X-RAY QUANTUM EFFICIENCIES OF CCD'S*

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ABSTRACT

All of the X-ray energy incident on a CCD does not contribute to the formation of charged carriers which show up as signals in external circuitry. There are three reasons why this is so. First, some energy is absorbed in insensitive insulating layers above the sensitive silicon bulk. Second, carriers released beneath the device depletion layer may recombine before collection. Third, high energy photons may escape the device entirely without the creation of charged carriers. As a result, the X-ray quantum efficiency is less than 100%. It is demonstrated that the X-ray quantum efficiency of a CCD is still high enough to obtain good X-ray imaging with this device. The range and response of the CCD to incident X-rays in the 5 - 14.1 KeV range are determined experimentally. Knowledge of this range and response allows direct measurement of quantum efficiency. Quantum efficiency decreases monotonically from 82% to 35% in the range studied. Comparison of experimental and theoretical quantum efficiencies allows a determination of silicon bulk electron diffusion length. For the device studied the electron diffusion length was 75μm.

INTRODUCTION

Charge-coupled devices (CCD's) are of great potential use in the quantitative study of X-ray intensity distributions.[1] The usefulness of CCD's in the field rests on the ability of these devices to convert X-ray energy efficiently into collectible charged carriers. There are three reasons why CCD's are not 100% efficient in converting X-rays into collectible charge. Some X-ray energy is lost in metallization and dielectric "dead" layers over the sensitive silicon surface. Second, high energy photons may pass through the device without creating any ionizations. Finally, carriers introduced in the CCD bulk below the depletion region may recombine before they can show up as signal in external circuitry.

In this paper, it is demonstrated that the conversion of X-rays to collectible carriers in CCD's is efficient enough to produce good X-ray images. The range and response of an X-irradiated CCD is then presented. A discussion of the method whereby range and response functions can be converted to quantum efficiency follows. It is further shown that a comparison of theoretical and experimental quantum efficiency allows a direct determination of electron diffusion length in the CCD bulk silicon.

EXPERIMENTAL

A standard CCD imager, the Fairchild CCD 201 array, was used in this study. This is a 100 x 100 picture element (pixel) array. Photo sensitive sites are 30μm by 20μm squares located on 30μm centers in the vertical and on 40μm centers in the horizontal directions. Appropriate clocks were provided to read out the array in a 100 line TV-type format with 2:1 interlace and a frame rate of 8 msec. The on chip pre-amplifier was followed by an off chip amplifier with gain 100. To reduce array dark current, the devices were cooled to about 150K. The image was displayed on a conventional oscilloscope. The CCD amplifier output provides oscilloscope beam intensity modulation.

The CCD was placed in the experimental setup as indicated in Figure 1. The X-ray beam was created by fluorescence of five materials (vanadium, iron, nickel, germanium, and strontium) with an MO-targeted X-ray tube. These fluorescers provided fairly monochromatic beams of 5, 6.4, 7.5, 9.9 and 14.1 KeV respectively.

To provide X-ray images, a nickel mesh with a 1 mm grid spacing was placed 1/2 cm from the surface of the CCD array. The shadow of this mesh is recorded by the CCD. To get a quantitive measure of the CCD response as a function of incident X-ray energy, the CCD was removed and Kodak no-screen X-ray film was substituted. The films were then read with a modified Leed and Northrup densitometer. The film data was converted to X-ray intensities using the computer program of Brown, Criss and Birks.[2]

RESULTS

In Figure 2 we see the shadow image of the grid, made with Germanium Kα photons. The image is distinct and no blooming is observed. In Figure 3, the response of the CCD (i.e., the voltage the stored pixel charge produces in external circuitry) is plotted as a function of X-ray fluence for the 5 different photon energies used. The response is linear from 0.8 volts to 4.0 volts. In Figure 4, the CCD response to germanium Kα photons is compared with the photographic response of Kodak no-screen film.

In Figure 5 the quantum efficiency of the CCD is plotted as a function of incident photon energy. Quantum efficiency is here defined as the ratio of the number of electrons which create a signal to the total number of electron hole pairs which would be formed if all the incident X-ray energy were converted to electron-hole pairs (expressed as percent). The solid curves are theoretical curves obtained assuming infinite 75μm and 10μm electron diffusion lengths in bulk silicon. The method used to calculate these curves is discussed below. The points are experimentally derived. Measured quantum efficiency decreases monotonically from 82% at 5.0 KeV to 35% at 14.1 KeV.

DISCUSSION

The above results indicate that X-ray intensity distributions can be imaged with CCD's.

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Figure 3 shows that for all 5 photon energies used in this study, the response is linear over a range of about 3 volts. The upper limit of the response curve is defined by the potential well saturation of the CCD. That is, each pixel will hold at most 5.0×10^{-14} coulombs of charge. Once this number of charges fills the well, further X-ray exposure will not lead to more stored charge. Hence, the response saturates. The 0.8 volt threshold limit in response is determined by the amplifier-preamplifier chain. The chain employed was not designed for low noise performance. Thus, the system was not sensitive to the smaller changes in voltage created by the lower fluences of incident X-rays. An amplifier-preamplifier designed for low noise performance would extend the CCD response curve to lower fluences.

Figure 4, however, shows that the threshold limit of the CCD is about the same as that of Kodak no-screen film. The saturation limit of the CCD response, though, is lower than that of film. The range of film response is about 20 times that of the CCD.

Knowledge of the CCD geometry also allows a determination of resolving power. The CCD used here has a resolving power of 160 line pairs/cm vertically and 120 line pairs/cm horizontally. Previous work in X-ray film[3] indicates the resolving power of Kodak no-screen film can be estimated at about 500 line pairs/cm.

As indicated in Figure 5, quantum efficiencies can be derived from the experimental data. First, the amount of charge in X-ray exposed pixels is calculated. This is done by assuming that when the saturation voltage is reached the full 5×10^{-14}C saturation charge is present in the cell. At lower voltages the amount of charge in the cell is the saturation charge multiplied by the ratio of the observed response voltage to the saturation voltage. Next the number of electron-hole pairs the incident X-ray beam would create if all X-rays were converted to electron-hole pairs is calculated. This is gotten by dividing the total X-ray incident energy by the energy needed to form an electron hole pair (3.6 eV). This number is converted to coulombs. The quantum efficiency is the ratio of the amount of charge in this well to the number of electron-hole pairs the X-ray beam would create if all X-rays were converted to electron-hole pairs (expressed as a percent).

The quantum efficiency of the CCD for a given photon energy incident can be calculated from first principles. To do this, one must understand why all the X-ray incidents are not converted to collectible electron-hole pairs. There are three sources of X-ray energy loss. The first is loss in oxide-metal dead layers above the sensitive silicon surface. X-rays absorbed in these dead layers will not produce electron-hole pairs. Second, some X-rays (particularly high energy X-rays) may pass through the device without being stopped by the material. Finally, electrons released below the depletion layer of the device may recombine before reaching the silicon surface. There electrons will not be collected. It is this last source of carrier loss that makes X-rays so useful as a probe of semiconductor material properties in the CCD bulk.

To perform the calculation, the device is broken into 3 layers: The metal-oxide dead layer above the active silicon; the depletion layer; and the bulk silicon beneath the depletion layer. The amount of energy absorbed in each layer is easily calculated from the formula:

$$I = I_o \exp{-\mu\rho x}$$

where:

I_o = incident intensity,

I = intensity emerging from the layer,

μ = mass absorption coefficience of the layer for the X-ray photon,

x = depth of the layer,

ρ = layer density.

No electron-hole pairs are collected from the dead layer. All electrons released in the depletion layer are assumed to be collected. In the bulk beneath the depletion layer, not all electrons released reach the surface. These recombined electrons will not show up as signal in external circuitry. The number of released electrons which reach the surface is gotten by breaking the bulk up into incremental thicknesses. The number of electrons released in each thickness (i.e., the X-ray energy absorbed divided by 3.6 eV) is calculated.

To account for recombination, a one-dimensional diffusion model is chosen. In this model, the number of electrons released in each incremental thickness is multiplied by $\exp(-x/D_e)$, where x is the depth of the incremental thickness below the surface. D_e is the electron diffusion length. The contribution from each incremental thickness is added to find the total number of electrons collected. The resulting curves are shown as solid lines in Figure 5.

This figure indicates that theory predicts an initial increase in quantum efficiency as photon energy increases. This is followed by a quantum efficiency decline at higher energies. Initially, there is considerable energy loss in dead layers. As the photons become more energetic, they penetrate more deeply and less energy is expended in the dead layer. As the penetration depth increases more energy is deposited beneath the depletion layer. Thus, for higher energies, the curves become sensitive to electron diffusion length. The apparent "anomaly" occurring at about 2.8 KeV is due to the silicon absorption edge. The experimental results are, for the most part, in agreement with the theory, assuming 75μm electron diffusion length. The one apparent exception to this occurs at 14.1 KeV (Strontium Kα X-rays). At this energy a considerable amount of energy passes through the material. There is a possibility that these high energy X-rays ionize the CCD flat pack and yield an apparently high efficiency by injecting electrons from the rear.

A final word must be said about radiation damage. It has been shown in the past that X-rays do damage CCD's. Based on the total dose tolerance of these devices the useful imaging life of a CCD for 10 KeV X-rays is 15 hours. Devices specifically designed for operation in ionizing radiation ambient (i.e., fabricated with particular care to provide radiation hard dielectric layers) should easily have an order of magnitude longer life. If X-rays are to be used to ascertain material parameters, such as electron diffusion length, the beam can be shuttered to give minimum exposure.

CONCLUSION

In this paper it was shown that CCD's convert X-ray quanta to electrical signals with sufficient efficiency to image X-ray intensity distributions. The threshold response for CCD imaging is similar to that of film, but the range is about 20 times less. Spatial resolutions is also somewhat poorer.

It was further demonstrated that X-rays can be a useful probe of the material properties of the CCD's. A comparison of observed quantum efficiencies allows a determination of bulk electron diffusion lengths.

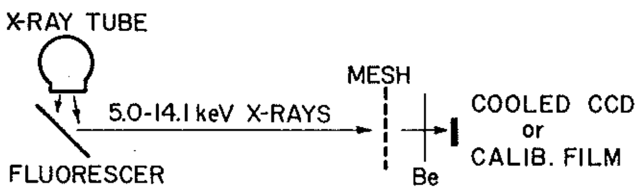

Figure 1. Schematic of the experimental arrangement. The mesh used to produce an X-ray pattern was removed to measure the response of the CCD and to calibrate the X-ray intensity with a photographic film of known response.

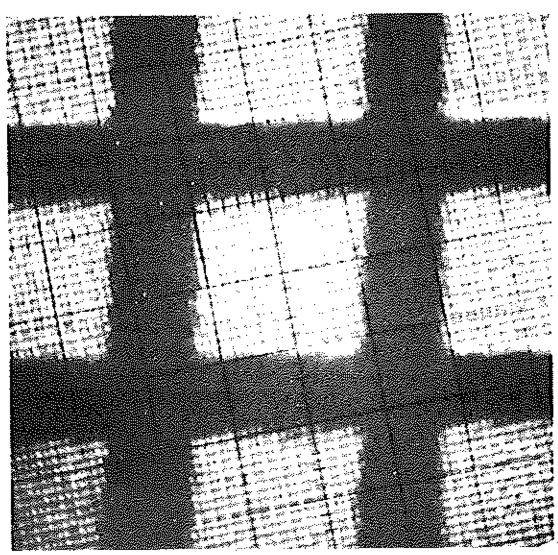

Figure 2. Shadow cast on a CCD array by a metal mesh in a beam of 9.9 keV X-rays. Wires in the mesh are 1 mm center-to-center. Individual picture elements (and the scale marks of the oscilloscope used to record this picture) are visible.

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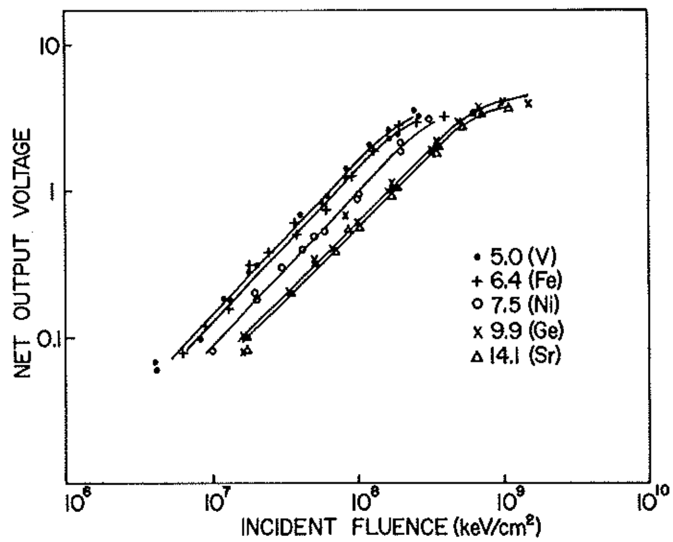

Figure 3. Measured CCD response (above a 80 mv noise level for five Kα X-ray energies produced using the fluorescent elements indicated in parentheses.

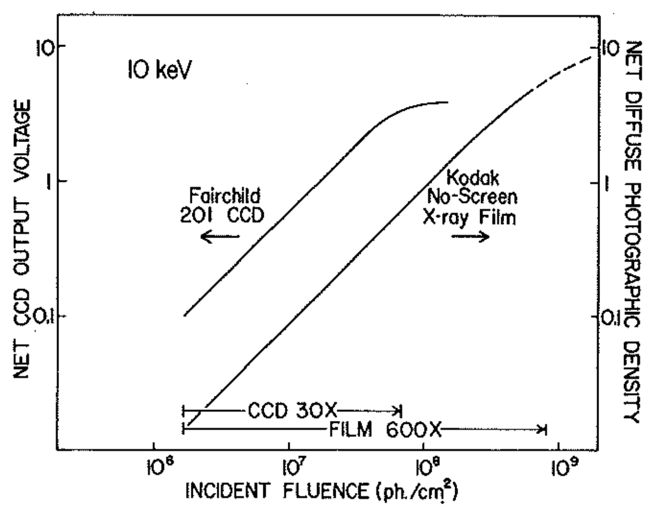

Figure 4. Empirical net responses of a CCD array (this work) and no-screen X-ray film[3] at 10 keV.

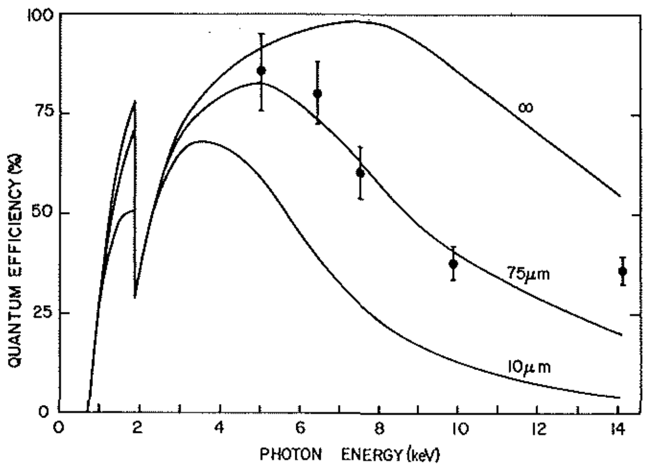

Figure 5. Quantum efficiency as computed for 10, 75μm and infinite carrier diffusion lengths and measured at five energies.