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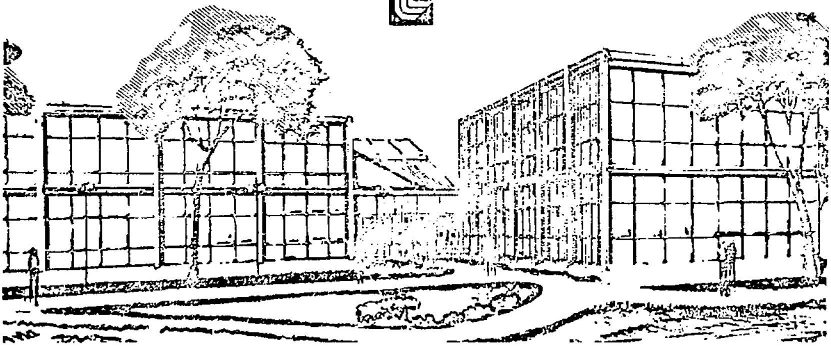

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MOS SOLID-STATE DETECTOR ARRAYS FOR X-RAY IMAGING

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Abstract

We have used two types of MOS detector arrays to sense directly patterns of soft x-rays, in the Lawrence Livermore Laboratory experimental laser-fusion program. A linear self-scanning photodiode array (SSPA) is used in a wave-length-dispersive spectrometer. A frame transfer charge-coupled device (CCD) facilitates the use of an x-ray microscope. Measurements and calculations of the x-ray sensitivity of these devices will be presented. Their linearity and dynamic range will be discussed, as well as data recovery systems for each detector. We will describe our experiences in using these devices to detect pulses of x-rays in laser-fusion experiments.

Introduction

In the experimental laser-fusion program of Lawrence Livermore Laboratory, microscopic targets containing mixtures of deuterium-tritium fuel are heated and compressed by high-brightness laser beams to initiate inertially-confined thermonuclear reactions. The most intensely-heated portions of the targets radiate soft x-rays. Diffraction crystal spectrographs are used to determine the spectral distributions of this radiation. Also, imaging devices such as the x-ray microscope and pinhole cameras routinely monitor the uniformity of heating of the targets and the degree of fuel compression achieved. The usual focal plane detector for the spectroscopic and imaging instruments is photographic film. We have investigated as replacements for film two types of x-ray-sensitive, spatially resolving, solid state detectors, a one-dimensional SSPA for the spectrometer and a two-dimensional CCD for the x-ray microscope and other imaging instruments. We report here on measurements of the x-ray sensitivity and response characteristics of each type of detector, and on the use of each in laser-fusion experiments.

Crystal Spectrometer

We have built and used an SSPA-fitted crystal spectrometer which monitors the distribution of energy in the x-ray line radiation of highly ionized silicon emitted by laser-heated glass fusion targets. The key components of the instrument are a light-tight beryllium entrance window, a flat potassuim acid phthalate (KAP) analyzing crystal. and the SSPA detector. The region of coverage for the measurement is from 1.8 to 2.3 Kev, which includes the resonance and satellite lines of heluim-like and hydrogen-like silicon

SSPA Detector

The SSPA detector is a planar silicon device built by MOS technology. It incorporates on a single chip of silicon a linear array of diffused PN junction photodiodes and a scanning circuit that sequentially biases the photodiodes and reads out their responses to radiation.

The photodiode array is formed by diffusing into the surface of an n-type substrate a series of shallow p+ strips. The strips are each 12.7 μm wide, parallel to the centerline of the array, and 432 μm long. There are 512 strips on the array, spaced on 25.4 μm centers. By the action of the scanning circuit a thin depletion layer is established at each junction of a p+ strip with the substrate.

The scanning circuit is a digital shift register consisting of a network of MOS transistors. The circuit causes the photodiodes, one after another, to be connected momentarily to a common bias line that runs beside the photodiode array. During the short time that the contact is maintained, the voltage on the line reverse-biases the diode, forcing the depletion layer at the junction. After contact with the bias line is broken by the scanning circuit, the depletion layer is maintained by charge stored at its boundaries.

The depletion layer thus appears as an isolated capacitor whose stored charge can be dissipated only by current sources in the silicon. Photocurrent generated by the absorption of x rays near the junction is one source, as is thermal dark current. The extent to which these sources discharge the depletion layer during an integration period between scans is sensed as a recharge current in the bias line when the photodiode is next addressed by the scanning circuit. A train of recharge current spikes on the bias line during a scan constitutes the output signal of the SSPA.

The usual operating frequencies of an SSPA are much too slow to allow time dissection of the radiation pulse from a laser-induced plasma. In our application the SSPA shift register is clocked at 100 kHz, implying a minimum scan period of 5.1 ms. All photocurrent due to the pulse of laser plasma radiation is integrated instantly at the photodiode junction, when compared to the time scale of operation of the SSPA.

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A useful consequence of this situation is that it is unnecessary to synchronize the scanning of the SSPA *with the time of arrival of the laser radiation pulse. If the laser event occurs in the middle of a* scan, a portion of the SSPA signals are recovered immediately during the remainder of the scan, while the rest of the data appears in the following scan. Hence we run the SSPA in a free-running, continuously scanning mode without loss of data.

X-Ray Sensitivity

We have found that the SSPA detector is fairly sensitive to low energy x-rays.[1] Figure 1 is a schematic cross-section view through the photodiode array that suggests the mechanisms for collection of photocharge at a diode junction. The active sensing region at the junction, represented by the depletion layer, is only about one micron thick, due to the low bias voltages (~5 V) that can be tolerated by MOS circuitry. A significant contribution to an x-ray-induced signal is made, however, by the diffusion to the depletion layer of photocharge created in the passive substrate region below the junction.

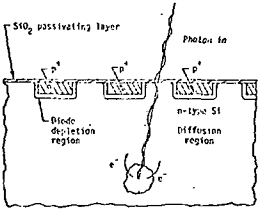

Fig. 1. Schematic cross section of the x-ray-sensitive portion of the photodiode array.

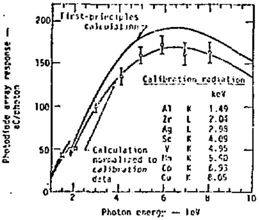

Fig. 2. X-ray sensitivity of the self-scanning photodiode array.

For the low resistivity silicon used as the substrate of the SSPA, the minority carrier diffusion length is of the order of 50 μm and the charge collection probability increases exponentially with diffusion length. We have calculated the x-ray sensitivity of the SSPA, accounting for deposition in the active and passive regions and for attenuation in a 1 μm-thick passivating layer of silicon dioxide that covers the photodiode array. The results of the calculation, as shown in Fig. 2, compare favorably with experimentally-measured sensitivities obtained with a calibrated x-ray machine. The minimum detectable flux is of the order of 8 x 10^6 photons/cm^2 at 2 keV, comparable to that of common x-ray film.

We have also found that the SSPA response is a linear function of x-ray dose. The dynamic range of the detector is limited by amplifier noise and other factors to a value of about 100:1.

Digital Data System

The serial data format of the SSPA lends itself to the processing of signal levels by digital techniques. We have built a data system that recovers digitized data from the spectrometer and distributes the information to various output devices. The system, which is diagrammed in Fig. 3, includes a sample-and-hold circuit, an analog-to-digital converter, and a set of solid-state memories into which the signal levels are loaded. A counter circuit synchronizes the loading of the memory with the time of occurrence of the laser pulse, so that a full set of data is recovered even if the pulse arrives in the middle of an SSPA scan.

An Intel 8080 microprocessor in the data system performs several arithmetic operations on the raw data and controls the distribution of the final data. Signal levels obtained during a scan after the x-ray event are subtracted, element by element, from the shot data. The results are then multiplied by an array of predetermined factors that account for variations in sensitivity between the photodiodes. The final data set is then distributed to a CRT display unit, an x-y plotter, and a teletype.

Laser Fusion Experiments

The spectrometer has been used with good results on a series of laser-fusion experiments at the Lawrence Livermore Laboratory Cyclops laser facility. Figure 4 is an example of the spectrum of silicon line radiation obtained for glass microsphere experiments. The quality of the data is comparable to that recovered with photographic film. The amount of time and effort required to produce the spectrum are greatly reduced, however.

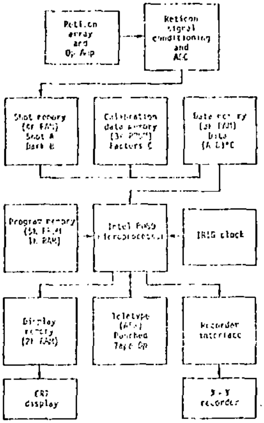

Fig. 3. Block diagram of the microprocessor-based digital data system.

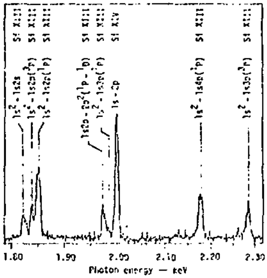

Fig. 4. Typical spectrometer data for laser-heated glass microspheres, recovered at the Cyclops laser facility.

CCD Video Sensor

The art of building metal-oxide semiconductor (MOS) solid state sensors for use in television (TV) systems has received a great deal of attention in the last few years. Of the various types of detectors that are now available, those built as CCD's appear to be the most highly developed and to have the greatest density and number of picture-element (pixel) sensing sites. The sensor we chose to evaluate is an RCA SID51232. This CCD is unique in that the two functions of a video sensor, the generation of signals at discrete photosensitive sampling sites and the read-out of the signals by a scanning network, are both performed by the same structural components of the unit, an array of 320, parallel, charge-coupled shift registers on the illuminated area of the chip.[2] This architecture gives the SID51232 the best prospects, compared to other available video detectors, of sensing ionizing radiation without disruption of its operation.

Other types of sensors, particularly self-scanning photodiode arrays and charge-injection devices, are built with discrete scanning networks laid down between the photosensitive pixel regions. Photocurrent generated in the networks can disrupt scanning operation. The devices are normally built with light-opaque masks of aluminum evaporated over the networks to prevent illumination of the latter. These shields are transparent to soft x-rays, however, and we anticipated that devices built with discrete scanning systems in the field of illumination might not function properly for x-rays, particularly for transient exposures.

SID Detector

A charge-coupled shift register is a series of close-spaced MOS capacitors built on a common silicon substrate. Applying a bias voltage to the metal electrode of a capacitor creates a potential well of arbitrary depth in which charge carriers will collect. If a deeper well is created under an adjacent capacitor, the charge will diffuse into it from the first well. By the proper clocking of bias voltages along the register, charge packets can be shifted down the register in an orderly fashion.

The architecture of the SID51232 is known as the vertical frame transfer format. As illustrated in Fig. 5, there are areas allocated on the front surface of the device for sensing a field of TV information, for storing the field outside the illuminated area prior to read-out, and for the line-by-line shifting of the signals to an output preamplifier by a horizontal register. The 320 registers of the sensing area, on the upper half of the device, are continued into the lower half to create the storage area. There are independent drive connections for the two areas, however, and they are operated in unison only during the vertical transfer of the image information from the sensing area to the storage area. At all other times, the sensing area is biased to create a matrix of photosensors, in a manner that will be described shortly,

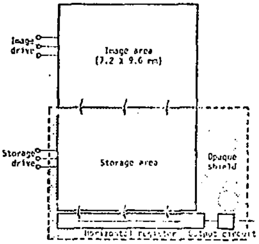

Fig. 5. The vertical frame transfer format of the RCA SID51232 imager. The storage area and horizontal register are shielded from light and x-rays.

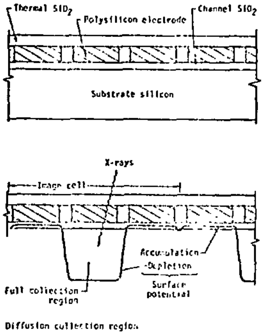

Fig. 6. Potential diagram for a photosensor cell in the SID detector. One of the three MOS capacitors in the cell is biased into depletion.

while the storage area is driven to shift the image information line-by-line onto the horizontal output register.

The SID sensor was purchased from RCA as a component of a complete closed-circuit TV camera system, which bears the model number TC 1155 AD. The camera conforms with the 525-line, television system standard, RS-170. At our request, RCA did not bond the glass window that protects the surface of the SID sensor to its header, but rather taped it in place so that it could be removed for x-ray detection.

The camera was operated most often in a vacuum. Since the camera dissipated 6W and could not be cooled convectively, we took the precaution of operating the camera for only one minute at a time.

SID X-Ray Sensitivity

The manner in which the SID senses radiation is illustrated in Fig. 6. Each of the parallel shift registers in the device's sensing area is divided into 256 identical cells, each of which contains 3 MOS capacitors. To sense radiation, one of the three capacitors is biased to create a depletion region in the silicon substrate beneath it. Charge generated by photon absorption and thermal dark current sources collects in the potential well of the depletion layer. The other two capacitors in the cell are biased into accumulation to more completely isolate the photosensor well. During alternate sensing periods, the capacitor under which the photosensor is formed is switched between the three available capacitors. This is to increase the effective spatial resolution of the sensor and to conform to the RS-170 requirement for an interlaced field TV format. The cell geometry of the SID51232 is a square, 30.5 microns on a side. This dimension sets the basic limit of spatial resolution of the detector.

Charge created by photon absorption within the depletion layer has a high probability of contributing to the photosensor's signal. The only significant mechanism for loss of photocharge in the depletion layer is recombination at sites on the interface of the SiO_2 dielectric of the capacitor and the substrate silicon. Charge generated below the depletion layer, deeper into the field-free substrate, can also contribute to the signal by diffusing up to the depletion layer. The efficiency of charge collection by diffusion is determined by the bulk recombination properties of the substrate.

SID Spectral Sensitivity

Experimental measurements of x-ray spectral sensitivity 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. The working volume of the machine is evacuated, and the beam strength and spectral content are monitored by a lithium-drifted silicon detector. The effect of spectral contamination on the sensitivity measurements was accounted for by a spectrum-unfolding code. The experimental values for sensitivity are shown as data points in Fig. 7, for an assumed signal integration time of 16.66 ms and pixel size of 30.5 x 30.5 μm. As will be described in the next section, experimental measurements indicated a non-linear response for the SID detector at medium-to-high signal levels. For calculating the spectral sensitivity, the relevant data were normalized to a uniform signal level of 225 mV.

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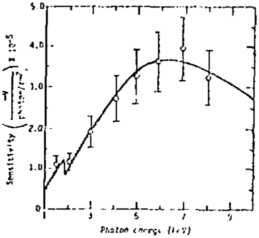

Fig. 7. Spectral sensitivity of the SID detector *for soft x-rays. The points are measured, and the* curve is a fit derived from a simple photocharge collection model.

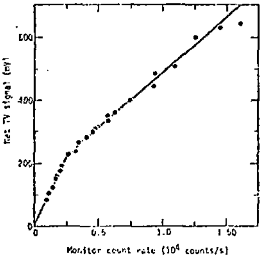

Fig. 8. Characteristic response curve of the *SID detector for 8-keV x-rays. Each of the two* segments of the curve are linear to within experimental accuracy.

The ratio of sensitivity on either side of the silicon absorption edge implies a thickness of 174 μg/cm² of silicon for the electrode structure above the sensitive substrate. This value is commensurate *with silicon and silicon dioxide layers of 5000 Å each, reported by the manufacturer of the SID.*

A simple model that accounts for signal generated by photon absorption in the depletion layer and in the substrate diffusion region was fitted to the experimental data. The model formula is:

$$S = E \cdot e^{(-\mu\rho x)_{Si}} \cdot e^{(-\mu\rho x)_{SiO_2}} \cdot \left(1 - e^{(-\mu\rho x)_{dl}} + \frac{\mu_{Si} \cdot L}{\mu_{Si} \cdot L + 1} \cdot e^{(-\mu\rho x)_{dl}}\right),$$

where

S is the sensitivity, $\sim \frac{mV}{photon/cm^2}$,

E is the photon energy,

$(-\mu\rho x)_{Si}$, $(-\mu\rho x)_{SiO_2}$ describe the electrode and silicon dioxide attenuation.
$(-\mu\rho x)_{dl}$ describes the depletion layer attenuation, and
L is the minority carrier diffusion length.

The fit is good for values of depletion layer thickness and diffusion length of about 5 and 50 μm, respectively.

SID Linearity and Dynamic Range

Data to determine the characteristic response curve of the SID camera were taken on an air-path x-ray machine that generated copper K series x-rays at 8.05 keV. As shown in Fig. 8, the curve has two linear regions, with an abrupt change in slope at about one-quarter full-scale. The upper part of the curve appears to fall off towards saturation beyond 640 mV. The change of slope in the response curve is *produced by an element in the camera's video amplifier known as the gamma correction circuit.*

In our measurements, the noise level in the video signal was no greater than 25 mV. We define the minimum detectable signal as that having a 1:1 signal-to-noise ratio. From the linearity curve, we find that the flux required to produce a signal of 640 mV is 49 times greater than that to produce 25 mV. Hence, the useful dynamic range is 49:1.

The sensitivity and dynamic range of the sensor do not appear to be high enough to assist in the calibration of x-ray imaging experiments with continuous x-ray sources. However, the use of the sensor with high-brightness laser fusion plasma sources appears feasible.

Radiation Damage

The SID detector suffers a permanent reduction in baseline voltage and sensitivity after it has received large doses of ionizing radiation. With the camera operating, an incident flux of about 4×10^{10} photons/cm² of copper radiation causes a 50 mV baseline shift and a 3% reduction in sensitivity. This flux is sufficient to produce nearly 2000 TV fields with full-scale signals.

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The damage may result from photogenerated charge trapped in the dielectric silicon dioxide. Trapped oxide charge reduces the electric field strength at the surface of the substrate silicon and is especially effective if concentrated at the dielectric substrate interface by the sweeping action of an applied electric field. We observed that the detector was damaged more readily if the camera was operating, rather than being turned off, during irradiation.

References

1. Koppel, L. N., "Advances in X-Ray Analysis, vol. 19, edited by C. O. Rund et.al, (Kendal/Hurst, Duirigue, Iowa), 1975.

2. Rodgers, R. L. III., Digist of Technical Papers, 1975 IEEE International Solid-State Circuits Conference (Philadelphia, PA., 1975) pp 188-189.