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DIRECT X-RAY RESPONSE OF SELF-SCANNING PHOTODIODE ARRAYS

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DIRECT X-RAY RESPONSE OF SELF-SCANNING PHOTODIODE ARRAYS*

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ABSTRACT

Self-scanning photodiode arrays were tested for their ability to measure the spatial distribution of low-energy x rays in a wavelength-dispersive spectrometer. X-ray spectral sensitivity was measured with a calibrated dc source of nearly-monochromatic characteristic-x rays with photon energies in the range of 1.5 to 8 keV. Photodiode response was found to be linear with x-ray flux. Exposure to large doses of copper radiation did not effect sensitivity. A mathematical model that describes the experimental data is presented. We found that spatial resolving power was lowered by the dispersal of photogenerated charges. This effect was investigated with collimated beams and is described with a formula that predicts the loss of diode signals.

INTRODUCTION

Bent-crystal spectrographs have relied exclusively on photographic film to record high-resolution dispersed spectra of x rays radiated by laser-heated plasmas (1). We investigated the low-energy x-ray response

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of a new solid-state detector — the photodiode array — that may supplement photographic film in x-ray spectrometers. This detector, originally used to sense optical patterns, may make collection and computerization of data significantly easier.

Several aspects of photodiode performance must be assessed before the arrays can be used for sensing x-ray patterns in a spectrometer. The sensitivity and spatial resolving power of the photodiodes must be sufficiently high to compete with photographic film, the response must be linear with x-ray flux, and the arrays must be able to survive radiation. We report on measurements of these attributes.

THE PHOTODIODE

The self-scanning photodiode array is a product of the electronics fabrication technology known as MOS (metal-oxide-silicon) that permits complex electronic devices to be built on the surface of a silicon chip. In Fig. 1, the photosensitive diodes are arrayed in the central dark region that extends the length of the chip.

Fig. 1. Photograph of a Reticon RL512C* self-scanning photodiode array.

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*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research and Development Administration to the exclusion of others that may be suitable.

The circuitry of a self-scanning array performs two functions: the sensing the x-ray pattern within a linear array of semidiscrete P-N junction photodiodes and the periodic reading-out and multiplexing of the photodiode responses by a scanning circuit.

PRINCIPLES OF PHOTODIODE OPERATION

The absorption and sensing of x-rays takes place in the bulk silicon below the surface of the photodiode array (Fig. 2). The entire surface of the photosensor region is covered by a passivating layer of 1-μm-thick silicon dioxide, allowing exposure to the ambient atmosphere. The mechanism sensing the charge developed by current sources in the silicon is derived from the properties of the diode junctions of the P^+ strips and the N-type substrate. Periodically, the scanning circuit cycles through the array, connecting each P^+ region in turn to bias lines (also called video lines) that run along either side of the photodiode array. During the short time that contact is maintained for each diode element, the voltage on the line reverse-biases the diode and forms a shallow depletion layer at the junction. Even after contact with the bias line is broken by the scanning circuit, the depletion layer is

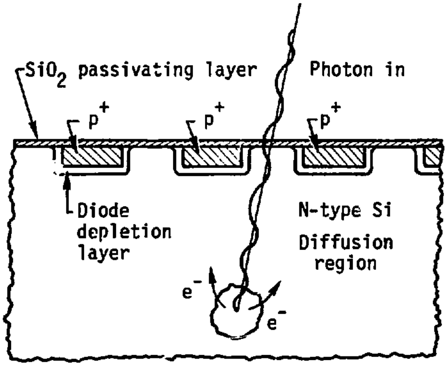

Fig. 2. A schematic cross-section of the photodiode array.

maintained by charge stored at its boundaries. The depletion layer thus appears as a capacitor whose stored charge can be dissipated between scans only by current sources in the silicon. Principal sources are thermal dark current and photocurrent arising from photon absorption. The extent to which these sources discharge the depletion layer is sensed at the same time that the diodes are sequentially biased in consecutive scan cycles. At room temperature, the period between consecutive scans, and hence the signal integration time of the photodiodes has an upper limit of several hundred milliseconds so that the dark current alone will not completely discharge the depletion layer.

Because the total thickness of the P^+regions and the depletion layer is about 4 μm, and this amount of silicon is fairly transparent to even low-energy x rays, most of the x rays entering the array from the top will be absorbed in the silicon below the depletion layer. This generates a signal that diffuses to the depletion layer for collection. It is possible that some of the charge generated under one photodiode will diffuse to and be sensed at the depletion layer of an adjacent photodiode. This effect reduces the spatial resolving power of the array for sensing an x-ray pattern.

The scanning circuit is a shift register that controls the biasing and reading-out of the photodiode elements. There is one stage of shift register and a silicon-gate transistor associated with each photodiode in the array. During a scan cycle, the shift register causes each transistor to close momentarily and connect the corresponding photodiode to the common bias line. Since the current that flows in the bias line at this time recharges the depletion layer to the level set in the previous scan, it is a measure of the amount of dark current and photocurrent integrated on the depletion layer capacitance between scans. The shift register samples the signal level of each photodiode in turn, and the sampling action moves down the array at a rate controlled by external clock generators. The time-history of current in the bias line thus indicates the spatial distribution of current sources in the diode array.

A certain amount of the noise signal arising from the switching action of the sampling transistors is capacitively-coupled into the bias line. Since this noise occurs within a fixed time pattern however, it can be moderated by external sample-and-hold circuits. The array's signal-to-noise ratio is limited to several hundred to one by random thermodynamic noise.

CONDITIONS FOR EXPERIMENTAL MEASUREMENTS

Calibrated x rays were used to measure the response of three RL512C arrays. A rectangular radiation shield of 0.030-in.-thick tantalum was used to prevent stray photocurrents from interfering with the photodiode signals and to prevent the destruction by radiation of the scanning transistors and shift register components. A 13-mil-wide slot was cut into each shield by electrical-discharge machining. The shields were aligned to expose only the central portion of the diodes to the x-ray flux.

Experimental measurement relied on external circuits provided by the Reticon Corporation to operate the arrays and process their signals. These circuits included clock generators to drive the shift registers, amplifiers to sense the bias line signals, and sample-and-hold circuits to eliminate fixed-pattern noise. The data were recorded on an oscilloscope. The clock frequency was precisely set at 100 kHz by a digital frequency counter, and the clock driver circuits were set to produce an integration time between scans of 40.96 msec.

X-ray spectral sensitivity measurements were taken in a calibrated low-energy x-ray machine. This is a dc source of nearly-monochromatic characteristic x rays with photon energies at eight points in the range from 1.5 to 8 keV (2). The lines of sight from the source to the photodiode array and to a lithium-drifted silicon-monitor detector were evacuated. The energy resolution of the detector was sufficiently high to disclose the distributions of spectral-contamination in the beams. A spectrum-unfolding computer code took this contamination into account. Since broad beams of x rays were used in these measurements, we assumed that the signal loss to diffusion was balanced from one photodiode element to another.

RESULTS

The measured sensitivity values, averaged for three arrays, and the calibrating radiations appear in Fig. 3. We found that photodiode array sensitivity is comparable to that of high-resolution x-ray film.

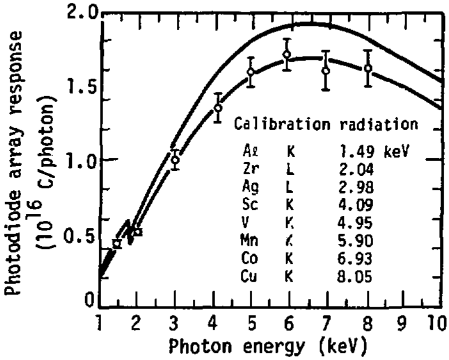

Fig. 3. Average spectral sensitivity of the Reticon array as a function of photon energy. The points are experimental results and the smooth curves are the original and corrected calculational results.

MATHEMATICAL MODEL OF PHOTODIODE SENSITIVITY

A calculational model for sensitivity was devised along the lines of Chester, et al. (3). The geometry of the photodiode array was simplified by creating a uniform layer of P^+ between the SiO_2 passivating layer and the Si substrate. This precludes two-dimensional charge-concentration gradients. Surface recombination gradients have been ignored. It is also assumed that all of the charge generated in both the P^+ region and the depletion layer is collected and contributes to the signal. The charge generated in the diffusion region contributes to the signal level in a manner controlled by the one-dimensional field-free continuity equation:

$$\frac{d^2p}{dy^2} - \frac{p}{L_0^2} = I_0 \left(\frac{E}{\varepsilon}\right) \frac{\mu}{D} e^{-\mu y} \qquad (1)$$

where p is the concentration of holes in the diffusion region, a function of the depth-wise coordinate y, measured from the lower edge of the depletion layer; I_0 is the incident x-ray flux; E/ε is the ratio of photon energy to the energy required to produce an electron-hole pair; L_0 is the minority carrier diffusion length; μ is the x-ray absorption coefficient; and D is the minority carrier diffusivity.

Boundary conditions for the equation are that $p = 0$ at the edge of the depletion layer and that at a great distance into the silicon, the only current is that from photon absorption. Where the thickness of the substrate is much greater than the diffusion length L_0, the amount of current going into the depletion layer from the diffusion region approaches

$$J_D = I_0 \cdot \left(\frac{E}{\varepsilon}\right) \cdot \frac{\mu L_0}{\mu L_0 + 1} \, . \tag{2}$$

This is the result if the collection probability was assumed to increase exponentially with the diffusion length, L_0. When a model that also includes the signal contributed by the full-collection region and the effect of the passivating layer is fitted to the measured data, the following result: the silicon oxide is 1.07 µm thick; the combined thickness of P^+ and depletion layer is 3.8 µm thick; and the diffusion length is 57.9 µm. These values are commensurate with those established by the manufacturer of the arrays (4). The analytical fit was successful, provided the results of the calculation were uniformly reduced by 11.9%. This misfit may be due to the simplified assumptions of the model or to diode construction. Original and corrected calculations are shown in Fig. 3.

LINEARITY AND RADIATION HARDNESS

Copper K radiation at 8 keV was used to test the linearity of array response to x rays. The response was found to be linear for signal levels from 10 to 95% of full scale within the limits of experimental accuracy.

Prior to the linearity measurement we exposed the array to large doses of copper radiation. No change in photodiode sensitivity was observed, even for doses as large as a quarter-million rad.

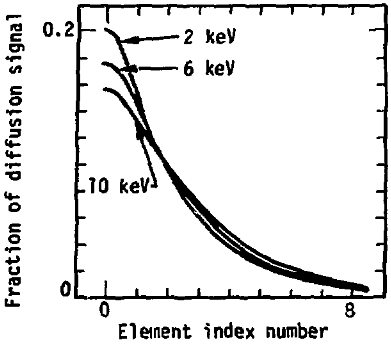

Fig. 4. Calculated dispersion of signal in the diffusion region.

SPATIAL RESOLVING POWER

When the photodiode array senses penetrating radiation, there is some loss of spatial resolving power to dispersal of photo-generated charge in the diffusion region. This effect is described by calculations that fit well with knife-edge collimator measurements. The calculations sum the charges diffusing from adjacent diodes. Each charge is described by

$$S_i(E) = \int_{\Delta x_i} \int_{y=0}^{L_t} I_0 \frac{E}{\varepsilon} \mu \, e^{-\mu y - \sqrt{x^2+y^2}/L_0} \, dx \cdot dy \qquad (3)$$

The coordinate x runs along the centerline of the array and is partitioned into intervals representing the distribution of photodiode elements. The probability of charge collection is assumed to decrease *exponentially* with the ratio of path distance to diffusion length, L_0. Calculation results are shown in Fig. 4. This model successfully calculated the roll-off of measured diode signals at two values of photon energy in the shadow of a knife-edge collimator. The measured and calculated signal levels are shown in Fig. 5.

CONCLUSIONS

The usefulness of photodiode arrays could be enhanced with several changes in operation. Several arrays placed end-to-end on a common ceramic header would extend the range of dispersed radiation that can be monitored. Also, cooling the arrays would reduce the level of dark current and increase the dynamic range and integration period. Finally, the signal output format of the arrays lends itself to data recovery by digital electronic techniques. We have work in progress in which an electronic microprocessor will control the serial digitization and scanning of photodiode signals in pulsed x-ray applications.

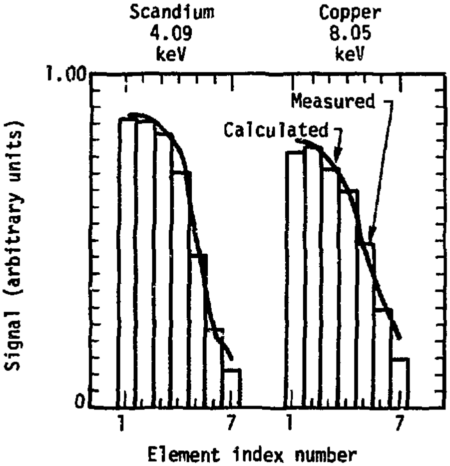

Fig. 5. Signal levels in a knife-edge experiment fitted by calculations.

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