UV Technology Overview

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Abstract

Ultraviolet (UV) image sensors have been and are actively being developed for a variety of space-borne astronomy missions. There is a large range in the maturity of UV detectors. Some systems have already flown numerous times and still continue to undergo refinements. At the other extreme, there are potentially breakthrough novel devices that require the development of several fundamental technologies before a sensor can become viable. The detector, which historically is one of the most problematic parts of any astronomical spacecraft, represents only a few percent of the total costs but plays a critical role in the overall capability of the instrument. For a telescope of a given aperture, it is the detector that determines the feasibility of various science projects. Although several types of image sensors are expected to make significant performance improvements, no existing nor future detector system will ever be ideal for all ultraviolet applications, not even the newest, most highly innovative devices. Each detector system has its own unique set of advantages and inherent limitations. This review presents an overview of UV technologies including those that are currently available as well as those that are in their early stages of development. Special attention is given to those devices not covered extensively in other reviews in this volume. In addition, special attention is given to the physical processes responsible for the inherent capabilities of a few important existing and future UV detectors.

Introduction

In general, image sensors can be broken down into several classes and subclasses. Two typical subclasses, Solid State and Photo emissive, are represented schematically in Figure 1 , which also demonstrates some of the inherent properties of each. A wavelength scale with corresponding photon energies and thermal equivalences are shown at the bottom Solid state devices, which absorb the photons into the semiconductor substrate, have sensitivities over a broad range of wavelengths while photo emissive detectors use various photo cathodes that are tailored to be sensitive to a specific, limited-wavelength interval.

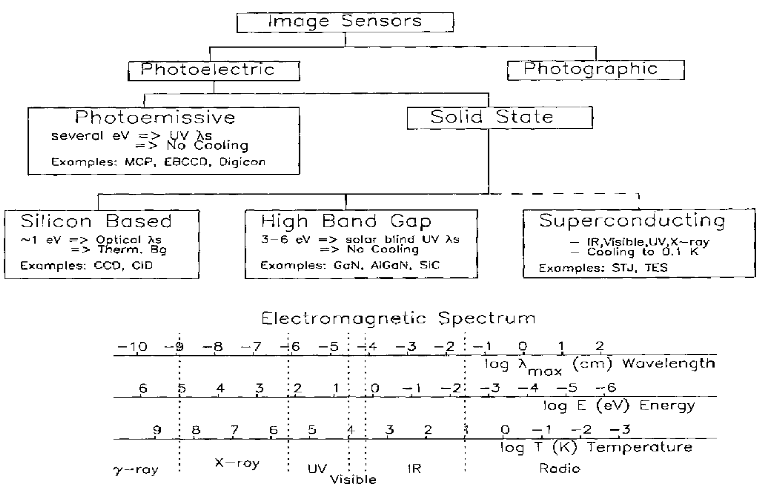


Fig. 1

In most solid-state devices, the photon causes an electron to transition into the conduction band. Currently, the most common devices are silicon-based CCDs where the detection process requires energies of approximately an electron volt. It is readily apparent from Figure 1 that CCDs should (and do) have excellent sensitivity in the visible and near-IR portion of the electromagnetic spectrum and that these devices should be sensitive to thermally induced backgrounds at room temperatures. Solid-state detectors made of GaN or other high-band-gap materials have the same properties but the activation energy is 3.4 eV or higher, making these devices inherently solar blind and UV sensitive without thermally induced backgrounds. Recently, super conduction sensors, a new subclass of solid-state detectors, have emerged. These ultracold ($T < 1$ K) devices include Superconducting Tunneling Junctions (STJs) and Transition Edge Sensors (TES). These sensors provide 3-dimensional imaging, two spatial as well as energy resolution. An incident photon breaks a number of Cooper pairs proportional to its energy. Similar to other solid-state detectors, STJs and TES have sensitivity over a broad range of wavelengths and have read noise. It is straight forward, however, to make super conducting sensors into photon counters.

In contrast to solid-state detectors, the photon in photoemissive devices must have sufficient energy to eject an electron from a photocathode material, typically requiring energies of a few electron volts. These image sensors are therefore natural UV detectors and are the sensor of choice for most UV missions. Photoemissive devices produce negligible dark backgrounds at room temperatures and can be constructed to be inherently solar blind. A single photoelectron, however, cannot be recorded reliably without some form of intensification, which implies high voltages and the inherent associated difficulties. If the intensification process is saturated and has sufficient gain, detectors that are photon counting with zero read noise can be constructed. Although all solid-state devices have read noise, researchers have had great success in reducing it in most cases to the point where the signal-to-noise ratios achieved with solid-state devices is competitive with photon-counting detectors except at very low flux levels or except where very high time resolution is required.

Obviously there is some overlap between various classes of detectors. For example, photoemissive devices with photocathodes such as the S20 have been developed with response well into the visible. Detectors with S20 photocathodes do have to be cooled to reduce the dark counts. There are also hybrid detectors such as the Intensified Charge Injection Device (ICD) or the Electron-Bombarded CCD (EBCDD) in which the detection process ends with electrons striking a solid-state sensor. There are far too many different UV detector systems to give adequate coverage to each. Out of necessity many are being omitted from discussion all together. Table 1 is a noncomprehensive list of recent or on-going UV/visible detector research funded by NASA in recent years. The list is included to give the reader some idea of the breadth of development efforts that have been undertaken recently.

Table 1: Examples of Recent Development Efforts

Detector/Technology	PI - Institution
MCP/Adv. Tech. MCP	Chakrabarti – Boston U.
	Siegmund – Berkeley
	Woodgate – GSFC
CCD	Collins – JPL
	Grunthaner/Nikzad – JPL
	Lesser - Arizona
APS/ADP	Fossum – JPL

	Fowler - Pixel Devices International
CID/ICID	Kimble – GSFC
	Ninkov – Rochester Inst. Of Tech
EBCCD	Lowrance – Princeton Scientific Instruments
GaN/A1GaN	Moses – Naval Research Lab
	Mott – GSFC
	Razeghi/Ulmer – Northwestern U
Diamond	Marchywka – Naval Research Lab
STJ	Labov – Lawrence Livermore
	National Laboratories
	Verhoeve – ESA
	Wilson - Yale
TES	Martinis – National Institute of Standards & Tech
	Cabrera – Stanford
	Tralshawala - GSFC

In some circumstances, specialized missions have fewer detector requirements than observatories designed for a broad range of applications. Occasionally, these missions can take advantage of a unique strength of a particular detector system that otherwise might not be competitive as a general purpose UV image sensor. For example, a mission to study UV bright early-type stars may not require extensive visible or infrared rejection so there is no special need for a solar-blind detector. In other circumstances, a near-UV capability might be desirable for an instrument designed primarily for visible wavelengths. To save cost and minimize complexity, the mission may choose merely to extend the range of wavelengths of the existing instrument rather than creating a separate near-UV channel having greater efficiency. Nevertheless, the science drivers require a general-purpose UV image sensor to have 5 primary properties above all else: 1) it should NOT be sensitive to light as visible wavelengths (commonly referred to as being solar blind), 2) it should have high Detective Quantum Efficiency (DQE), 3) it should have a high Local Dynamic Range (LDR), 4) it should have low backgrounds since noise arising from the background often dominates in faint UV observations and 5) it should have a large multiplexing capability (i.e. a large number of pixels or in some cases simultaneous imaging and energy discrimination) to maintain sufficient field of view or to record significant amounts of spectra simultaneously. Obviously, there are many other important parameters. Some of these extra parameters are normally achieved with current technologies and are therefore of less concern. Still others including weight, volume, and power have improvement efforts that are on going.

One of the most successful types of ultraviolet detector is that based on the microchannel plate (MCP). (See the review of MCP systems by Siegmund this volume.) Since most current and future UV missions use or will use this type of sensor, the performance of the MCP will be taken as a standard comparison. An MCP essentially is a small, thin disk of lead-oxide glass with numerous microscopic channels, running parallel to each other from one face of the disk to the other. When an electric potential is applied between the two faces, the MCP becomes an image intensifier. The device can be considered to be a compact assemblage of photomultipliers since electrons striking the walls of a pore liberate additional electrons in a continuous dynode fashion to produce an avalanche. If the potential is sufficiently large, a photoelectron then gives rise to a saturated electron cloud with a total charge falling within a narrow range that can be easily "counted" electronically.

No single detector system is uniquely well suited for all applications, not even the newest, most highly innovative devices. This review attempts to highlight the advantages and disadvantages based on the physical processes of a few key UV image sensors that have or will soon have significant impact on ultraviolet astronomical observations. The reader is referred to two previous invited reviews of UV technologies by Joseph (1995, 1997) for additional information and a list of earlier reviews.

2. Detective Quantum Efficiency

Perhaps the first parameter to consider in any discussion of UV image sensors is its sensitivity. Here a distinction is made between Quantum Efficiency (QE) and Detective Quantum Efficiency (DQE). The latter takes into account all losses. At UV wavelengths, one pays a strong penalty for each reflection or transmission element and there is normally a substantial difference between DQE and QE. In addition, photon counters most often used as the UV sensor have electronic conversion efficiencies, which are not perfect, reducing the DQE further. At visible wavelengths, many optical elements (filters, lens, etc.) have transmission efficiencies of 95% or greater and the distinction between DQE and QE is often very minor.

While recognizing not all applications require the sensor to be solar blind, this review shall always take UV DQE to be solar blind DQE unless otherwise specified. For many observations, the source itself produces far more flux at visible wavelengths than it does in the UV. Astronomical objects often emit 10^4 to 10^8 visible photons for every UV photon in the 100 to 200 nm wavelength region. If the detector also has good sensitivity at these longer wavelengths then the detector will be swamped with flux and the corresponding data will contain an enormous background contribution that substantially increases the noise. These statements are valid even if a UV filter is used, which typically has a 10^{-3} to 10^{-4} out-of-band leakage (transmission) at a visible wavelengths.

To summarize detector Quantum Efficiencies, Figures 2 and 3 show the current status of QEs and DQEs of common detectors. Figure 2 shows the QEs that can be obtained with various configurations of thinned, back-illuminated CCDs. (See the review in this volume by M. Clampin.) Future antireflection coatings, depicted as a dot-dash line, may extend the range well into the UV. A lumogen phosphor coating on a thinned chip has been demonstrated to have the QE shown by the curve with solid dots. Unfortunately, when placed behind a Woods filter to make it insensitive to visible wavelengths (solar blind), the QE drops to the level depicted by the bold solid curve.

Fig. 2

Figure 3 shows the Solar-Blind Efficiencies or DQEs obtained by various UV sensors. Once again the lumogen coated CCD plus Woods filter combination is plotted with a bold-line curve. This DQE curve is for a pristine CCD/Woods combination before contamination becomes a factor. All of the DQE curves for the MCP detectors are actual demonstrated values as is the FUV curve for the EBCCD (see Joseph, 1995). Note that EUV (» <90 nm) DQE values do not include the plastic or thin-film filter normally used to block UV (not visible) photons. Plotted as dotted lines are the expected UV DQEs for two future EBCCDs. These EBCCD curves incorporate all known losses such as that due to the entrance window. Also plotted as dotted lines are the expected DQE curves for future A1GaN solid-state detectors. The red side cutoff is set by the relative alloy content of Al versus Ga in the nitride. Not plotted are the ~50% QE curves for STJs and TESes.

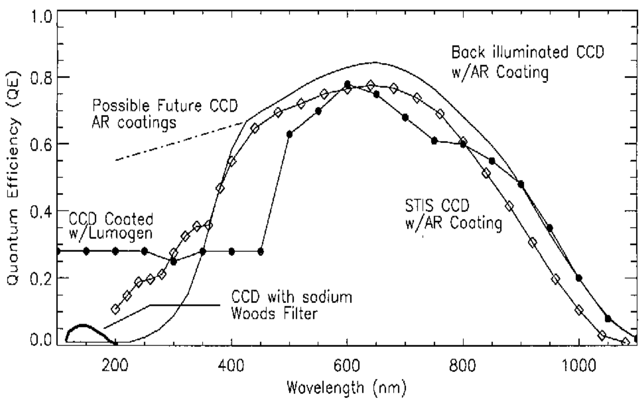


Fig. 3 showing QEs of various configurations of thinned back illuminate CCDs.

Fig. 3

As can be seen in Figures 2 and 3, there is a severe penalty to make detectors solar blind. If the device is operated at cold temperatures, condensable contaminants even in the vacuum of space reduces the sensitivity by another factor of 4 or 5. Thus a cold detector that has visible response may end up having a UV DQE of only 2% when it started with a QE of 50%. Also note that a significant improvement in the near-UV capabilities would be possible with EBCCDs in the near term (~few years).

3. Local Dynamic Range

LDR is defined as the maximum level of flux that can be accommodated in a small area of the detector minus the faintest level that is still 3 standard deviations above the background plus read noise (if present). The LDR is determined for practical integration times. We distinguish between LDR and GDR (global dynamic range), the total flux rate spread over the whole detector. These two types of dynamic range are normally set by two distinctly separate physical processes in MCP photon counters. Note that most UV astronomical scenes have most of the light in a relatively few pixels or are generally faint so that the GDR is rarely important for imaging applications. GDR is important nevertheless for echelle spectra of bright hot stars or for observing the sun. Similarly, the GDR determines the time required to accumulate a calibration flat field to measure the pixel-to-pixel sensitivity.

Figure 4 shows both GDR and LDR envelopes for several important photoemissive devices. To facilitate the comparison, all detector systems have been normalized to a common format and MCP resistance. All envelopes in Figure 5 represent the 10% coincident loss point. (See Joseph 1995, 1997 for more details). As an example, the distribution of light in the focal plane is shown for the medium resolution mode of STIS, denoted as STIS: R= 2 X 10^4 . In this medium-spectral-resolution mode, the distribution of light on the detector from any hot star will fall somewhere along this dashed line. The GDR for MCP-based detectors is limited by the speed of the electronics, which must process each photoevent sequentially. Coincidence losses occur when the photons arrive too rapidly. The LDR, on the other hand, is set by the recharge timescale of the MCP. When light is concentrated into a small region of the detector, rapid pulsing of the MCP can lead to incomplete recharging between pulses and a corresponding sag in gain.

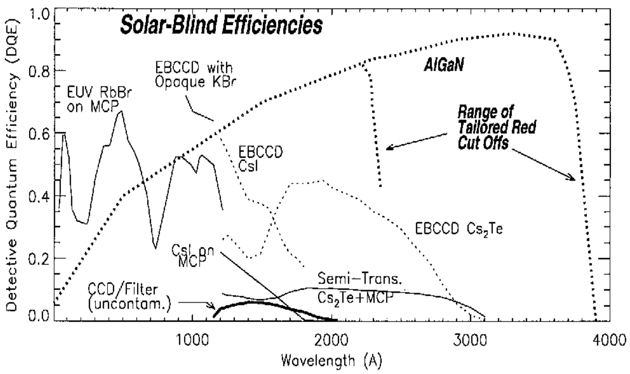


Fig. 4 showing solar-blind UV DQEs of various detectors.

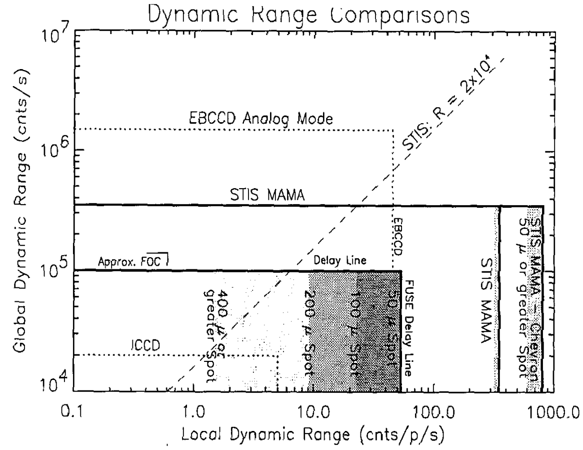
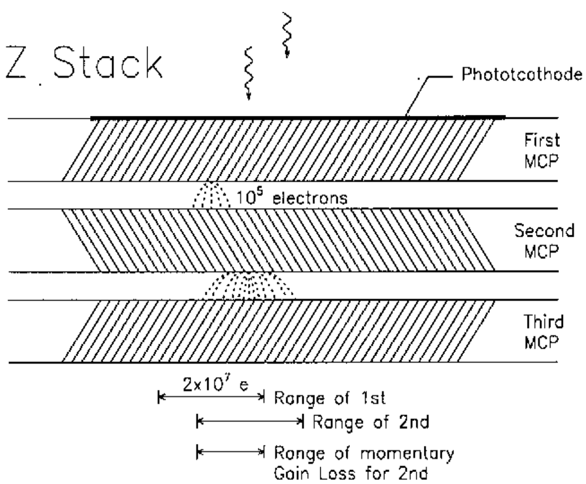


Fig. 5 showing dynamic range envelopes.

[Fig. 4](#) [Fig.5](#)

The distribution of light at the focal plane can significantly impact sensor performance. Whenever the LDR is exceeded, the MCP becomes nonphotometric and introduces image distortions, especially for detectors using a Z stack of MCPs. The LDRs for these Z stacks are strongly dependent upon the scene being recorded. The shaded regions show the limits where simultaneous loss in resolution and photometry occur as a function of spot size. The LDR for the STIS MAMA in the Chevron Configuration, for example, is independent of spot size for spot diameters of 50 ¼m or larger. The Delay Line, however, has an LDR over 50 for a 50 ¼m spot but only and LDR of <2 cnts/pixel/second for a 400 ¼m or greater diameter spot.

The physical processes responsible for this limitation can be seen in [Figure 5](#). The Delay Line requires at least 2 X $10^7 e_-$ to achieve <25 ¼m resolution (Siegmund, Lampton, & Raffanti 1989). To achieve this level of gain, a Z stack such as that shown schematically in [Figure 6](#) must have charge spreading between each MCP so that numerous MCP channels are activated in the final plate for each event. If a second photoevent occurs in a time interval comparable to- or shorter than- the recharge timescale and within a distance comparable to the final charge cloud, the second event will have significantly less gain because some of the channels in the third plate that would have participated in the event are still depleted of charge. Thus, the centroid of the second pulse will have a systematic error. In the example of [Figure 5](#), the second photo event will either not be detected or will be erroneously displaced to the right, if it is detected.



[Fig.6](#)

An additional disadvantage of Z stack MCPs is their inherently short lifetime compared to single-plate MCP detectors. All MCPs degrade with use. Z stacks degrades faster because the stack uses many more pores for each event. It is important, however, to note that Z stack detectors have unique advantages as well. In general Z stack MCP detectors have more generous spatial tolerances than do other MCP detectors. Large focal plans for possible and fewer electronics circuits are required than a single-plate MCP system.

4. Backgrounds and Read Noise

Contributions to the background include internal detector darks and externally induced sources, and for solid-state devices read noise. For example, cosmic rays interacting with MgF_2 faceplates used in image tubes can in some circumstances produce measurable amounts Cherenkov radiation or phosphorescence. Dark backgrounds in space-borne CCDs are generally higher than for ground-based CCDs since on-board thermal electric coolers cannot achieve the cold temperatures of dewar-based systems. In addition, cosmic ray events for CCDs in space are at least a factor of 10 higher than those operating on the ground. The integration times of individual CCD frames are usually set by the levels of cosmic ray hits that are tolerable. The backgrounds of most detectors are thus sensitive to their environment (i.e. whether or not the sensor is in the South Atlantic Anomaly or above or below the Van Allen Radiation Belts).

5. Selected, Individual Detector Systems

MCP: Traditional glass MCPs are a mature technology dating back to the night vision industry started in the 1960s. These are the detector of choice in most UV missions. Recent work includes the fabrication of small-pore MCPs to increase resolution. Typical pores in the new MCPs have 8 ¼m pores on 10 ¼m centers. There has been recent research to improve the sensitivity of photocathodes for wavelengths longward of 120 nm. In addition, Advanced-Technology MCPs (AT-MCPs) are being developed. An AT-MCP represents a radical departure in the use of materials and fabrication methods. AT-MCPs use photolithography and dry etch techniques. The principal advantage is the ability to align individual pores from one MCP with the next or with an anode structure. **Strengths are**: 1) mature technology with plenty of flight history, 2) good solar blind DQEs of 10 – 25% over wavelengths of 120 – 250 nm, 3) the ability to build zero-read-noise systems, 4) adequate dynamic range (GDR ~ 3 X 10^5 cnts/sec and LDR ~ 50 cnts/pixel/sec, and 5) radiation hard. **Weaknesses are**: 1) requires high voltage, 2) sensitivity is a strong function of angle of incidence, and 3) large surface areas of MCP requires special handling during fabrication.

EBCCDs: While having very high (>70%) peak DQEs, EBCCDs have traditionally been bulky and heavy. Recently, new cladding magnet designs have dramatically reduced weight and size, making these competitive with alternative detectors (Lowrance et al. 1991). The new magnet designs have improved image quality and leak very little magnetic flux. This detector system potentially represents a short-term solution to increasing near UV (180 <» <300) efficiencies from the meager 10% currently obtained to DQEs of 40%. **Strengths are**: 1) very high DQEs, 2) size and weight are competitive, 3) design is rugged and straight forward to implement, 4) can be operated in photon counting and analog modes simultaneously for maximum LDR, and 5) radiation hard. **Weaknesses are:** 1) requires large high voltage (10,000 V), 2) a sealed tube design for near-UV applications has never been fabricated, and 3) fast optical systems (< f/8) are not possible due to high voltages.

A1GaN or GaN: These are very immature technology solid-state detectors. There has been recent success in obtaining high, solar-blind DQEs in excess of 60%. Several device structures have been fabricated including 256x256 pixel arrays. Material quality of the GaN and A1GaN continues to impact adversely the detector performance. Several multimillion-dollar programs in materials science funded by the Defense Department have been making progress to reduce defect and dislocation rates in these materials. **Strengths are**:1) high-band-gap offers natural UV detector with no thermal background and very high, solar-blind UV DQEs; 2) compact, rugged, detectors can be fabricated which are radiation hard 3) very large LDRs, and 4) red side cutoffs can be tailored between 195 and 365 nm. **Weaknesses are**: 1) material quality currently is inadequate leading to very high leakage background currents, 2) as with all solid-state detectors, GaN devices have read noise.

STJs and TESes: These novel devices are very immature technology, but are undergoing rapid improvement in the US, Europe, and Japan. Currently, investigators have produced discrete arrays with LDRs of approximately 10^4 counts/sec and are beginning to fabricate 2-D imaging arrays. Substantial development efforts are required on space-qualified cryogenic systems and ultralow temperature amplifiers among others. **Strengths are:** 1) very good QE over IR/visible/UV/X-ray wavelengths, 2) 3-D imaging including energy resolution within a pixel, and 3) solid-state detector providing photon-counting capability. **Weaknesses are:**

1) not solar blind making these less suitable for general-purpose UV sensors, 2) must be operated at ultra cold temperatures adding complexity and further reducing UV efficiencies due to condensibles, and 3) visible photons that are coincident with UV photons can cause incorrect energy assignments and shifts in spatial addresses.

6. Summary

Several new types of UV detectors have appeared in recent years as demonstrated in this review. Technological improvements to these as well as the mature, standard workhorse detectors is on going. Each detector system has its own set of inherent strengths and limitations that are rooted in the physical processes involved in the detection process, making no single detector system ideal for all applications. Even within a single subclass of sensor (e.g. MCP Z stack vs single plate), the physics dictates significant performance differences. This review has provided an overview of the requirements for general-purpose UV sensors and the technologies associated with various UV detectors.

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