Back Thinned CCD's for Direct Electron Imaging

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Abstract: Issues in imaging keV electrons using back illuminated CCD's are discussed. A proximity focused Gen III image intensifier has been built using a back illuminated 512 x 512 CCD in place of the phosphor screen. Signal to noise, spatial resolution, minimum resolvable signal and life are discussed. In addition, a model of the back thinned CCD in the electron bombarded mode is presented.

Introduction: Very low light level imaging is driven by the need for high quantum efficiency detection of single photons at the highest possible speed and the highest spatial resolution. The scientific back-illuminated CCD provides excellent quantum efficiency, spatial resolution and low noise at slow-scan speeds and has found application in astronomy, spectroscopy and microscopy. In areas such as surveillance, where video rates are necessary, the Gen III image intensifier fiber-optically coupled to a front illuminated video rate CCD (ICCD) has found application. The GaAs Gen III photocathode quantum efficiencies can approach 30% at visible wavelengths. However, the image intensifier uses a micro-channel plate (MCP) as a gain stage, which increases noise above shot limits, is not linear and contributes to the poor spatial resolution of the system. The numerous interfaces and photon to electron conversions cause scattering which further degrades spatial resolution. It has long been realized that direct imaging of a GaAs photocathode by a back-illuminated CCD (EBCCD) will improve detective quantum efficiency to the level of the GaAs photocathode due to the 'built in' gain in the electron-bombarded silicon (EBS) process, thereby providing the highest possible sensitivity. Elimination of the MCP will increase noise performance to near theoretical limits throughout the dynamic range of the device and the simplicity of the design will eliminate the interfaces that cause poor spatial resolution. Perhaps most importantly, the EBCCD may be run at high speeds.

Through a joint effort between SITe and Intevac EO Sensors, two proximity focused GaAs image intensifiers have been built using the SITe SI502AB in place of the phosphor screen. The performance of these tubes, one, a bare SI502AB and the other, an SI502AF fiber-optically coupled to a high quality Intevac GaAsP image intensifier, has been measured and compared. In addition, a model of MTF and signal to noise vs spatial frequency has been developed for the three types of sensors. In earlier work a model for the EBS gain analogous to a photon quantum efficiency model for the back-illuminated CCD has been developed and fit to match both EBS gain data and QE data using the same set of physical parameters.

EBCCD Principles: Back-illuminated CCD's are sensitive to kilovolt-energy electrons incident on the back surface through the EBS gain process. The incident electron loses energy through a series of inelastic collisions that result in the production of electron-hole pairs at the rate of about one per 3.64 eV. Due to the correlated nature of the electron cascade, the variance in the number of pairs created is reduced below shot noise by the Fano factor (approximately 0.12 in silicon). This lowering of noise in the gain process leads to system noise being limited by the shot noise of the incident photoelectron signal.

The incident electron is absorbed very close to the silicon surface and for energies up to 10 keV creates all of it's 'child' electron-hole pairs within the first micron. If nothing were done to accumulate the back surface, the electric field caused by the presence of charged native oxide would tend to force the electrons to the back surface where they could recombine. Backside enhancement techniques such as UV charging, ion implanting, and annealing and flash gate technologies are designed to reverse the field near the surface so that electrons generated there are repelled and collected in the CCD well. Between the field at the back surface and the buried potential well there is a field-free region of some thickness; the thickness is a process parameter. In high quality silicon, the diffusion constant is much longer than the field free region, thus the 'child' electrons drift fairly unimpeded through this region. The spatial distribution in the CCD well depends on the angle of emission of the electron in the pair creation process as well as the distance from the point of emission to the edge of the depletion region. The result is charge spreading and degradation of spatial resolution.

Although kilovolt-energy electrons primarily produce electrons in silicon, X-rays are also generated, mainly the 1.74 keV K_α characteristic with 11.9 µm 1/e attenuation depth, but also broad-band Bremsstrahlung. A percentage of these X-rays travel through the silicon to be absorbed in the gate dielectric where they can cause a flat-band voltage shift or in the silicon-dielectric interface where they can create additional interface states -- a source of dark current in non-MPP operation. A practical way to reduce X-ray radiation damage is to reduce the electron energy below 1.74 keV. Thicker expitaxial silicon also reduces damage, but does so at the expense of spatial resolution.

The proximity-focused EBCCD image intensifier is much less complicated in design than the ICCD. The ultra-high vacuum requirement of the GaAs photocathode dictates that no organics be used in the CCD fabrication process and packaging, and the CCD must withstand tube bake-out temperatures. The assembly tolerances are looser than those of a tube incorporating an MCP. In addition, the size and weight of the EBCCD tube is much less than the standard image intensifier.

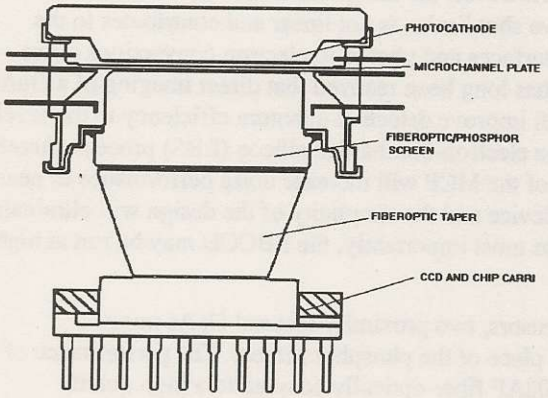

Figure 1. Cross-sectional drawing of a conventional fiberoptically-coupled ICCD.

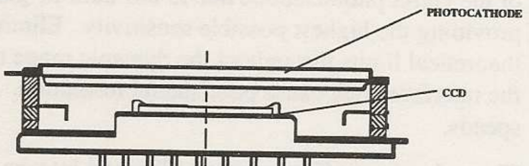

Figure 2. Cross-sectional drawing of a proximity focused EBCCD.

Models: A measure of the spatial resolution of a system is the modulation transfer function (MTF), which is simply the modulus of the Fourier transform of the system's point spread function (PSF). The system MTF is the product of the MTF of the components. However, the discretized CCD is anisoplanatic, i.e. the PSF is not invariant under spatial translation (a different distribution is found for a point light source focused on the intersection of four pixels compared with the same source centered on a single pixel). This adds a degree of complication in the analysis of small data sets.

The back-illuminated CCD's MTF is simply a sinc function, the Fourier transform of the square pulse. Thus

$$\mathrm{MTF}_{\mathrm{ccd}} = \frac{\sin(Wk/2)}{(Wk/2)} \tag{1}$$

where W is the pixel pitch (mm), and k is the spatial frequency (lp/mm).

The EBCCD MTF is comprised of four terms. The first term is for charge spread in the vacuum diode, the second is due to charge spread in the CCD and depends only on the thickness of the field-free region as described above. Due to the field in a proximity focused vacuum diode, backscattered secondaries create a 'halo' around the incident primary spot, accounted for by the third term. Finally a CCD MTF term is needed.

$$\mathrm{MTF}_{\mathrm{ebccd}} = e^{(-4\pi^2(\frac{\mathrm{Vim}}{\mathrm{Vs}})(fL)^2)} * e^{(-2\pi^2(d)^2(k)^2)} * [1-\eta\ (G/G_0)\, e^{(-1/(2Lk))}] * \frac{\sin(Wk/2)}{(Wk/2)} \qquad (3)$$

where, ***Vim*** is the maximum radial emission energy of photoelectrons from the cathode (eV), ***Vs*** is the cathode to anode voltage (V), ***k*** is the spatial frequency (2π lp/mm), ***L*** is the cathode to anode spacing of the proximity focused diode (mm), *d* is the field-free region thickness(mm), η is the backscattering coefficient, ***(G/G₀)*** is the ratio of the average EBS gain of the secondary electrons to the primary gain, and W is the CCD pixel pitch (mm).

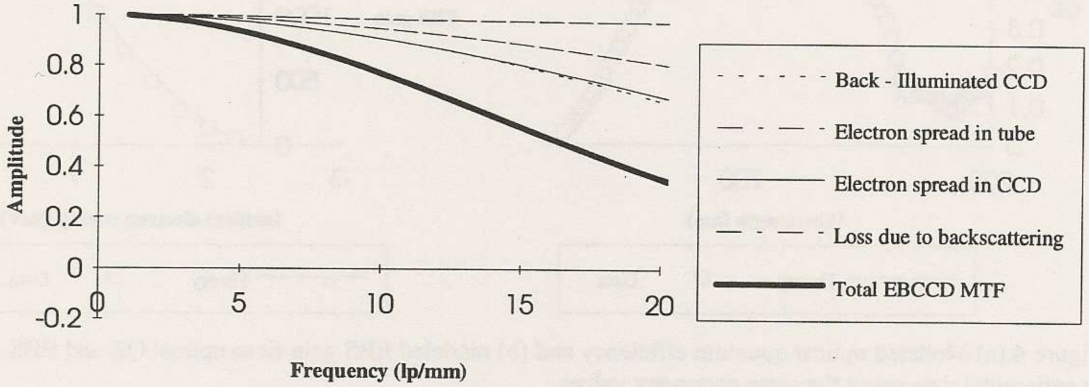

Figure 3. Modeled MTF of the components that make up the total EBCCD MTF.

MTF alone is not sufficient to determine spatial performance of a system because the presence of noise tends to 'wash out' higher frequency signals. The signal to noise ratio (SNR) vs frequency curve is a better barometer of low light level performance. The signal (in electrons) in the bright area of a target at spatial frequency *k* and wavelength(λ) can be written as:

$$\mathrm{Sig} = \Phi(\lambda) * \mathrm{QE}_{\mathrm{PC}}(\lambda) * A * G * \pi/(kW) * \mathrm{MTF}(k,\lambda) * \tau \qquad (4)$$

where $\Phi(\lambda)$ is the incident optical flux (photons/s/mm^2), $\mathrm{QE}_{\mathrm{PC}}(\lambda)$ is the photon to electron conversion quantum efficiency, G is the system gain, $\pi/(k\mathrm{W})$ is the number of pixels in the bright area, $\mathrm{MTF}(k,\lambda)$ is the system MTF at incident wavelength λ and spatial frequency k, τ is the integration time(s), and A is the area of the faceplate that is mapped onto a single CCD pixel (mm^2).

The variance (in e^2) over both the bright and dark areas can be given by:

$$\mathrm{Var} = \mathrm{Sig}(1+f)/2 + 2 * I_{\mathrm{dk\text{-}PC}} * G * \tau * A * (\pi/(k\mathrm{W})) + 2 * I_{\mathrm{dk\text{-}CCD}} * \tau * A_{\mathrm{CCD}} * (\pi/(k\mathrm{W})) + 2 * N_{\mathrm{read}}^2/(\pi/(k\mathrm{W})) \qquad (5)$$

where f is the gain noise factor (the Fano factor for EBCCD's), $I_{\mathrm{dk\text{-}PC}}$ is photocathode dark current density (e/s/mm^2), $I_{\mathrm{dk\text{-}CCD}}$ is CCD dark current density (e/s/mm^2), A_{CCD} is the area of a CCD pixel (mm^2) and N_{read} is the read noise per pixel (e).

For both the ICCD and the EBCCD the shot noise term dominates, however the noise factor of the MCP (~2.0) compared to the nearly noiseless Fano factor makes the ICCD variance much higher. In addition, the poorer MTF of the ICCD contributes to the fact that the EBCCD dramatically outperforms the ICCD at all signal levels and spatial frequencies.

In 1991 Blouke, *et al* presented a simple model of the back illuminated CCD which included the effects of surface recombination, the surface field, and the length of the field-free diffusion region. An analytic solution for optical quantum efficiency was found which produced excellent agreement with experimental data taken on anti-reflective coated, backside-enhanced CCDs. This model was extended to the general case by finding the probability of collection of an electron generated at any given depth. The general solution was applied to the special cases of optical generation and keV electron generation and *using the same values of surface recombination, electric field strength and field-free region thickness*, was used to generate curves which were in agreement with experiment.

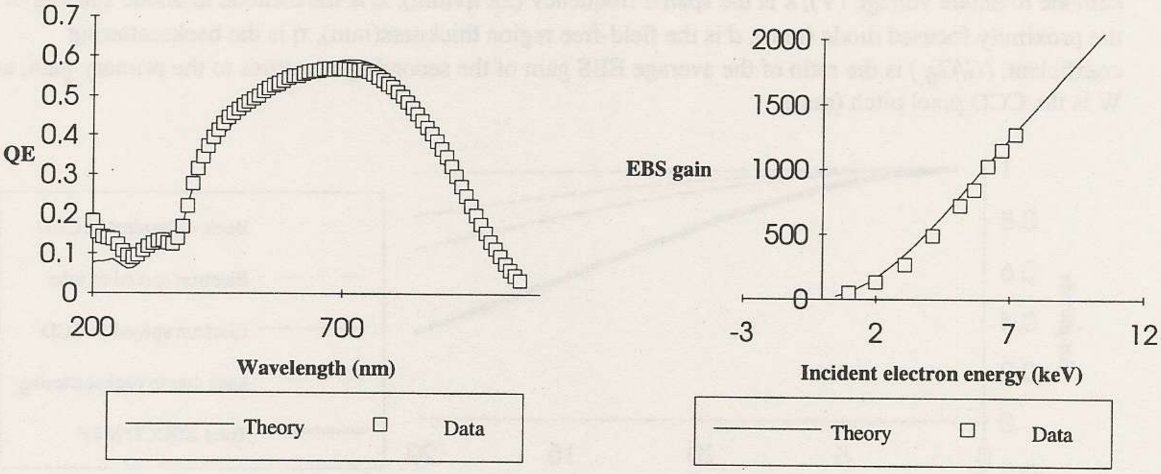

Figure 4.(a) Modeled optical quantum efficiency and (b) modeled EBS gain fit to optical QE and EBS gain experimental data using the same parameter values.

Tube performance: The SI502AB is scientific, slow scan, 512x512 element, 24 µm pixel back-illuminated imager and was used at room temperature for all of the resolution experiments.

Contrast transfer function was measured on both EBCCD tubes as a function of both acceleration voltage and light level. In addition, the ICCD was measured under identical illumination conditions so that a comparison of CTF could be made.

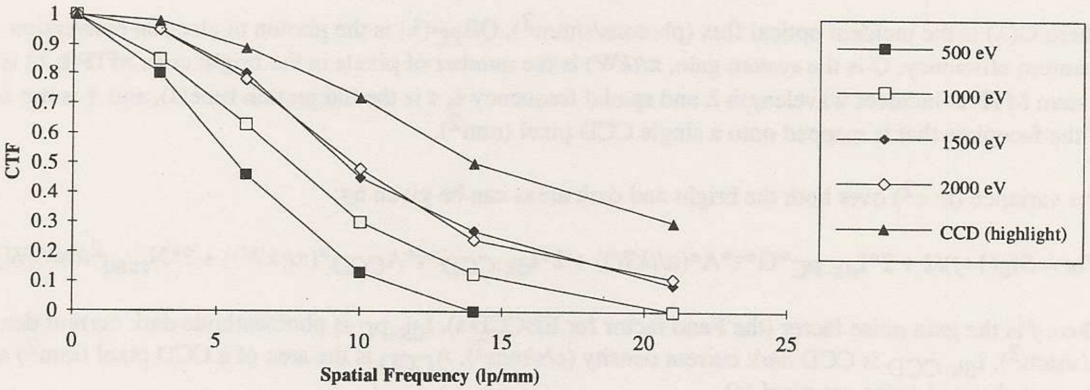

Figure 5. Measured CTF for GaAs SI502AB EBCCD for various acceleration energies @ $1*10^{-4}$ footcandles faceplate illumination using a 590 nanometer wavelength source. The CTF for a back-illuminated SI502AB CCD is also shown.

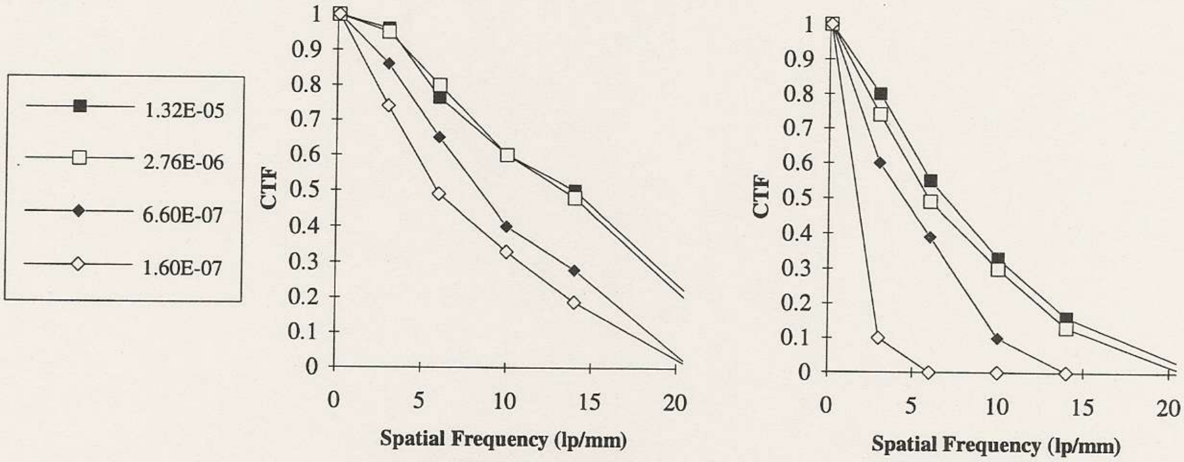

Figure 6. Measured CTF for (a) GaAs SI502AB EBCCD at 1.8 keV (b) GaAsP SI502AB ICCD for various light levels (footcandles of faceplate illumination using a 590 nanometer wavelength source)

The improvement in the contrast transfer function of the EBCCD over the ICCD is apparent at all light levels. This was also obvious in the visual display quality of the test pattern images.

A difference frame of two identical flat field frames at a 'high' light level was used for the measurement of variance versus mean in the EBCCD tube. Because the EBCCD has nearly noiseless gain, at very low spatial frequencies the ratio of the variance (in electrons) to the mean (in electrons) is just the EBS gain. However, at higher spatial frequencies, charge spreading results in correlation of noise, reducing variance. Figure 7 shows the results of binning various numbers of pixels in software before calculating the variance to mean ratio. The effect was modeled using a simple gaussian spread of standard deviation 13 μm (pixel size is 24 μm)

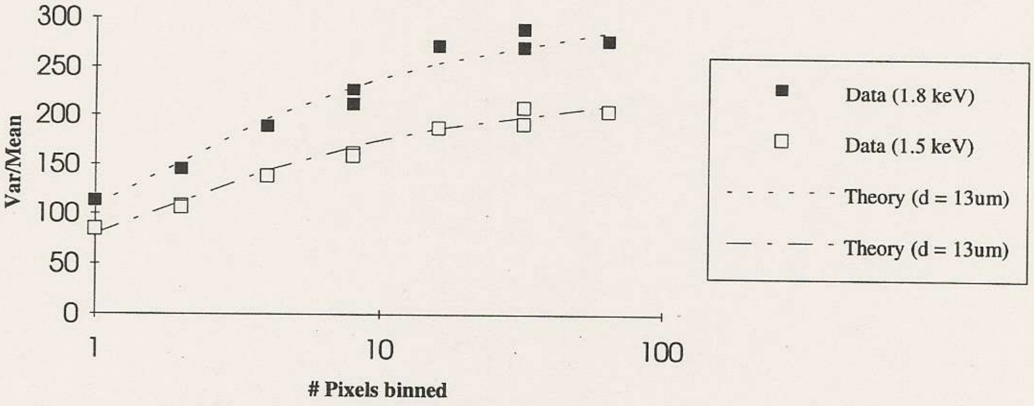

Figure 7. Ratio of variance to mean versus number of pixels binned into 'super pixels' showing the dependence of signal to noise ratio on MTF.

<u>**Future work**</u>: The high performance of the experimental EBCCD tubes reinforces the long held belief in the advantages of direct electron imaging CCD's. What remains is the development of a video rate EBCCD coupled to a GaAs photocathode to provide perhaps the ultimate in low light level imaging: single photon detection and high speed readout.