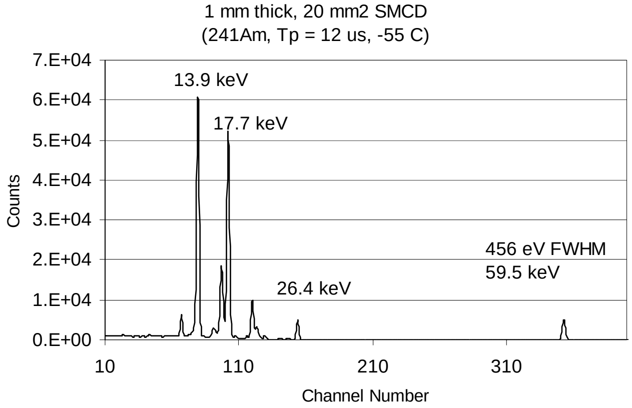

Fig. 5 X-ray response of 20 mm^2, 1 mm thick SMCD to ^{241}Am; energy resolution is 456 eV FWHM at 59.5 keV (12 µs peaking time, -55 °C).

Figures 6 and 7 show the spectral response of a 1.5 mm thick 10 mm^2 SMCD to ^{55}Fe and ^{241}Am, respectively. The energy resolution of the 1.5 mm thick device was as good as the 1 mm thick device at short peaking times (293 eV FWHM at 5.9 keV, 0.5 µs peaking time), but at longer peaking times it was poorer, due to the elevated dark current on this particular device.

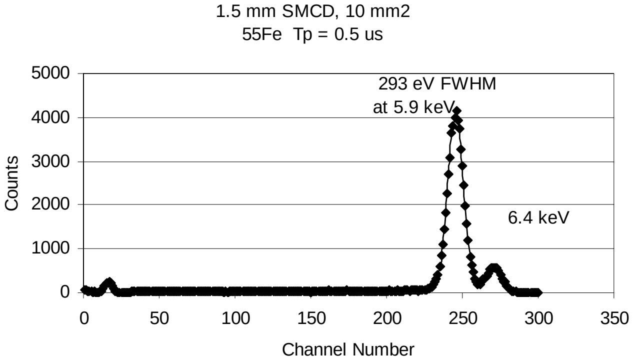

Fig. 6 X-ray response of 10 mm^2, 1.5 mm thick SMCD to ^{55}Fe; energy resolution is 293 eV FWHM at 5.9 keV (0.5 µs peaking time, -55 °C).

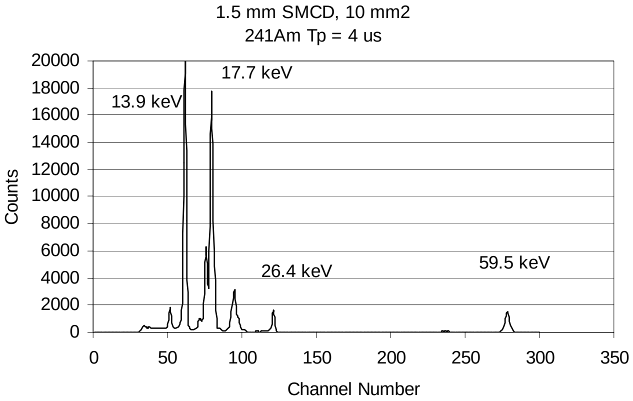

Fig. 7 X-ray response of 10 mm^2, 1.5 mm thick SMCD to ^{241}Am; energy resolution is 630 eV FWHM at 59.5 keV (4 µs peaking time, -55 °C).

B. *Efficiency Measurements*

The efficiency of 0.3, 1 and 1.5 mm thick SMCDs was measured using ^{241}Am, and with ^{55}Fe and ^{109}Cd together. Figure 8 shows the measured spectral response of a 0.3 mm thick SMCD using ^{241}Am under similar conditions as the measurement on the 1.5 mm thick SMCD of Figure 7. It is clear that the 1.5 mm thick detector is much more efficient for *both* the 17.7 and 59.5 keV peaks, compared with the 0.3 mm detector. By normalizing to the 13.9 keV peak (and taking into consideration that 0.3 mm of Si is 60% efficient at 13.9 keV, while 1.5 mm is 97% efficient) then the relative efficiencies of the two detectors at 59.5 keV can be estimated: The 59.5 keV peak is ~ 5.6 times greater in the 1.5 mm device compared with the 0.3 mm device, which compares well with the calculated value of 5.4. (These measurements were not absolute, due to slight differences in test setup).

The 0.3 mm and 1.5 mm thick detectors were also compared using ^{55}Fe and ^{109}Cd together in one spectrum. The ratio of the 22/5.9 keV peaks was 3 times higher for the 1.5 mm detector compared with the 0.3 mm detector, close to the 3.2 calculated value.

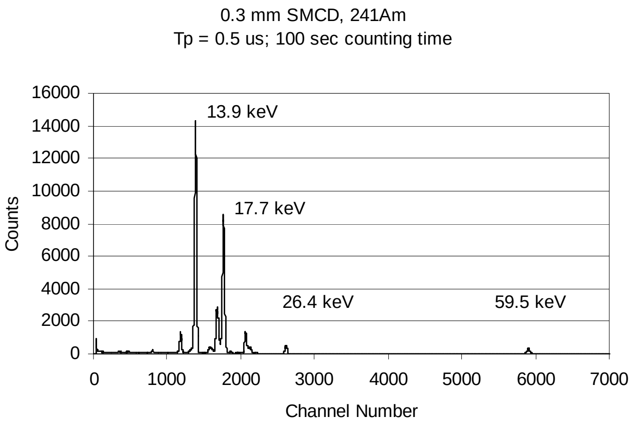

Fig. 8 Response of 0.3 mm thick SMCD to ^{241}Am; measurements taken under the same conditions as those in Figure 8 for the 1.5 mm thick SMCD.

C. Count Rate Performance

The count rate capability of the SMCDs is considerably higher than with conventional Si(Li) or HPGe detectors, due to the very low capacitance of the SMCD, which allows it to operate at very short amplifier processing times and high count rates, without a debilitating loss in energy resolution [2]. Figures 9-12 show the count rate performance of 1 mm and 1.5 mm thick SMCDs, in response to Cu x-rays fluoresced with a Rh-anode x-ray tube. Both the 1 mm and 1.5 mm detectors were able to handle 1.5 Mcps input count rate, with 600 kcps output count rate. This is over an order of magnitude improvement in count rate compared with conventional Si(Li) or HPGe detectors. The energy resolution decreased by only ~ 5% as the count rate increased to 1.5 Mcps, (at 0.25 μs peaking time) for both the 1 mm and 1.5 mm thick SMCDs (see Figures 10 and 12, respectively).

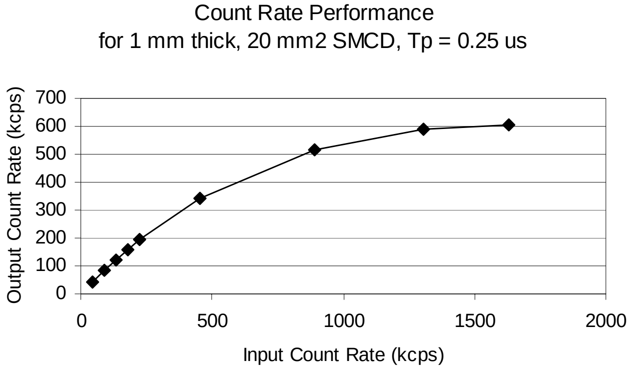

Fig. 9 Throughput performance for 1 mm thick SMCD, using digital processor, 0.25 μs peaking time.

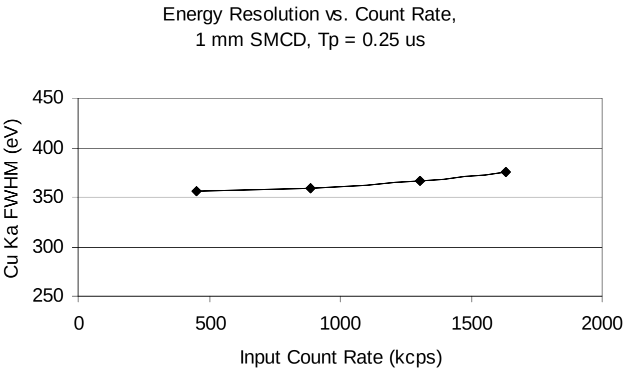

Fig. 10. Energy resolution of Cu K_α for 1 mm thick SMCD, as a function of count rate, at 0.25 μs peaking time.

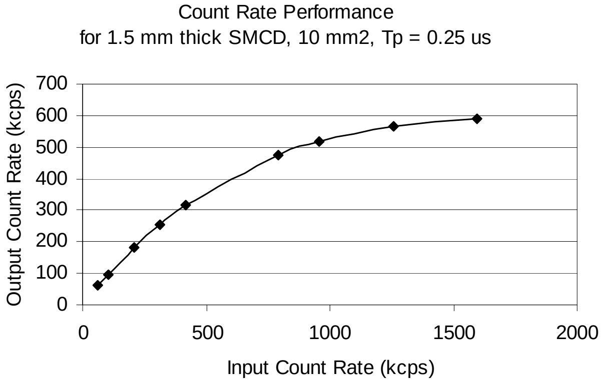

Fig. 11. Outgoing count rate as a function of incoming count rate, for 1.5 mm thick SMCD, using digital pulse processor, 0.25 μs peaking time.

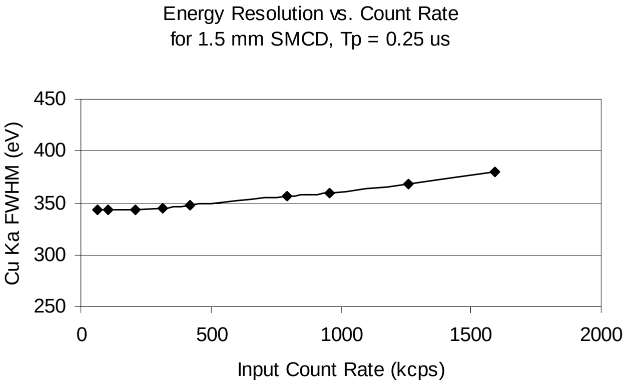

Fig. 12. Energy resolution of Cu K_α for 1.5 mm thick SMCD, as a function of count rate, at 0.25 μs peaking time.

IV. DISCUSSION AND CONCLUSIONS

We have designed and tested new 1 and 1.5 mm thick silicon multi-cathode detectors. To the best of our knowledge, this is the first time that such thick drift-style detectors have been successfully fabricated. Both the 1 mm and 1.5 mm thick detectors had very good energy resolution and count rate performance, with the energy resolution on the 1 mm detectors

.

reaching 158 eV FWHM (at 5.9 keV, 12 μs peaking time). The 1 and 1.5 mm thick detectors have substantially improved efficiency for higher energy x-rays, similar to calculated values, as compared with a standard 0.3 mm thick SMCD. Future work will focus on further optimizing the detectors to achieve the higher level of performance achieved with the thinner SMCDs (~250 eV FWHM at 8 keV and 0.25 μs) and to increase the active area to 50 mm^2. The reduced energy resolution measured in the thicker devices, compared with the thinner ones, is probably due to weak field regions in the detector volume, due to un-optimized bias conditions and potential distribution. These thick, high efficiency silicon multi-cathode detectors can be utilized in many low noise, high count rate radiation detection applications, such as in bench-top XRF, synchrotron XAS, electron microscopes and nuclear science applications.

V. ACKNOWLEDGMENT

The authors thank the NIH and DOE funding agencies for supporting this work; and Elena Volkhonskaya and Jeffrey Combe of Radiant Detector Technologies, LLC for assistance with the detector spectral response measurements.

VI. REFERENCES

[1] G. F. Knoll, chapters 11-13 in *Radiation Detection and Measurement*, 2nd edition, John Wiley & Sons, New York (1989).

[2] S.P. Cramer, S.J. George, H. Kraner, L. Rogers, S. Rescia, V. Radeka, M. Yocum, J. Colaresi, O. Tench, and O.C. Mullins, "Fluorescence XAFS Array Detectors for 0.3 - 20 keV", in *X-Ray Absorption Fine Structure*, S.S. Hasnain, ed. Ellis Horwood, West Sussex (1991), pp. 640-645.

[3] J. S. Iwanczyk, B.E. Patt, C.R. Tull, J.D. Segal, C.J. Kenney, J. Bradley, B. Hedman, and K.O. Hodgson, "Large Area silicon Drift Detectors for X-Rays- New Results", IEEE Trans. Nucl. Sci. vol. 46 (1999) 284-288.

[4] U.S Patent #6,455,858 B1 "Semiconductor Radiation Detector", 2002.

[5] J.S. Iwanczyk, B.E. Patt, L. Feng, S. Barkan, C.R. Tull; "High Throughput, High Resolution Silicon Drift Detectors for X-Rays", in press, IEEE Trans. Nucl. Sci. Vol. 50 (2003)

[6] S. Barkan, J.S. Iwanczyk, B.E. Patt, L. Feng, C.R. Tull and G. Vilkelis, "Vortex™ – A new high performance silicon drift detector for XRD and XRF Applications", to be published in *Advances in X-Ray Analysis* Vol. 46 (2003).

[7] P. Lechner, et.al. "Silicon drift detectors for high count rate x-ray spectroscopy at room temperature", Nucl. Instr. And Meth. A 458 (2001) 281-287.

[8] A. Castoldi, C. Guazzoni, P. Rehak and L. Struder, "Spectroscopic-grade x-ray imaging up to 100-KHz fram rate with controlled-drift detectors", IEEE Trans. Nucl. Sci. Vol. 48 (2001) 982-986.

[9] Roentec Holding AG (Berlin, Germany): www.roentec.com

[10] Princeton Gamma Tech (New Jersey, USA): www.pgt.com

[11] Z. Cai, B. Lai, W. Yun, I. McNulty, A. Khounsary, J. Maser, P. Ilinski, D. Legnini, E. Trakhtenberg, S. Xu, B. Tieman, G. Wiemerslage, E. Gluskin, *Performance of a High-Resolution X-Ray Microprobe at the Advanced Photon Source*, AIP Proc. 521 (SRI-99), 31 (2000).

[12] K. Kemner, B. Lai, J. Maser, M. Schneegurt, Z. Cai, P. Ilinski, C. Kulpa, D. Legnini, K. Nealson, S. Pratt, W. Rodrigues, M. Lee Tischler, W. Yun, *Use of the High-Energy X-Ray Microprobe at the Advanced Photon Source to Investigate the Interactions Between Metals and Bacteria*, AIP Proc. 507 (X-Ray Microscopy VI), 319 (2000).

[13] J. Maser, Argonne National Laboratory, private communication.