THE INTENSIFIED CCD

An investigation into the operation and usage of intensified CCDs

A report by Justin Lund

APPLIED OPTICS - PH 5/464
ABSTRACT

The intensified CCD is the combination of an intensifier and a CCD. The Intensifier makes it possible for a standard CCD to detect down to a single photon and have remarkably fast shutter speeds.

THEORY & OPERATION

The intensified CCD is really composed of two separate devices. One is the CCD (Charge Coupled Device) which is responsible for converting incoming photons into charge. The intensifier, which is the primary focus of this paper, is responsible for converting photon into electrons, multiplying the electrons, and reconverting the electrons back into photons for the CCD to detect.

CCD (CHARGE COUPLED DEVICE)

The charge coupled device operates under the principal of the photoelectric effect. Specifically, an incoming photon impinging upon a surface has a probability of liberating an electron in the valence band into the conduction band.

Figure 1: Concept of a CCD

CCDs are composed of millions of photodiode, photogates, or a combination of the two. In a photodiode an incoming photon impinges upon an n-type well on a, lightly doped, p-type silicon substrate. This frees an electron from the valence band into the conduction band. This freed electron also produces an opening in the crystal lattice. (a hole) Because there is a difference in potential between the n-type and the p-type silicon, the electron-hole-pair is separated across the junction which produces a corresponding current. For intrinsic detectors, absorption is largely determined by the band gap of the semiconductor material. If a photon of energy $h\nu$ is less than the band-gap energy, the photon will not be absorbed. If the energy of the photon is greater than the band gap energy, $E_g$, the photon will be absorbed. However, if the photon is too energetic, the photon will be absorbed near the surface where the chance of electron–hole recombination is the highest. The photogate operates on similar principles except that charges accumulate on the surface of the gate which produces a corresponding inversion region directly beneath the gate. In this inversion region, it is possible for charge to conduct across the channel.
Each of these photodiodes or photogates represent a single picture element. (or pixel for short) There can be many millions of these pixels on a single CCD. The CCD has a unique way of transporting the accumulated charge off-chip for voltage conversion. Each photogate accumulates a certain amount of charge (from the light source) and also accumulates charge from thermal excitations. Each pixel could be thought of as an empty bucket that slowly fills with water. To move charge from one pixel to another, a bias must be applied to a nearby photogate to form a lower potential well. Since this well is at a lower potential than the pixel nearby, the charges drift over to the lower potential well. One could envision this as a train of buckets; moving charge from one photogate to the next. All these buckets must make their way off the chip to charge-to-voltage converter to later be amplified.

Once the charge has been collected off-chip, the charge is converted to a voltage by storing the charge on a capacitor with a known capacitance. The charge to voltage relationship is simply expressed as:

\[ V = \frac{q}{C} \]

This voltage is applied to a high-gain, low-noise amplifier which scales the voltage up to a more discernable level. Each voltage represents a certain amount of charge accumulated on each pixel. Since the CCD must continuously be scanned to refresh the pixels, an analog signal is produced by this amplifier. This signal can be saved indefinitely by converting the analog voltage into a digital signal using a analog to digital converter (ADC). The ADC then samples the analog stream and quickly converts an analog voltage into an N-bit digital representation; the more bits that the ADC uses, the lower the error is between the analog and digital representations of the charge for a given pixel.
The spectral sensitivity of a bare CCD is determined mainly by the material of the CCD and physical design of the CCD. Most CCDs use a silicon process due to its low cost and ideal absorption characteristics in the visible spectrum.

For silicon:

\[ E_g = 1.11 \text{ eV} \]

\[ E_g = hf_i \rightarrow f_i = \frac{E_g}{h} = \frac{1.11 \text{ eV}}{4.1357 \times 10^{-15} \text{ eV} \cdot \text{s}} = 2.68 \times 10^{14} \text{ Hz} \]

\[ c = \lambda f \rightarrow \lambda = \frac{c}{f} = \frac{3.00 \times 10^8 \text{ m/s}}{2.68 \times 10^{14} \text{ Hz}} = 1.12 \times 10^{-6} \text{ m} = 1120 \text{ nm} \text{ (infrared)} \]

As stated before, photons with energy less than the band gap energy of the material will not be absorbed; the material will appear transparent to that photon. So for silicon, we know that the sensor cannot detect anything below photons with wavelengths greater than 1120 nm. For frequencies above the band gap energy, these photons will be absorbed. However, various other losses begin to appear as the frequency increases.

![Quantum Efficiency chart for a silicon-based CCD image sensor](image)

**Figure 4: Quantum Efficiency chart for a silicon-based CCD image sensor**

**QUANTUM EFFICIENCY (QE)**

Quantum efficiency refers to the percent of incoming photons that are converted into electrons. The figure above shows the spectrum quantum efficiency of the Hubble Space Telescope’s Planetary Camera and Wide Field Cameras 2 through 4. As we can see on the far right, the sensor doesn't detect wavelengths larger than about 1100nm. Ideally, this chart would show a steep rise right around 1100 nm but we are seeing many losses associated with other issues. An easy explanation for the drop in QE at shorter wavelengths is that the photon is absorbed at the surface of the semiconductor. The produced electron-hole pair is too far from the potential well, that the electron-hole pair recombines before the charges get swept apart. This simply causes the sensor to warm up a little bit.

The other losses are attributed to various absorption and reflections produced by antireflective coatings on the CCD and the optics. There is also an inherent loss in the design of the sensor; only the active region of a pixel can detect a photon, other physical structures on the wafer can absorb or reflect incoming photons.
CHARGE-TRANSFER EFFICIENCY (CTE)

As discussed earlier, the charges generated in each pixel must eventually be collected off-chip to produce to be analyzed. As with all things practical and real, this process also involves losses. When we switch on a neighboring gate to lower its potential well, we move most of the charges from the neighboring photogate. Some of the electrons get trapped near the insulator-substrate interface because of dangling electron bonds, and trapped ions in the insulator. Notwithstanding, a charge transfer ratio of 0.999 is actually consider horrible. The reason being, on a high resolution camera, it may be necessary to shift by more than 2000 times to read a pixel.

Total Transfer Efficiency, \( TTE = (0.999)^{2000} = 0.135 \)

On average, only 13.5% of detected photons make it to the amplifier if there are 2000 shifts involved. A CTE of about 0.99999 will yield a TTE of 0.980 to the amplifier; this is considerably better. A higher CTE can be accomplished by implanting positive ions deep below the insulator-substrate interface to make a lower potential well further away from the insulator. A CTE of 0.9999999 is not uncommon in modern scientific CCD sensors. Cameras with a low CTE tend to show streaking, even if the camera is completely still.

![Figure 5: CCD sensor with a high CTE](image1)

![Figure 6: CCD with a low CTE](image2)

SIGNAL TO NOISE RATIO (SNR)

We only want to see photons that are seen by the image sensor. Of the photons that make it to a photogate, get successfully absorbed, get converted to an electron-hole pair, get swept across the junction and survived the myriad of charge-transfers, how can we be sure that the electron that reaches the amplifier indeed came from a photon from a specific pixel at a given time? Short answer: hope! Because of thermal excitation, there are electrons constantly being excited from the valence band into the conduction band of the material. This current is called “dark-current” because there is a constant small trickle of electrons popping into the conduction band even when no light is reaching the sensor. Extremely sensitive applications generally require cooling the sensor to -40°C or lower to reduce the thermal noise. This assumes using an image intensifier is not an option.

There is also a chance that not all of the charges got transferred from a designated pixel during charge transfer. This introduces a random amount of noise in the final image. Because there are so many tiny capacitors being switched on and off so quickly in a CCD, it is very hard on the final amplifier to filter out all of these voltage spikes. In general the signal to noise ratio is expressed as:

\[
SNR = \frac{P_{\text{signal}}}{P_{\text{noise}}}
\]

\[
SNR_{\text{dB}} = 10 \log \left( \frac{P_{\text{signal}}}{P_{\text{noise}}} \right)
\]
While the focus of this project is on the image intensifier, it’s job is to merely augment a CCD sensor. The general role of the intensifier is to take incoming photons, convert them into electrons, multiply the electrons, and reconvert them back into photons for the CCD sensor to detect. This process will be further explored in the figure below:

**THE PHOTOCATHODE**

An incoming photon encounters the photocathode which is an electrically charge screen. When the incoming photon contacts the screen, electrons are ejected off of the back surface of the photocathode and accelerated towards the micro-channel plate (MCP). The acceleration is accomplished by the voltage across “A”. This voltage is typically around 200V. This is also termed the “gating voltage” because turning this voltage off, or reversing will prevent incoming photons from ever effectively reaching the CCD. Hence, the photocathode acts as a shutter for intensified CCDs.
THE MICRO-CHANNEL PLATE (MCP)

The role of the micro-channel plate is to multiply the incoming electrons into a tightly configured package of electrons with low divergence. (near-collimation) The MCP is constructed out of a high resistivity material, it is thin plate (usually 2-3mm thick) that contains millions of tiny little holes (≈10μm) that are milled out slightly off of optical center by about 8°. A voltage of about 1kV is maintained across the MCP ("B") to increase the kinetic energy of the electrons as they collide against the walls in the MCP. The electron is guaranteed to hit a wall in the MCP due to the design geometry. The repeated collisions inside the MCP produce an exponential increase in electron.

THE PHOSPOR SCREEN

Finally, the “packets” of electrons are emitted from the backside of the MCP. These packages of electrons are accelerated by 6kV towards a phosphor screen. This is similar to how a TV works, except with no scanning and there is no discerning between colors. The electrons careen into the surface which excites the phosphor. Naturally, the phosphor will fall to its lower energy state and spontaneously emit one or more photons. Each of the electrons from the MCP produces a photon location spatially located at the same location that the original photon entered the intensifier.

Typically there is fiber optic plate attached to the back of the intensifier to transport the photons to the CCD. A fiber optic plate is composed of millions of micron-sized fiber optics that are all parallel to one-another. The photons stay collimated all the way to the CCD sensor.
The applications of intensified CCD are fairly widespread. Their cost generally makes them outside of most consumers budget.

**APPLICATIONS**

High Speed Analysis - Utilizing an intensifier to have an extremely rapid shutter and short exposure time.

Fluorescence Microscopy – Utilizing an intensifier to capture the fluorescence of specimens

Spectroscopy – Accurately measuring the wavelengths of light from vaporized samples to determine composition
**MILITARY**

**Night Vision** – The military invests a considerable amount of money in intensifier research. Namely, because soldiers need the latest that the technology has to offer in terms of improving field-of-view, improved sensitivity, auto-brightness adjusting, low voltage (rain, sweaty soldiers), and low power. (due to the weight of batteries)

![Night Vision Device](image1.png)

**CONSUMER APPLICATIONS**

**Safety** – Night driving to watch out for pedestrians and wildlife

![Optional night vision system for BMW 5-series](image2.png)
Security – Using an intensified CCD to see thermal infrared in low-light for security applications

![Figure 16: Thermal Camera showing intruder climbing a fence](image)

Thermal Imaging – Using an intensified CCD to see thermal infrared of a motherboard

![Figure 17: Thermal infrared image of a running circuit board](image)

**CONCLUSION**

The intensified CCD is actually a fairly simple concept when the components are individually broken down. In essence, an intensifier merely takes a photon, converts it into an electron, multiplies it, and re-emits the electrons as photons. The CCD takes care of all the rest. While the intensifier does trade off color information for sensitivity and extremely fast exposure times, it performs remarkably well in the applications that it is used in.
• Hamamatsu, Inc. – Manufacturer of various optical equipment

• ASII Imaging

• ANDOR, Inc.
  http://www.andor.com/learn/digital_cameras/?docid=326

• Dalsa Inc.
  o http://www.dalsa.com/markets/ccd_vs_cmos.asp

• ICCD
  http://www.iccd-camera.com/technology_main.html

• Wikipedia - Quantum Efficiency

• NASA – CCD Imagers
  http://wfc3.gsfc.nasa.gov/MARCONI/machines-see.html