Linear position-sensitive x-ray detector incorporating a self-scanning photodiode array

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A linear position-sensitive x-ray detector for x-ray spectroscopy and diffraction applications has been tested which can provide excellent spatial resolution, wide dynamic range and good sensitivity. The heart of the system is a self-scanning, photosensitive silicon diode array. It is interfaced *via* fiber optics to a thin layer of ZnS which fluoresces visible light upon absorption of x-radiation. The conversion to visible light and optical coupling provide severalfold gain in the efficiency of detection as compared to the direct detection of x-ray by the diode array. Equally important is that the array is protected from irreversible damage by high energy radiation, a limitation which previously hindered this application of silicon diode technology.

INTRODUCTION

Both the advent of new and more intense x-ray sources, such as synchrotron radiation, and the growing interest in x-ray astronomy have placed new demands on the quality of instrumentation for detecting this region of the electromagnetic spectrum. This observation is evidenced by the proliferation of various kinds of x-ray detectors, particularly those which provide spacial resolution in at least one dimension. These include fast and slow scan television-type detectors, electro-optical image intensification systems, various position-sensitive proportional detectors, microchannel plate photon detectors and charge-coupled diode arrays. The advantages and limitations of each kind of detector were reviewed during recent conferences on x-ray instrumentation for synchrotron radiation research[1] and small angle x-ray scattering research.[2]

The requirements of a particular experiment dictate which device may be most suitable. For example, the x-ray optics define the overall size and necessary spatial resolution of the detector. In common with all experiments, however, is the desirability for maintaining (1) signal-to-noise ratios consistent with counting statistics for each pixel, (2) fast readout and storage of data, and (3) wide dynamic range for measuring both high and low intensity radiation. The linear x-ray detector described in this report has the potential for satisfying these requirements.

Silicon photodiode (SPD) arrays have been considered for the direct detection of x rays since the late 1960's. Early technology used a scanning electron beam for readout of the residual charge on each diode.[3] Subsequent advances in integrated circuit technology have made possible self-scanning devices in which both the diode array and the necessary switching circuitry for readout are placed on one substrate. Because the associated circuitry must be adjacent to each diode, such devices are fabricated most conveniently as linear detectors. Other kinds of solid-state imaging devices are available and their applicability to spectroscopy has been reviewed.[4] In principle, all these devices may be used in place of the SPD array described in this report. However, the SPD array has certain advantages, such as low noise and broad dynamic range,[4] which make it more useful as an x-ray detector than other types of arrays.

Silicon photodiodes of appropriate thickness have been used to detect x-rays directly in the 1.8–2.3 keV range[5] and the 5–20 keV range[3,6] provided the protective, optically transparent window is removed from the photosensitive surface. There are two difficulties with this approach. First, the sensitivity to x rays decreases rapidly above 5 keV.[6] The second concerns damage to the SPD array by x rays. Even if nonphotosensitive areas are properly shielded, prolonged exposure to high intensity x rays apparently increases the dark current,[3,6] thus reducing the sensitivity.

These difficulties are eliminated by converting the x rays to photons in the visible spectrum with a phosphor. The emitted light is conducted by fiber optics to a SPD array. The output is a train of pulses in which the amplitude of each pulse represents the amount of light received by each element (pixel) in the array. The information, intensity as a function of position, may be recorded electronically or on film (oscilloscope photograph).

I. OPTIMAL DESIGN

As one would expect, many of the specifications of the x-ray detector are determined by the characteristics of the photodiode array. The SPD array used in our detector, model RL512B/24 (Reticon Corp., Sunnyvale, CA 94086), consists of 512 photodiodes equally spaced along a 1.27 cm length. The dimensions of the photosensitive area for each pixel are 600 μ high by 25 μ wide.

Four video lines, each sampling the output of every fourth pixel during the appropriate clock pulse, are connected from the SPD array to adjacent recharge amplifiers. The output voltages of these amplifiers are proportional to the charge depleted in the photodiode when visible light is absorbed. A 10-bit A/D converter with sample/hold circuitry digitizes these voltage levels. A background subtraction circuit removes the "fixed pattern" readout noise in real time, and the difference is converted to an analogue signal. The resultant video signal is displayed on an oscilloscope while other circuitry stores the data in a multichannel analyzer and, subsequently, on diskettes.

The output of each pixel is presented very 0.5 ms, which limits the minimum integration time between readouts to about 250 ms. Integration times up to a few seconds are possible at room temperature, and if the array is cooled with LN_2 in order to minimize dark current and related noise, integrations may be usefully extended to at least 30 min.[7]

In addition to the specifications supplied by Reticon Corp., other operating parameters, particularly those applicable to astronomical spectroscopy, have been determined by others.[7-10] The following discussion will be concerned with estimating the capabilities of a linear detector which is designed optimally for x-ray detection in view of the known specifications. Later, data acquired with a prototype detector will be presented.

A. Conversion efficiency

Almost all of the incident x radiation, 8 keV in energy, can be absorbed by 120 μ of powdered ZnS phosphor, activated by silver.[11] For purposes of calculation, we will assume that all of the incident x rays are absorbed in the layer of ZnS (Ag). The radiant efficiency for a phosphor depends on several factors, such as the specific composition and grain size. For a particular mixture of ZnS–Ag, dePoorter and Bril[12] have determined the radiant efficiency to be 17%, a value which will be used here. Because the phosphorescent particles are settled on the fiber optics faceplate, the grain size effects both the amount of light scattered and the nature of the optical interface.[12,13] The contact area for large-grain particles ($>25\ \mu$) is small, and therefore air may be assumed to be in contact with the faceplate. The other end of the faceplate directly contacts the SPD array. For high quality fiber optics, the numeric aperture is 1.0, and the overall transmission is 48%.[14] If all of the phosphorescence is assumed to be at a wavelength of 550 nm, then approximately 145 visible photons arrive on the SPD array per x-ray photon.

Following the absorption of the visible light generated by an x-ray photon, the charge across a photodiode is depleted by a small amount which is proportional to the number of visible photons which arrive on the photosensitive area. As the pixel is scanned, the recharge amplifier replaces this lost charge, and produces a proportional output signal. The quantum efficiency for electron–hole (e–h) pair production within a photodiode is approximately 75%.[7] Consequently, about 110 electron charges are depleted across a photodiode for each absorbed x-ray photon.

It is important to note that some possible losses in efficiency have not been included. For example, there is partial absorption of visible light by the large grain phosphor. Also, the spectrum of the visible light emitted extends over a broad range, part of which the quantum efficiency of the photodiode is reduced. Therefore, the value of 110 electron charges/x-ray photon is an upper limit of the conversion efficiency.

B. Sensitivity, maximum signal-to-noise ratio (S/N) and dynamic range

The noise during readout determines both the overall sensitivity and maximum S/N which may be obtained with the SPD array. Vogt and colleagues[7] have considered the various sources of both fixed-pattern and random noise for SPD arrays. In the limit, they observe that "reset" noise and preamplifier noise dominate. Both kinds of noise have their origins in the capacitances which are inherent in the design of the array. With careful attention to component selection and layout, the overall noise can be reduced to the equivalent of about 1000 (e–h) pairs (rms) per readout.[7] Therefore, the noise on readout would be equivalent to approximately 10 x-ray photons per pixel. The S/N should approach that expected from counting statistics for as few as 200 x-ray photons per pixel, i.e., the contribution from noise becomes smaller than the statistical fluctuation in x-ray intensity.

The maximum charge which may be stored in each pixel of the RL512B/24 is 3.6 pcoul, which is equivalent to 2.2×10^7 (e–h) pairs. For an overall gain of 110 (e–h) pairs/x-ray photon, the pixel saturates at 2.0×10^5 x-ray photons per integration period. Consequently, the dynamic range over which counting statistics should be the predominant uncertainty is 200 to 200 000 x-ray photons, or about 10^3.

II. LABORATORY TESTING

In our prototype, schematically shown in Fig. 1, x-rays impinge on a 120-μ layer of powdered phosphor containing silver activated ZnS. The visible light which is produced on conversion enters the fiber optic plate (5.5-μ fibers, numerical aperture of 1.0). This plate is held in contact with another fiber optic bundle which is drawn for a twofold demagnification. Hence, the actual photosensitive surface at the ZnS layer (and the apparent pixel size) is doubled in each dimension as compared

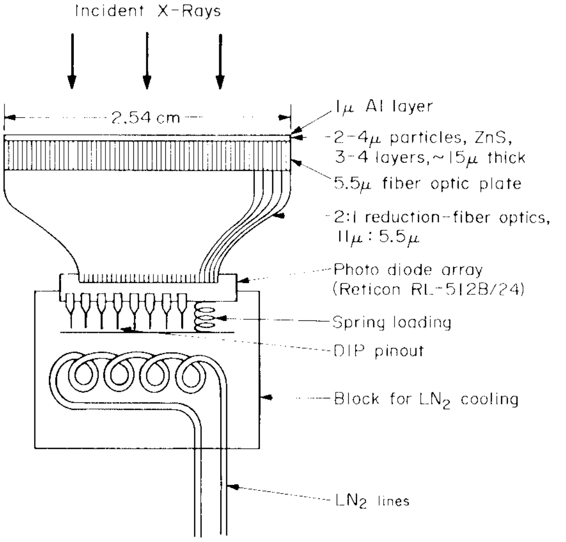

FIG. 1. Schematic representation of the position-sensitive x-ray detector. For some tests (see text) a 120-μ layer of activated ZnS was coated on the outer fiber-optic bundle in place of the 15-μ phosphor coating.

to the SPD array. The reduced side of the bundle is held in direct contact with the array by spring loading.

The two-fold demagnification is an advantage in that it increases the effective length to 2.5 cm and the pixel length to 50 μ, a more reasonable resolution element for 500–1000-μ beam size. However, there is penalty with the 2 : 1 taper. The effective N.A. becomes 0.5, reducing the transmission of the fiber optic system fourfold.[15] Also there is a small coupling loss between the two fiber optic plates. These transmission losses will be considered later.

The operating characteristics of the prototype detector were determined by using a sealed 1.5 kW x-ray tube with a tungsten target. Under low voltage conditions, a large fraction of the x-ray flux consists of the *L* emission 1.48 Å from the target. The x-ray beam, collimated to 0.5 mm diameter, was attenuated with several 25-μ Al foils, and its intensity was measured using a gas proportional counter of known quantum efficiency. Incident fluxes ranged from 3.4×10^4 photons/s (mean intensity is ca. 1400 photons/s/pixel area of 60 000 μ^2 at the ZnS layer) to 10^8 photons/s (4.2×10^6 photons/s/pixel).

The detector was mounted so that a profile of the x-ray intensity across the center of the beam could be measured. The full width at half-maximum (FWHM) of the x-ray beam is 14 pixels [Fig. 2(a)], or 700 μ. Because the diameter at the base of the profile is approximately 28 pixels, most of the circular x-ray beam impinges on the active surface of the SPD array, whose height is equivalent to 24 pixels. By knowing the incident flux and the integration time, the sensitivity of the detector may be calculated. The intensity profile in Fig. 2(b) is the result of a 1.6-s exposure to an x-ray beam of 34 000 photons/s. The peak intensity, calculated from the integrated intensity profile, represents about 3500 incident photons/pixel (0.68 V). The rms noise during readout, estimated from the data in Fig. 2(c), is about 12 mV. Therefore, the readout noise is equivalent to about 62 incident x-ray photons. This value is approximately six-fold greater than the noise equivalent of 10 photons which was calculated earlier for the optimal system.

The performance of the position-sensitive detector was also examined using monochromated and focused x-rays from the Biology Beamline[16,17] at the Stanford Synchrotron Radiation Laboratory (SSRL) in July, 1978.

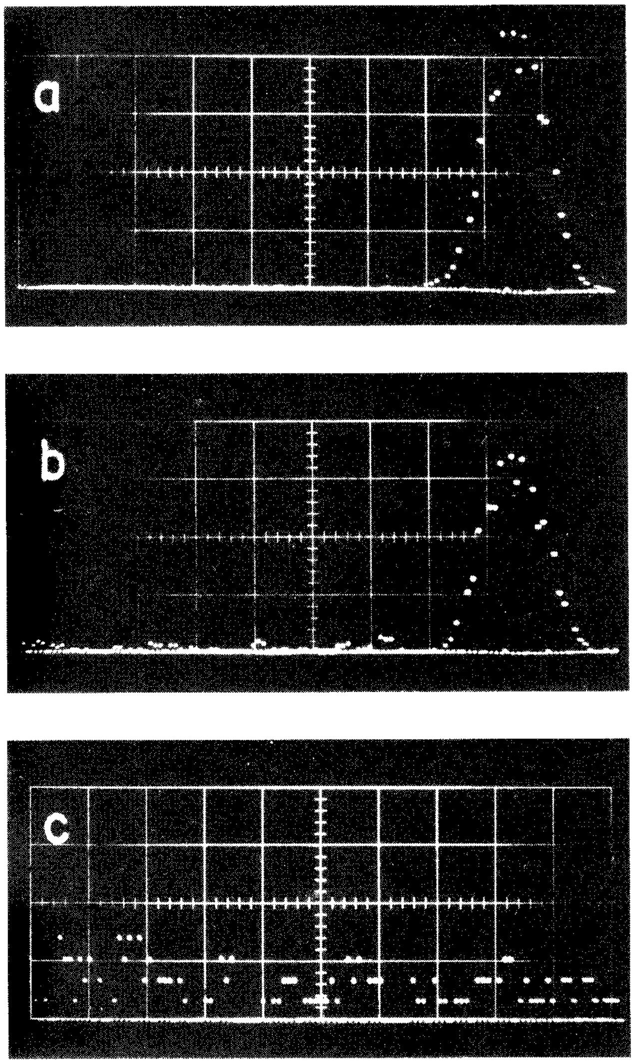

FIG. 2. Analogue output of the SPD array after background subtraction. The oscilloscope photographs represent the intensity (volts) *vs* distance along the array. Only the output of about 100 pixels near the center is displayed. During this test, a defective video amplifier caused every fourth pixel to be nonfunctional; the data were appropriately corrected when calculating the sensitivity and dynamic range. (a) An attenuated readout of the direct beam from a conventional sealed source (*W* target, 1.5 kW, 0.5-mm collimation). The peak intensity (2V/division, 0.5-s integration) is near the saturation level of the SPD array. The point-to-point variation is caused by differences in the overall efficiency of each pixel, a parameter which can be normalized in subsequent data reductions. (b) The output from a low intensity direct beam (0.2 V/division, 1.6-s integration). The integral under the peak represents approximately 54 000 incident x-ray photons; the peak intensity is about 3500 photons/pixel. (c) Readout in the absence of an x-ray beam (0.02 V/division, 0.5-s integration). The noise is quantized from the digitizing circuitry which is necessary for background subtraction. The rms noise is equivalent to 12 mV.

The flux for 7.1 keV x-rays was varied from several thousand to 3 × 10^9 photons/s at focus (350 μ × 700 μ, FWHM).

For these tests, a thin 15-μ layer of phosphor was coated on the front surface of the fiber optics. The 50-μ spacial resolution made possible rapid and precise focusing of the beam, a task which involves 18 independent adjustments. The quality of the vertical and horizontal focus, shown in Fig. 3, is substantially better than that obtained either by using film or else by observing the beam with a scintillation crystal and magnifying fiber optics.[16,17] The performance of the detector did not deteriorate even after several hours exposure to the direct beam.

The capability of the detector for collecting x-ray diffraction data was also examined at SSRL. A powder pattern from the mineral pyrite, FeS_2, (Fig. 4) was obtained in 5 min. The small pixel area and the low quantum efficiency of the detector (the thin phosphor layer had twelvefold less absorption than the 120-μ layer) clearly limited the rate of data accumulation.

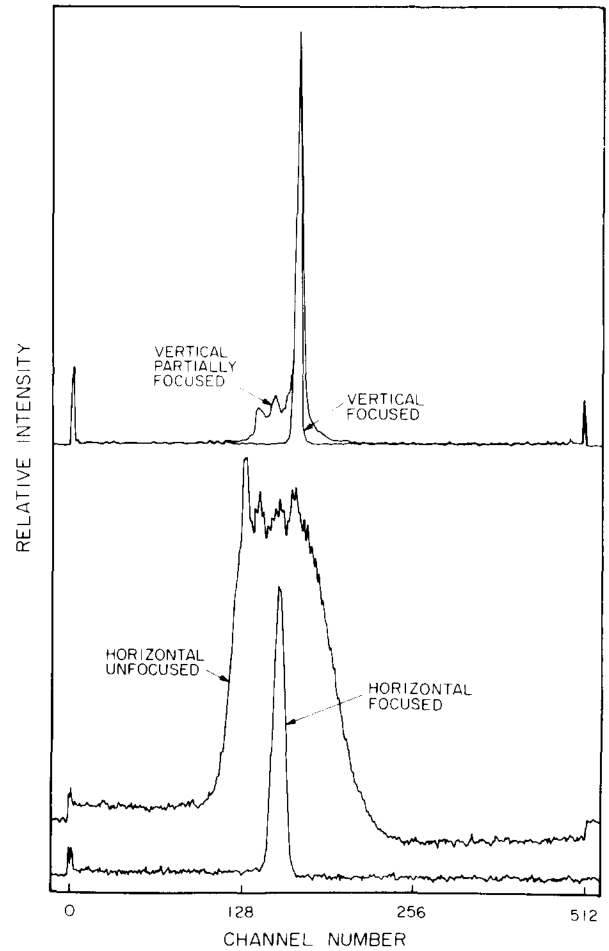

FIG. 3. The attenuated direct beam from the Biology Beamline at SSRL before and after focusing. The full widths at half maximum are 350 μ and 700 μ for the vertical and horizontal foci, respectively. Different integration times were used for each recording; the reduced areas under the peaks for the focused beams, therefore, do not indicate lost intensity. The intensity as measured by an ionization chamber decreased less than 30% after focusing.

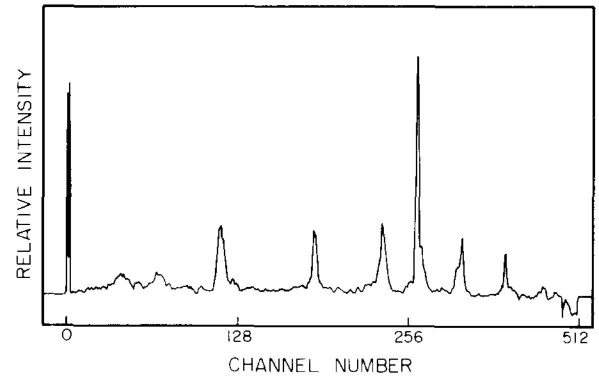

FIG. 4. The first eight reflections of a diffraction pattern from powdered pyrite (small angle near origin). The sample was not rotated, a necessary requirement if the relative intensities are to be accurate.

III. DISCUSSION

The detective quantum efficiency DQE is a parameter which can be used to summarize the sensitivity and dynamic range of the device. Using the nomenclature of Reynolds and colleagues,[18]

$$\mathrm{DQE} \equiv (S_o/N_o)^2(S_i/N_i)^{-2}, \qquad (1)$$

where S_o is the integrated output signal in volts/pixel, N_o is the rms integrated noise on readout in volts/pixel; similarly, S_i is the integrated input signal in photons/pixel, N_i is the rms fluctuation of S_i in photons per pixel. For an x-ray source exhibiting Poisson statistics and S_i photons arriving on the pixel during the period of integration, then $N_i = \sqrt{S_i}$. For our detector, $S_o = gcS_i$, where g is the overall conversion gain, $(e-h)$ pairs/x ray, and c is a factor converting the number of $(e-h)$ pairs to a voltage which is measured on readout. (The fluctuation in g is neglected.) Defining the noise contributed by the detector system itself as N_d, it follows that $N_o = gcN_i + N_d$. Substituting into Eq. (1), we have

$$\mathrm{DQE} = \frac{(S_i)}{(\sqrt{S_i} + N_d/gc)^2}. \qquad (2)$$

N_d is essentially independent of S_i and equal to 12 mV/pixel [Fig. 2(c)]. We also note that $(gc) = 0.194$ mV/photon from the peak intensity measurement [Fig. 2(b)]. Substituting these values, our result is

$$\mathrm{DQE} = \frac{S_i}{(\sqrt{S_i} + 62)^2}. \qquad (3)$$

The uncertainty of counting statistics predominates only in measuring intensities above 3800 photons/pixel.

The fourfold reduction in transmittance caused by the tapered fiber optic plate accounts for most of the discrepancy between the optimally designed detector (noise equivalent ~10 photons) and the prototype (noise equivalent ~62 photons). Longer arrays which eliminate the need for tapered fiber optics and, in addition, possess larger pixel areas, are recently available from

Reticon Corp. The RL1024S array, for example, is 2.54 cm long and has a fourfold greater pixel area (2500 μ high × 25 μ wide). The remaining 50% difference could be accounted for by some of the other possible light losses discussed earlier.

No attempt was made to minimize the noise of the recharge amplifiers used in the prototype. Quieter amplifiers which are presently available should increase the sensitivity and, correspondingly, should broaden the dynamic range.[19]

No correction was made in these tests to compensate for the different relative efficiency of each pixel. The calibration procedures outlined by Reynolds and colleagues[18] for their image intensifier–TV area detector are applicable here. Corrections for spacial distortions, of course, are not required for SPD arrays. However, some normalization for uneven baselines (see bottom Fig. 3) will be necessary. Amplifiers with baseline restoration circuitry may remove this difficulty; otherwise, a computer algorithm can provide the needed corrections. As with any x-ray detector using a phosphor, the intensity of visible light emitted is not proportional to the incident x-ray intensity at high x-ray levels. Again, appropriate normalization for intensity can be performed by computer software.

IV. CONCLUSIONS

The test results presented here have shown that a position-sensitive x-ray detector based on the current technology of a self-scanning photodiode array can be used successfully with a medium to high flux. For example, precise focusing and alignment of x-ray sources can be greatly facilitated with this detector.

The unfavorable detective quantum efficiency at low integrated intensity can be a limitation for low flux experiments which do not require data with a high S/N ratio. For example, even a well designed SPD array detector would have readout noise which is significant compared to the statistical noise at levels below 400 photons per pixel. However, as x-ray sources become more intense, e.g., synchrotron radiation sources,[20] and as more experiments are performed whose success depends on acquiring data of high precision, then SPD array detectors can be operated at integrated intensities where the DQE is more favorable. With the improvements described, the SPD array detector should be capable of collecting data in low flux experiments, such as x-ray diffraction studies and x-ray absorption spectroscopy in which the absorption at many wavelengths is measured by using x-rays dispersed from a flat crystal.

Because the actual readout time for a pixel is only a few microseconds, the minimum integration time for the entire array may be reduced at least 100-fold, provided a fast scintillator is used and the subsequent electronics are designed to handle the higher throughput of data. Consequently, time-resolved x-ray diffraction experiments in the msec time range should become possible.

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[19] This enhancement may be easily seen by substituting in Eq. (3) the new value of 15 photons (instead of 62 photons) for the readout noise/pixel in equivalent photons. The noise value of 15 photons assumes the readout noise from better amplifiers may be reduced to 1200 electrons/pixel.

[20] Particular to synchrotron sources is their pulsed nature. For example, the electron-position storage ring, SPEAR, emits 300 ps pulses at 1.28 MHz.[21] The increased probability for two photons arriving on a pixel during the same pulse at high fluxes can distress detector systems which depend on time, usually much greater than 300 ps, to process electronically each photon. Thus, count rates above 10^5/s require at least the equivalent of "dead-time," i.e., first-order corrections, to properly normalize the measured intensity. At fluxes near 10^6, however, the such detectors will "saturate." The SPD array detector avoids this difficulty by integrating the intensity at the pixel, and, provided the pixel is not saturated before readout, no correction for the pulsed nature of the beam is necessary. It is important to note that the ability to discriminate photons of differing energy is completely lost by integrating at the photodiode, and, therefore, monochromatized radiation is best suited for SPD array detectors.

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