LOW LIGHT LEVEL CCD-TV

L. V. Caldwell, J. J. Boyle, A. J. Kennedy, W. Tardiff and S. Tomarchio

ABSTRACT

The performance characteristics of two different types of intensified CCD-TV cameras with both low light level and low contrast images are described. The first method is accomplished through direct fiber optical coupling of conventional image intensifiers to CCD arrays. This "hybrid" approach allows the selection of low cost, highly reliable daylight modules for the imager. The intensifier is selected based on the optimum tradeoff between gain, MTF, noise figure and CCD noise. The intensifier chosen consists of two stages. The first is a gallium arsenide 18mm wafer diode and the second stage is an S-20 inverter tube with built-in 18:14 demagnification. Square wave amplitude response measurements which show a negligible resolution loss at the CCD-fiber optic interface will be dis- discussed.

The second potential candidate for low light level CCD-TV is the electron bombarded CCD. Camera tubes have been fabricated with high photocathode sensitivities (up to 450 microamperes/lumen), electron gains in in the CCD up to 3000 at 15 kilovolts and array dark currents as low as 2.5 nanoamperes/cm^2 after tube processing. These tubes have been shown to be stable under operating conditions and have produced discernable images with 8×10^{-6} lux incident on the photocathode. One of the major degradation mechanisms for the electron-in CCD (i.e. EBS-CCD) has been found to be damage due to soft x-rays generated by the electron beam. Dosimetry data obtained or thinned silicon wafers indicate that with 4×10^{-10} amperes/cm^2 signal current (~1/2 full well) at 10 kilovolts, 10^4 rads (Si) can be deposited in the oxide in approximately 100 hours. While this dose is essentially that at which noticeable dark current increase occurs, the CCD can be operated for significantly longer times.

INTRODUCTION

With the abandonment of the direct photon-in approach to low light level imaging and the realization that gain before the CCD was necessary for any practical imaging system two different approaches have been considered. The fiber optical coupling of a conventional image intensifier to a CCD or "hybrid" approach was pursued because it offered the potential of using low cost standard modules. The concern associated with the loss of MTF at the coupling interface has been shown to be unfounded.

The remaining concerns with this approach are the system size and the choice of the phosphor. Most image intensifiers have green phosphors of the P-20 type chosen so as to optimize the human eye response, but not the optimum for front surface CCD response. In addition, these phosphors typically have emission times that can last several seconds.

US Army Night Vision & Electro-Optics Laboratory, Fort Belvoir, Virginia

While faster phosphors are available they are non-standard and usually blue which makes the CCD response even further degraded. Red phosphors on the other hand enhance the CCD response but degrade the resolution of the image because of the lower optical absorption in silicon. Phosphor lag can be transformed into temporal MTF loss in applications where relative motion exists between the target and sensor. In the present hybrid camera P-20 phosphors were used.

The EBS or electron-in mode of operation has demonstrated considerable progress since last reported.(1) At that time reasonable quality electron imaging and the potential for low light level operation was demonstrated in a demountable imaging system. Since then CCDs have been developed which can withstand the tube processing schedule with little or no change in operating characteristics. No serious degradation of CCDs has been observed while operating in the alkali environment of the tube and the S-20 photocathode has been shown to be stable during operational life. The uncertainty in cost of the EBS-CCD remains, unless a thinned chip with significant commercial interest can be developed.

FIBER OPTICALLY COUPLED CCD

The two stage cascaded image tube used is shown in Figure 1. The smaller tube is the first stage gallium arsenide wafer diode. This tube has a photocathode sensitivity of 900 microamperes/lumen and a spectral response which extends from 6000 Å to 9000 Å. The cathode to phosphor spacing is 2 mm and this tube has a limiting resolution of 36 lp/mm at 9 kV. This diode is coupled to the S-20 inverter tube shown in which an 18/14 demagnification occurs. The overall brightness gain of the combination has been measured to be 13,500 ft-L/ft-cd with 9.5 kV on the first stage and 16 kV on the second.

With the camera used this was not enough gain to be photon shot noise limited under overcast starlight conditons. (i.e., brightness gain of 13,500 corresponds to 400 electrons/pixel in the CCD at 2x 10^{-6} lux.) However, the higher MTF and lower noise figure of this combination when compared to a microchannel plate tube makes this system superior in performance at starlight illumination levels and above. The camera is shown in Figure 2. In addition, to the coupled intensifier, the power supplies, camera housing and lens, and CCD assembly are shown. A one inch long fiber optic has been fitted and bonded to the CCD imager by Fairchild Corporation. The length was conservatively chosen to stand off the 16 kV applied to the output phosphor of the inverter stage. The in-phase vertical square wave amplitude response of the camera taken with the green light image focused on the fiber optic is shown in Figure 3.

This square wave response is comparable to data obtained on daylight cameras(2) and indicates negligible loss at the fiber optic CCD interface. Also shown in Figure 3 is the MTF of the intensifier combination. In addition, the square wave amplitude response of the complete camera has been calculated from the measured data on the individual components.

The measured data is plotted in Figure 3 along with the calculated values. The measurement agrees well with the expected results, except that the data is consistently slightly higher. This is not unexpected in this case with the low frequency degradation in the image intensifier. The low light level performance of the camera is shown in Figure 4. The photon-in curve shows degradation at 10^{-1} lux on the photocathode even at 100 percent contrast. While this is typical of daylight cameras it does occur at a relatively high light level (1.2×10^{-1} lux corresponds to 10,000 electrons/pixel). The expected low light level performance of the coupled camera assuming that the performance is chip limited (rather than photon shot noise limited) cannot be estimated from first principals since the degradation is obviously due to a non-fundamental source. It can be estimated from the photon-in data, the MTF, and the assumption that the signal to noise is not shot limited and, therefore, directly proportional to the gain.

Good agreement was obtained between the estimated results and the experimental values especially at low spatial frequencies. At higher spatial frequencies the model is critically dependent on how the MTF is incorporated and here some divergence can be seen. The highlight limiting resolution for the coupled camera was chosen to agree with the limiting resolution which could be observed. Also shown in Figure 4 is lower contrast (i.e. 20 percent) data taken with this camera. It will be compared in the next section with other cameras.

EBS-CCDs

Three different tube geometries are being investigated for the electron bombarded CCD. These are shown in Figure 5. The curved cathode tube shown is an S-20 inverter (Varo) with the thinned CCD inserted in place of the phosphor. This tube has received the most emphasis. Photocathode sensitivities as high as 450 microamperes/lumen have been made in this configuration. Tube processing schedules have been developed in which tubes of high sensitivity, low dark current and high electron gain can now be fabricated. An example of this is the demonstration of a tube with a photocathode sensitivity of 330 microamperes/lumen, an electron gain in the CCD of 3000 at 15kV, and an array dark current of four nanoamperes/cm^2 after processing. Photocathode life tests under operating voltage conditons have shown stability well in excess (10x) of goggle tube specifications. Also shown in Figure 5 are two tubes fabricated by Varian Associates. The inverter is fairly large, but offers a gallium arsenide photocathode. The wafer tube shown also has a gallium arsenide photocathode but so far full operational voltage has not been obtained in this tube (i.e., 10 kV, 2.5mm) due to leakage currents and field emission. The on axis square wave amplitude response of both inverters is shown in Figure 6. Due to the flat cathode the Varian tube is expected to degrade as the image is moved off axis, however, due to the small size of the CCD this effect was not measured in this tube. The low light level limiting resolution of an S-20 EBS-CCD tube is shown in Figure 7 and compared to data on a high performance ISIT. At 100 percent contrast there is little difference between the two systems except at the lowest light levels where the ISIT is superior. The CCD tube however shows a clear advantage at 20 percent contrast which is more typical of real scenes. The low contrast performance of several devices are shown in Figure 8. As expected the photon-in results are superior to the low light level results. Texas Instruments 100x160 array showed no loss in resolution down to the limit of the measurement facility, (i.e. two percent contrast). Comparing the EBS and ISIT curves shows a clear advantage of the electron-in CCD approach over the ISIT for the range of contrasts typically found in real scenes. Also shown is the data obtained on the fiber optically coupled camera. This shows significant degradation when compared to either the ISIT or the EBS-CCD.

X-RAY EFFECTS IN EBS-CCD

The self induced X-ray dose effects on the performance and characteristics of intensified CCDs were investigated. A backside thinned and accumulated 100x160 CCD imager was placed in the electron optical focal plane of a demountable inverter image intensifier tube. Imaging electrons from the photocathode irradiated the substrate side of the CCDs at energies ranging from 5 to 15 keV. In silicon, the electron energy is deposited within a range[3] of $R = 0.0319\ E_B(\text{keV})^{1.67}$ um, which is approximately 1.49 µm at 10 kV and 4.75 µm at 20 kV. Some of the dissipated electron energy produces X-rays, a fraction of which is transmitted through the 10 to 13um silicon substrate to the SiO_2 layer of the MOS CCD.

Experimentally the electron fluence and voltage dependence of the fraction of the X-ray dose that is absorbed in the SiO_2 layer of the CCD was determined.[4]

The transmission spectra consist of two components. One is the K_α line and the other is the bremsstrahlen of significance between 3 keV and E_{max}. The relatively large self absorption of silicon X-rays in silicon produces the maximum absorption at the low energy end. Since the Si and SiO_2 absorption spectra below 3 keV are similar, most of the energy absorbed in the SiO_2 layer is, therefore, from the characteristic K_α X-ray. The relative effects of the K_α line and the bremsstrahlen have been estimated.[4]

The dosimetry data on thinned silicon wafers, together with the shape of the transmitted X-ray spectra, provided the basis for calculating the absorbed x-ray energy in the SiO_2 layer. An application of this data to estimate the dose dependent degradation of a TI 100x160 CCD operated in the backside intensified mode is shown in Fig. 9. The signal current level was chosen to be approximately one-half full well. As can be seen dark current increases were noticed after 100 hours of operation, which corresponds to 1.1×10^4 rads. Since in real scenes the average irradiance is somewhat less then the peak irradiance and since dark current increase is the major device degradation up to about 5×10^5 rads, operational life of 10,000 hours appears feasible.

CONCLUSIONS

The present status of intensified-CCD imaging has been discussed. The fiber optically coupled camera has shown good low light level performance but reduced performance at low contrast. The EBS tubes have shown good potential for both low light level and low contrast imaging, however, have not yet been built with full tv size arrays. For applications where exceptionally long life is important it has been shown that self-induced X-ray damage must be considered.

REFERENCES

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4. A. J. Kennedy, "Absorbed X-ray dose in the SiO_2 layer of backside electron irradiated ICCD imagers," proceedings IEEE Conference on Nuclear and Space Radiation Effects, Santa Cruz, CA., July 1979.

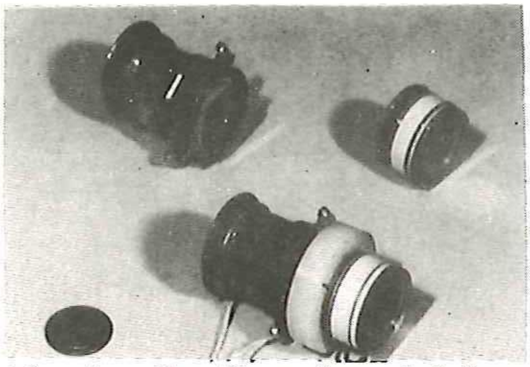

Fig. 1. Two Stage Cascaded Image Tubes for Optic CCD-TV.

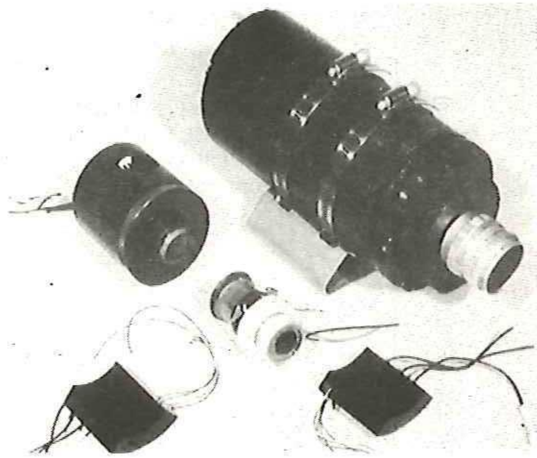

Fig. 2. Fiber Optic CCD-TV Camera

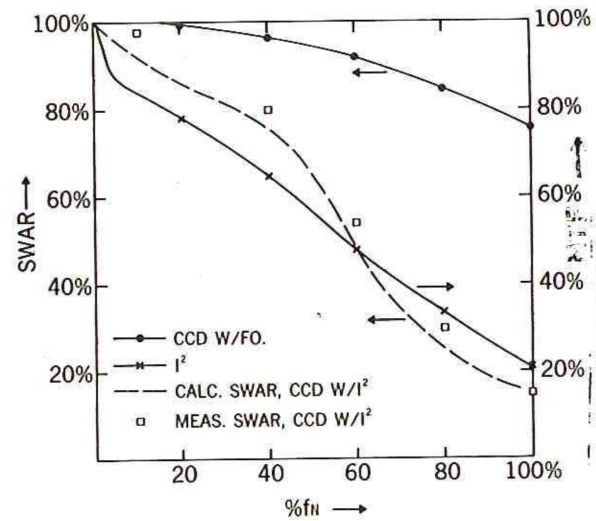

Fig. 3. SWAR and MTF of Hybrid Components.

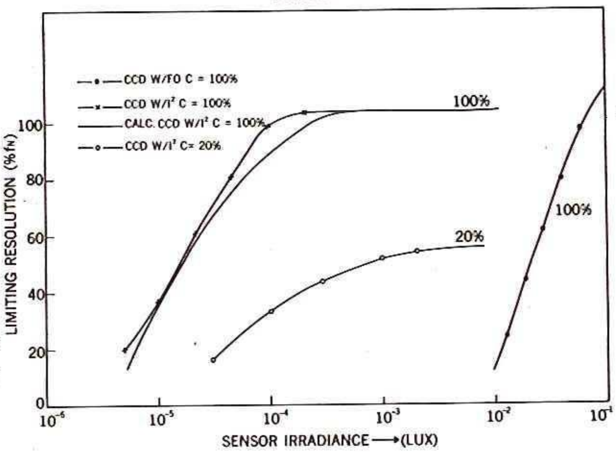

Fig. 4. Low Light Level Performance of Fiber Optic CCD-TV Cam.

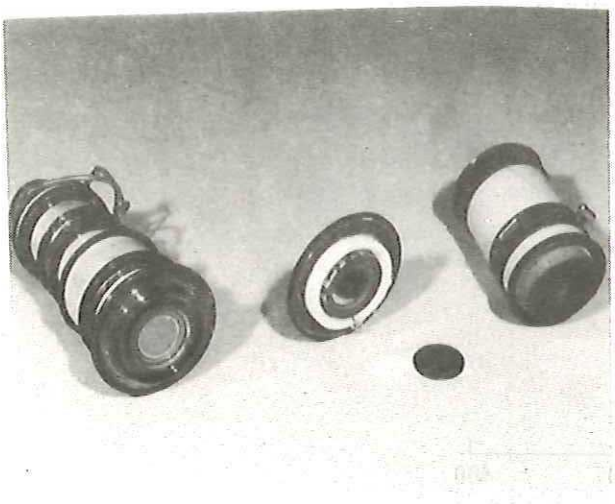

Fig. 5. EBS-CCD Imaging Tubes

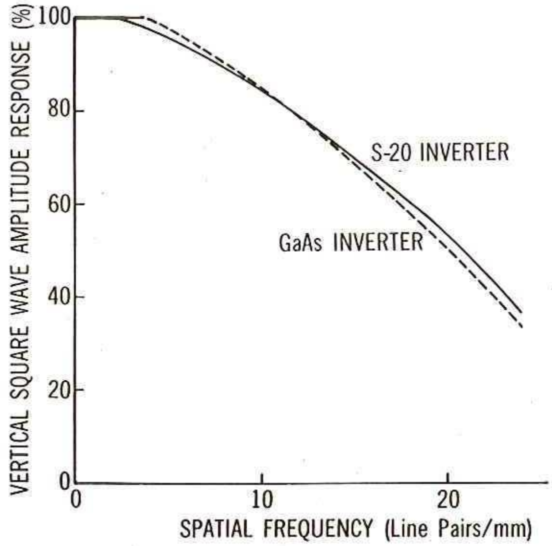

Fig. 6. SWAR of EBS-CCD Inverter Tubes.

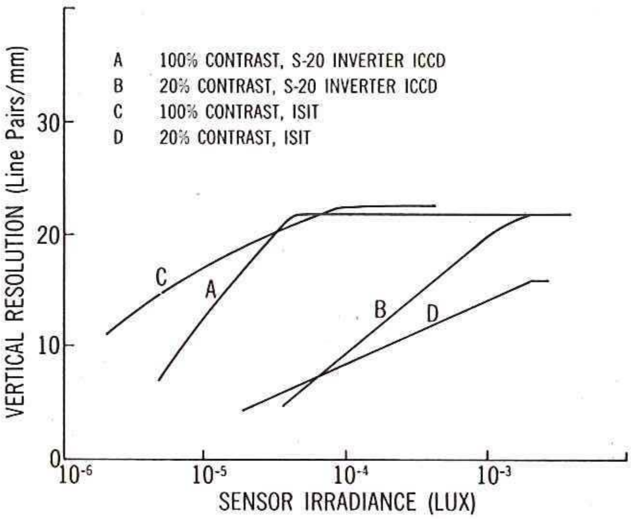

Fig. 7. Low Light Level Comparison of EBS-CCD and ISIT

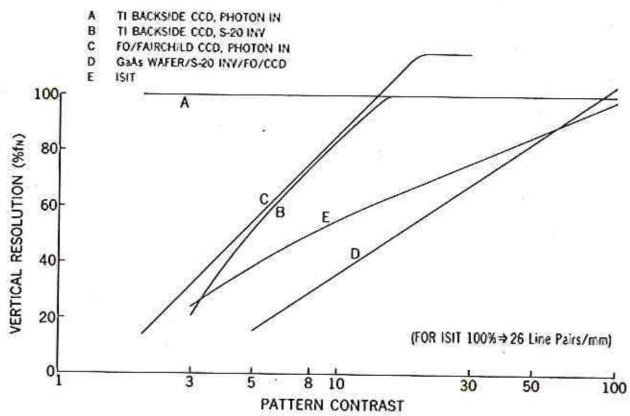

Fig. 8. Resolution vs. Contrast for Imaging CCDs.

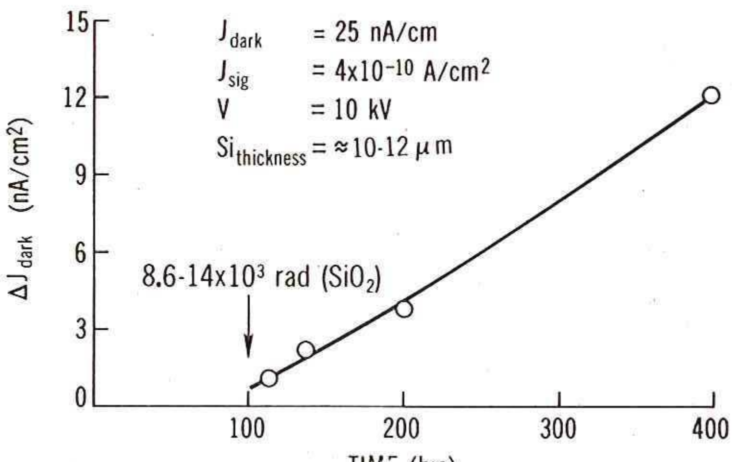

Fig. 9. Self-Induced X-ray Damage in EBS-CCD.