DEVELOPMENT OF A CCD FOR ULTRAVIOLET IMAGING USING A CCD PHOTOCATHODE COMBINATION*

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For many space experiments, imaging and spectroscopy require excellent ultraviolet sensitivity. CCD imagers are promising sensors because of their low power, light weight, and high reliability. However, high responsivity at wavelengths below 0.4 micron is difficult to achieve with silicon CCDs even using thinned backside illumination. The use of a CCD in the electron-in mode, coupled with a bi-alkali photocathode to produce UV photon conversion, will provide the following desirable features:

(1) High UV response of the bi-alkali photocathode
(2) Excellent imaging quality of a CCD area array
(3) High signal-to-noise ratio due to the EBS (electron bombarded silicon) gain of the CCD operating in a tube configuration

This paper describes the rationale and progress made in developing a CCD for use as an UV imager.

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The CCD area array geometry, and electrical and optical characteristics are described along with the technology used to fabricate the sensor. The advantages of using a thinned backside illuminated CCD in order to maintain MTF (modulation transfer function) and gain for the electron-in mode of operation are explained. Experimental data obtained using a scanning electron microscope as the signal source is presented on gain vs. accelerating voltage and MTF degradation due to lateral carrier diffusion from the back surface. Detailed discussion is given on the method of mounting the CCD within a tube structure to achieve backside illumination, cooling, multiple electrical connection to the CCD in the tube vacuum, and minimal cross-contamination between the CCD and the photocathode.

I. INTRODUCTION

Ultraviolet imaging and spectroscopy are primary mission goals for a number of planned space experiments. The capability for observing in the ultraviolet from a platform above the absorbing terrestrial atmosphere (0.3-micron cutoff) affords a number of advantages, including: (1) increased angular resolution, (2) extended wavelength baseline, (3) accessibility of important spectral resonance transitions, and (4) data on extremely hot or nonthermal sources nearer to their peak. The imaging of faint sources through band-limiting optical filters and spectroscopy, coupled with spatial resolution perpendicular to the wavelength dispersion direction, will also provide important new information. Representative planned programs include the study of stellar evolution, particularly by observations of the stars in hot-terminal stages of evolution, spatial characterization of the physical conditions within hot extended interstellar clouds, and the delineation of the physics and structure of the central regions of normal and high-excitation galaxies.

Figure 1 shows the spectral responsivity of photon-in (direct view) thinned backside illuminated CCDs. It may be seen that typical responsivity is unsatisfactory below 0.4-micron wavelengths. But it is possible to fabricate devices with near-ideal backside accumulated surfaces and obtain near-theoretical quantum efficiencies at 0.4 micron (absorption length 0.13 micron in Si). However, examination of spectral resonance transitions below 0.3 micron (50-Å absorption length), such as the Lyman α line at 0.1216 micron, is not feasible with a photon-in CCD.

The purpose of this paper is to describe recent work in the development of an ultraviolet converter tube which will be particularly suited for space imaging or imaging spectroscopy. The tube uses a photocathode/window combination to convert ultraviolet (and visible) photons into photoelectrons, which in turn are focused by an applied electrostatic field onto a thinned charge-coupled device in close proximity to the photocathode. In this electron bombardment mode, the CCD provides a target for the photoelectrons with an inherent gain depending upon the accelerating voltage applied.

II. PHOTOCATHODE/TUBE SELECTION

A number of different photoemissive materials/window combinations can be used to produce the photoelectrons. Figure 2 illustrates the quantum efficiencies* of several combinations involving semi-transparent coatings which are suitable for UV applications. The Bi-alkali/MgF_2 combination has been selected for the developmental tube since it provides sensitivity in the visible and UV, thereby simplifying testing and evaluation. Immediate application at a ground-based telescope is therefore possible.

Quartz has an optical cutoff at approximately 0.2 micron and hence is of limited use as window material. This 0.2-micron cutoff of quartz also prevents the use of conventional curved fiber optic windows used in electrostatic inverter tubes. Hence, for UV applications, the flat window requires the use of either a proximity, magnetically focused, or pentode tube. From the standpoint of size, the proximity tube, has a distinct advantage since the photocathode and CCD are separated by only ~0.1 inch. However, the electric fields developed in such a tube structure may limit the accelerating potential that can be applied.

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*Ref. EMR Photoelectric, wall chart.

III. CCD TARGET FABRICATION

The CCD imager chosen to be incorporated with a photocathode is a 160 × 100 resolution element, n-channel, buried-channel, double-level $A\ell$-$A\ell_2O_3$-$A\ell$ metallization, thinned, backside illuminated structure. This CCD imager is discussed in detail in a companion paper (Ref. 1). A cross section of the sensor is shown in Figure 3. The silicon membrane serves as the target for impinging electrons, and thinning is necessary to maintain spatial resolution near the Nyquist limit. Although in principle, the electrons could impinge upon the CCD from the front (metallized) side, the presence of the necessary gate oxide layer would eventually result in the buildup of charge in the oxide layer and drastically affect operation of the CCD. The performance of a single-level $A\ell$ metallization surface-channel CCD was found to degrade within a few seconds when operated while being irradiated on the front (metallized) side in a SEM (scanning electron microscope, 15-kV acceleration voltage). The same device could be operated in the SEM for a period of days with no degradation, with the electrons impinging on the thinned back surface.

IV. DESIRABLE PROPERTIES OF A CCD MOUNTED WITHIN A TUBE

The features desired or necessary for incorporating a CCD into a photocathode tube are listed below:

(1) Conventional semiconductor integrated circuit techniques for mounting the CCD.

(2) Parallel photocathode and CCD surfaces.

(3) Multiple electrical connections (~30) from the CCD to the tube exterior.

(4) Sturdy electrical connections (pins) at the rear rather than the side of the tube for ease in electrical testing.

(5) Simple CCD header, which is part of the vacuum tube wall.

(6) Minimization of cross contamination between the CCD/header and the photocathode.

(7) Header construction to facilitate cooling the CCD.

(8) Header construction to allow pressure equalization across the thin membrane, especially during vacuum evacuation of the tube.

(9) Header construction to withstand the tube temperature bake cycles (~350 to 400°C) without harming the CCD.

The ease with which the above properties can be achieved involves complicated tradeoffs in mounting and header, CCD, and tube fabrication.

V. HEADER CONSTRUCTION

Mounting a thinned backside illuminated CCD within a tube structure presents additional problems over those encountered in mounting a frontside illuminated device. The thinned surface must face the photocathode and yet allow electrical connections to be made to the CCD. An obvious method of mounting the CCD in such a fashion would be to flip-chip mount the CCD to a circular ceramic header with electrical feedthroughs. However, the concept of flip-chip mounting a CCD, much less a thinned CCD, would require a substantial CCD fabrication development effort. Hence the ceramic substrate on which the CCD is mounted must have an opening in it to expose the thinned silicon surface to the electron flux. Since the thin membrane will not withstand the pressure differential of the vacuum, the CCD itself cannot be part of the vacuum wall. This requires an additional vacuum wall element. However, the desire for ease in making multiple external electrical connections requires the substrate to be part of the vacuum wall. This feature in turn requires that the header have both a "cover" over the CCD and pressure relief vents between the main tube volume and the cover cavity.

A proposed CCD header configuration is shown in Figure 4. The ceramic substrate is brazed to a Kovar reentrant flange. The ceramic substrate itself is formed in two layers, providing a buried metallization path from the bond pads to the connector pins, which eliminates a potential vacuum leakage path. An alloy stage is brazed to the bottom of the ceramic substrate for mounting the thinned CCD. A seal flange is brazed to the top of the ceramic substrate. After the CCD has been alloyed to the alloy stage and bonded to the bond pads, a Kovar cover is heliarc welded to the seal flange, providing the outer vacuum wall. A small hole through the ceramic substrate provides the pressure relief vent between the main part of the tube and the CCD cavity. After the cover has been sealed, the tube flange may be heliarced to the main tube body.

This header design has all of the desirable features listed above. The alloy stage provides a good thermal expansion match to the silicon CCD during the prolonged 350-400° C tube fabrication process. The only possibility for cross contamination between the CCD and the photocathode is through the small vent holes. While the contamination of the CCD MOS structure by alkali vapors is a real concern, remote processing of the photocathode can reduce the probability of this occurrence. Should cross contamination prove to be a problem, it is possible to eliminate the vent holes and evacuate the two regions separately. Attaching a thermoelectric cooler to the Koval cover will permit easy cooling of the CCD. Accurate registration and planarity of the CCD to the photocathode are assured by maintaining a flat surface on the alloy stage, and by proper alignment of the tube flange to the alloy stage.

VI. SIMULATED TUBE OPERATION USING A SCANNING ELECTRON MICROSCOPE

In order to obtain information on the electron-in mode of CCD operation prior to actual tube operation, a SEM was utilized. While no imaging could be performed in this experiment, critical performance in the 8- to 20-kV accelerating potential range was obtained. Figure 5 shows a plot of EBS (electron bombarded silicon) gain vs. acceleration voltage for three different CCDs. For comparison, both theoretical and typical SIT (silicon intensified target) tube gains are presented. The gains obtained are less than ideal; however, the devices were tested with the electron beam at a 45-deg angle of incidence to the target, increasing the effective "dead voltage." These devices were also fabricated with blue responses (0.4 micron) of less than 10%, indicating insufficient back surface accumulation. It is anticipated that sensors with near-ideal blue response will provide lower dead voltages and higher gains.

The effect of lateral carrier diffusion on the MTF (modulation transfer function) for the electron-in mode of operation is similar to the results obtained with blue light. For the resistivity of the p-type substrate used (8 Ω-cm), the depletion depth is approximately 4 microns. The thickness of the thinned membrane is approximately 10-12 microns. Thus the undepleted silicon is only 6-8 microns in thickness, compared to the 23-micron center-to-center separation of the resolution elements. Thus the degradation in MTF due to lateral charge diffusion is small. This may be seen in Figure 6 from a plot of output signal vs. beam position, as a beam is traversed across adjacent resolution elements.

VII. CONCLUSIONS

While the operation of a CCD in conjunction with a photocathode for UV imaging remains to be demonstrated, many problems concerned with this concept have been satisfactorily addressed. The thinned electron-in backside illuminated CCD has demonstrated gains of 3000 and excellent resolution. Furthermore, the difficult technology needed for mounting a thinned CCD within a tube appears feasible. Major questions still to be resolved involve operation and reliability of the photocathode and CCD once the tube is activated.

While the major emphasis of this paper has been UV imaging, it is appropriate to comment on the much broader consequences of this EBS CCD operation. The gains possible with a CCD/photocathode combination are not only useful for faint UV imaging but are also extremely important for all LLLTV (low light level TV) applications. Due to the high gain preceding the CCD and the inherent low noise of the CCD (less than 100 electrons/pixel at room temperature), a simple CCD/photocathode proximity tube should provide equivalent preformance to an ISIT (intensified SIT) tube. Furthermore, by maintaining the gain G of the EBS CCD at a sufficiently high level and reducing the noise such that G is approximately ten times the rms noise equivalent number of electrons per packet, one should be able to sense individual photon events, since the signal charge per packet resulting from a single photoelectron will be approximately G.

REFERENCE

1. G. A. Antcliffe, L. J. Hornbeck, J. M. Younse, J. B. Barton, D. R. Collins, "Large Area CCD Imagers for Spacecraft Applications," Proceedings of this Symposium.

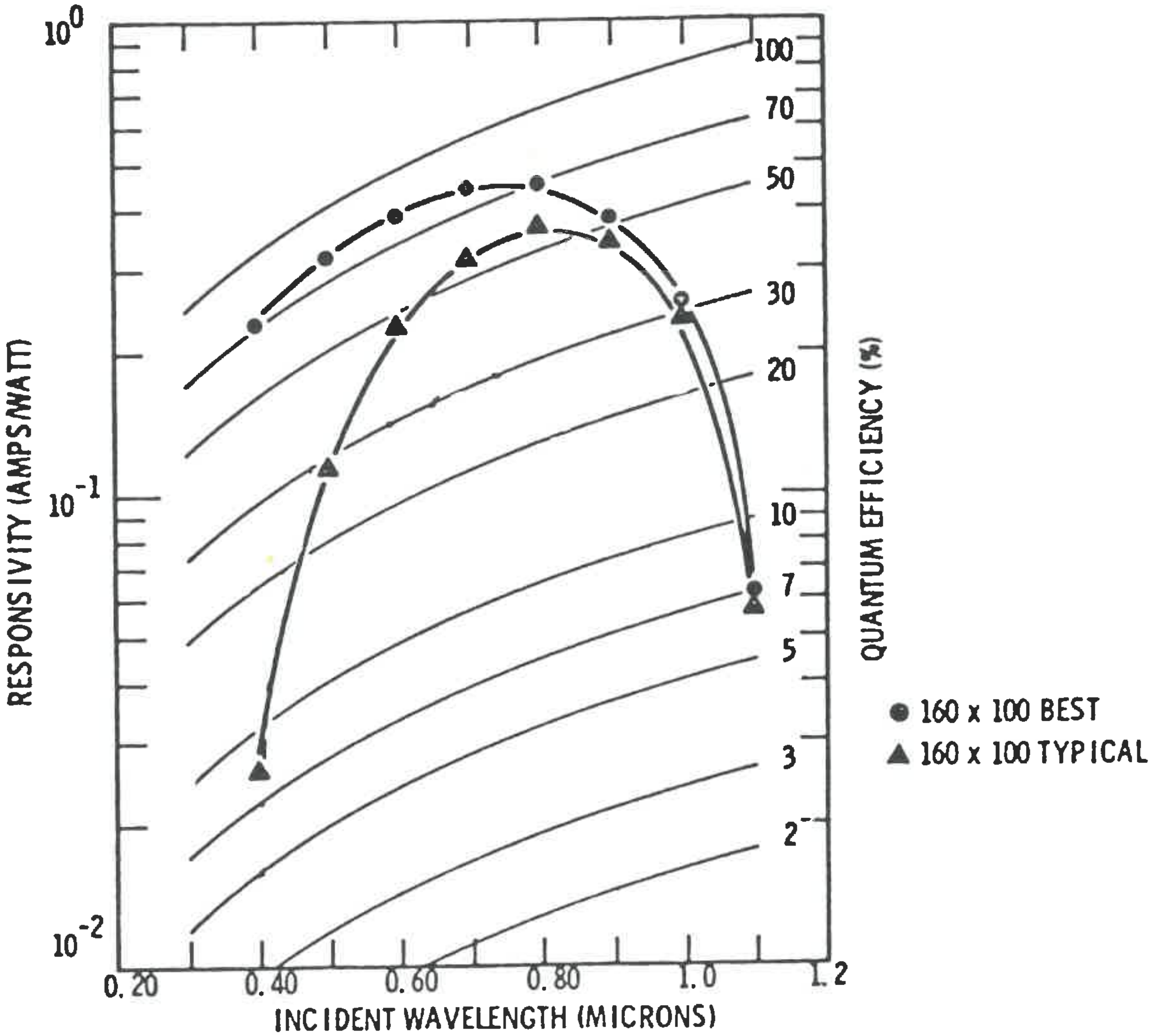

Figure 1. Spectral responsivity of near-ideal and typical thinned backside illuminated CCD area imagers

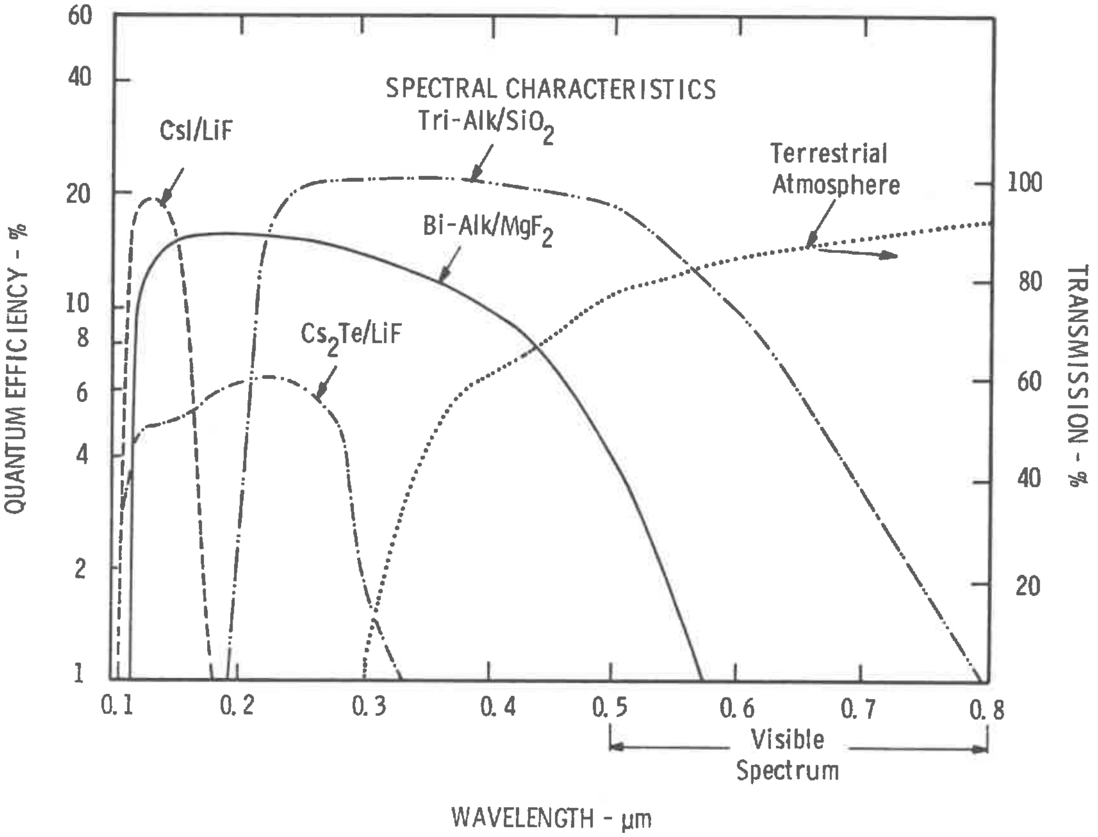

Figure 2. Quantum efficiencies of different photocathode/window combinations as a function of wavelength (Transmission of the earth's atmosphere as a function of wavelength is also presented.)

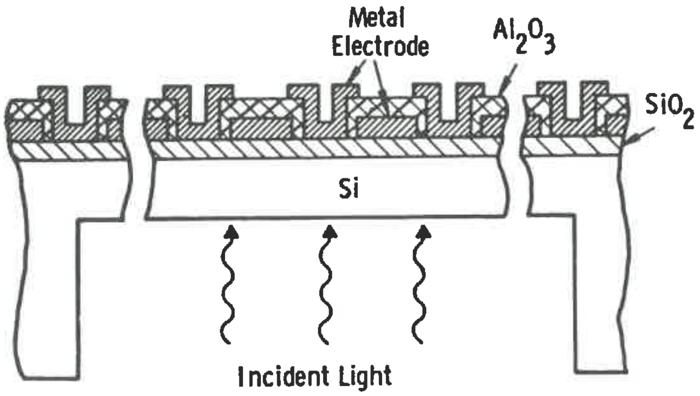

Figure 3. Cross section of a thinned CCD area imager (Membrane thickness is approximately 10-12 microns.)

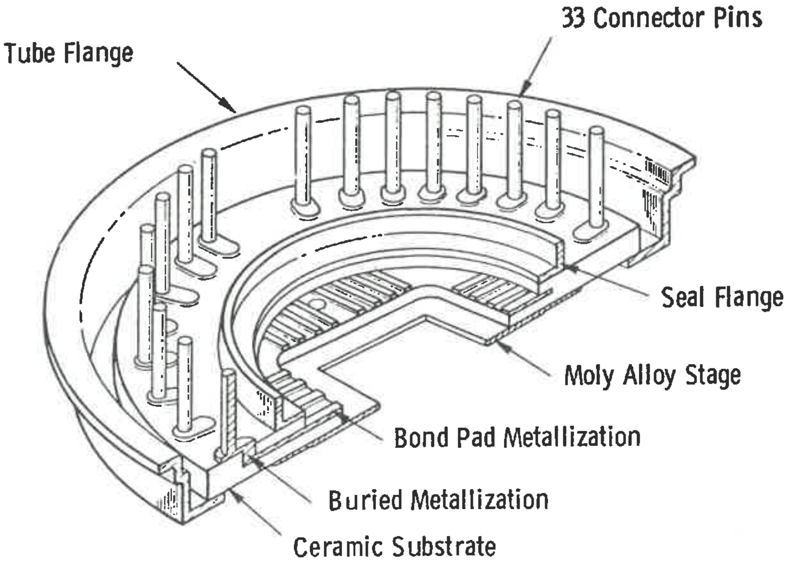

Figure 4. CCD header configuration

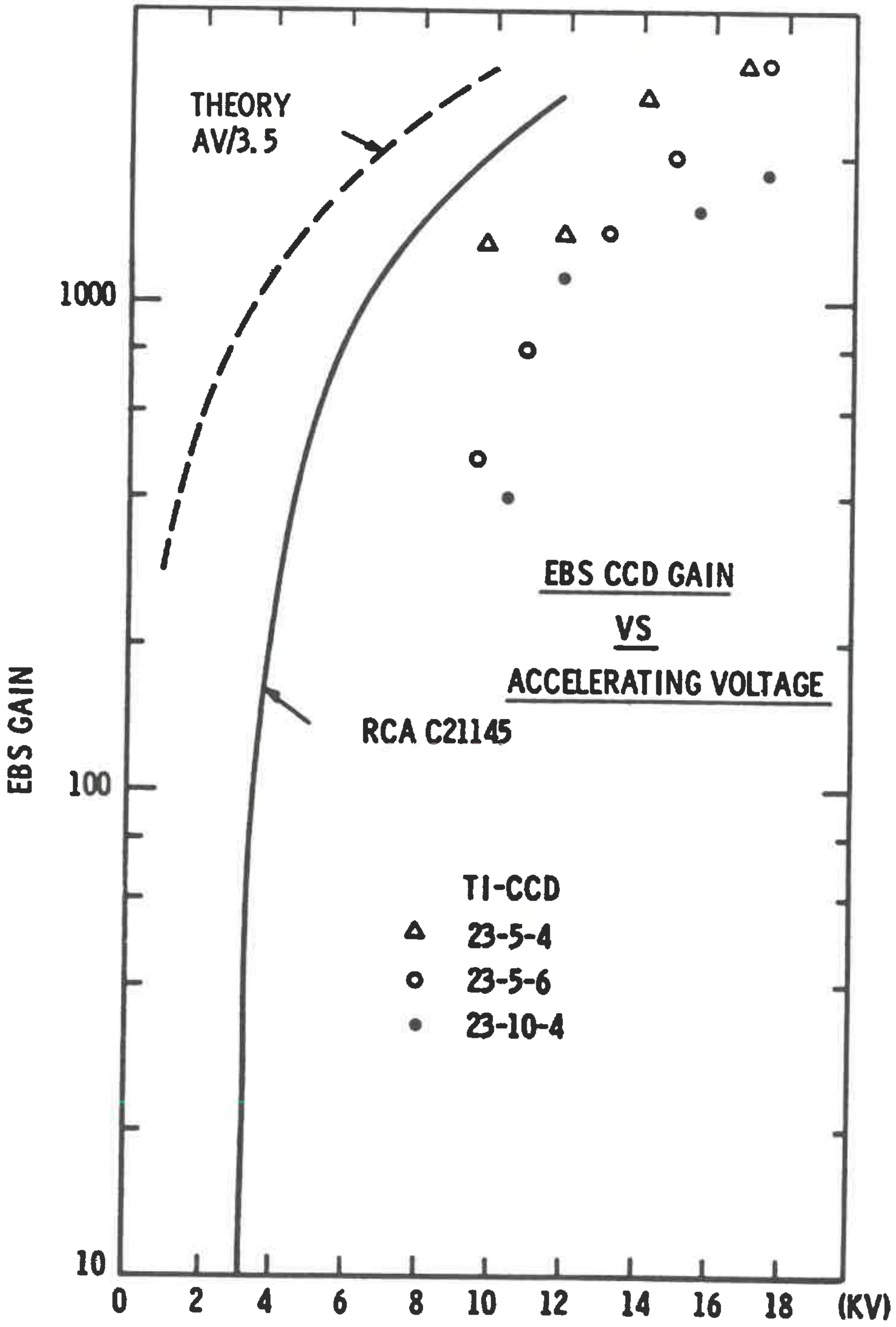

Figure 5. EBS gain of three CCDs vs. acceleration voltage. Theoretical and typical SIT data shown for comparison (Data taken with e-beam at 45° incident angle to the thinned silicon surface.)

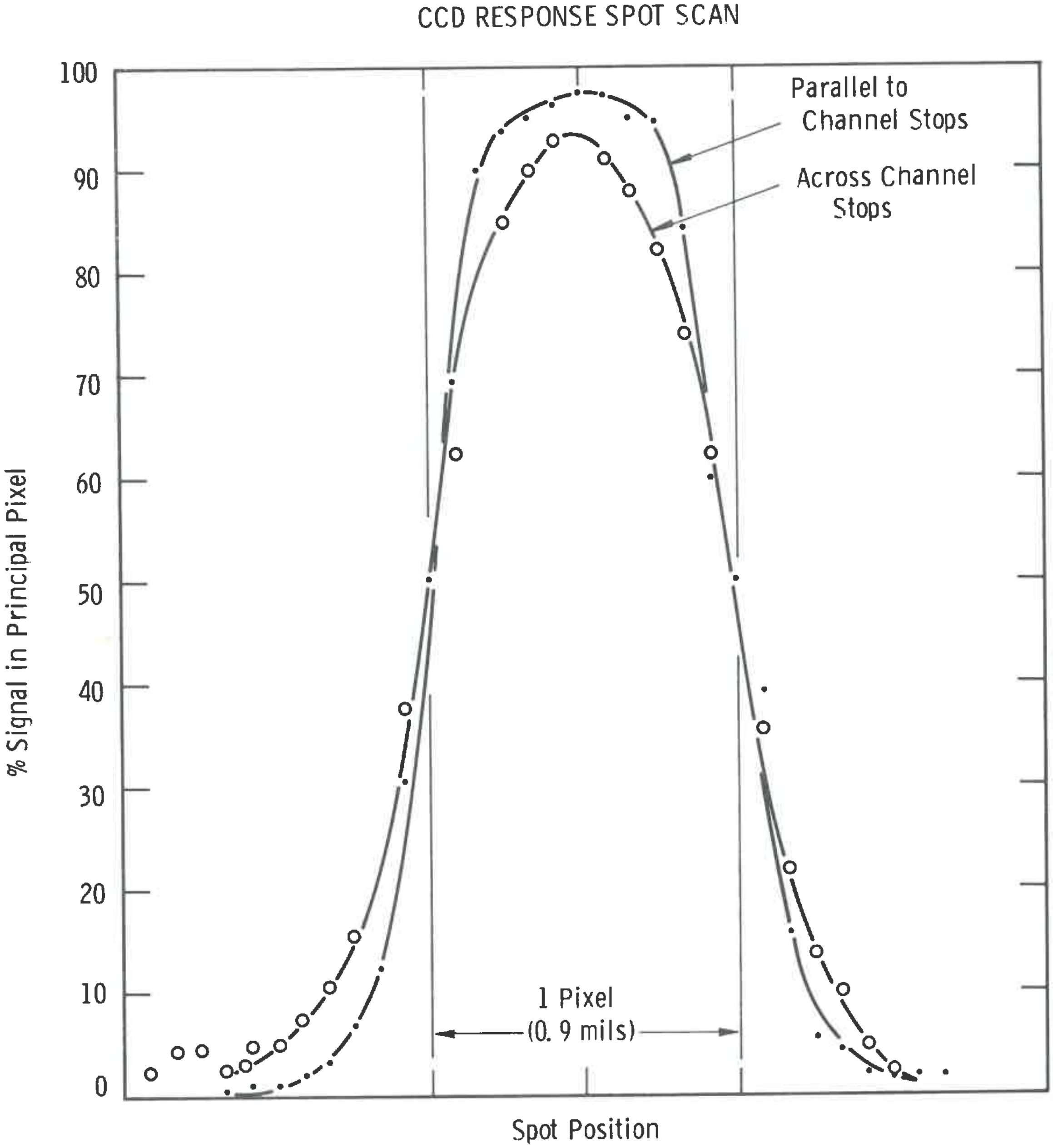

Figure 6. Plot of output signal vs. e-beam position relative to the pixel boundary for a 0. 9 × 0. 9 mil pixel (Data is presented for e-beam motion both parallel and perpendicular to the channel stops; e-beam acceleration voltages of 8-10 kV were used with effective range of approximately 1 micron. Variation in data between the parallel and perpendicular data may be primarily due to inaccuracy in focusing of the e-beam on the silicon surface.)