— 25 —

Intensified solid state sensor cameras: ICCD and IAPS

Udo Schühle[I]

Abstract

We describe the general design of intensified charge coupled devices and intensified active pixel sensors: cameras using microchannel plate intensifiers in combination with imaging arrays, like CCDs or CMOS-APS sensors. Several design options are compared and the capabilities and shortcomings of these devices will be highlighted and discussed. We describe, in particular, the properties of the intensifiers, phosphor anodes, and coupling schemes. The coupling between the intensifier and the image sensor is a special technological step that adds to this type of camera a great amount of flexibility and design options.

Introduction

An intensified charge coupled device (ICCD) or an intensified active pixel sensor (IAPS) camera is just a special form of a microchannel plate (MCP) detector system where the image encoding system uses a CCD or a CMOS-APS sensor chip for building a digital image. The MCP-intensifier in this case is using a phosphor anode to convert the electron pulse into visible light, which will be accumulated in the imaging sensor. Like all MCP detectors, they can be used in a large spectral range from the visible to the extreme ultraviolet where secondary electron emission from a suitable photocathode material is efficient. But after the development of thinned, back-side illuminated CCDs for the EUV range, MCP intensifiers have more been used in the particular photo-emission regime in the VUV, where materials are not transparent enough to allow penetration of the radiation into the bulk of the sensor where charge carriers can be collected.

The use of MCP intensifiers with an imaging chip increases not only the complexity to the camera design but it also adds important flexibility:

- the intensifier can be made more sensitive in a preferred spectral range by selection of the photocathode material,
- by switching the high voltage of the MCP, the intensifier can be used as an electronic shutter,

---

[I] MPS—Max-Planck-Institut für Sonnensystemforschung, Katlenburg-Lindau, Germany

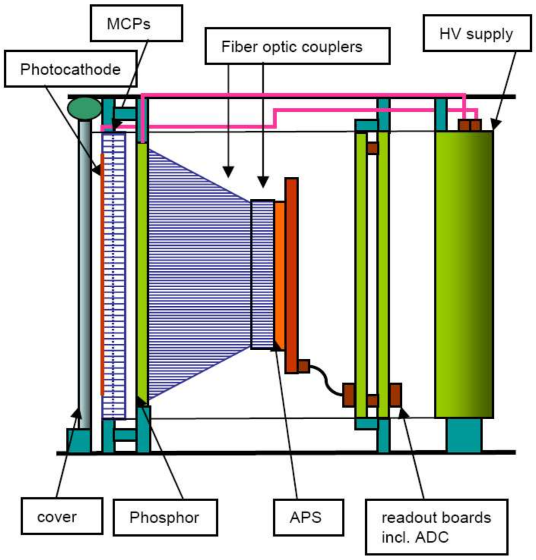


Figure 25.1: General scheme of ICCD / IAPS cameras. The size of each individual component is not to scale and may be selected according to availability and the performance goals of the assembly.

- the size of the focal plane, and thus the image scale of the optical system, becomes independent of the imaging chip size, as it can be adapted by the optical magnification of the coupling system,

- the intensifier can be made blind in visible light without an additional filter,

- the amplification of the intensifier, given by the high voltage of the intensifier and the phosphor conversion factor, can be adjusted within a large range to the signal strength,

- it allows the image sensor to be used in current accumulation mode or in single-photon counting mode.

In addition, in photon counting mode the signal can be discriminated against the dark noise. This allows operation at room temperatures without the need for cooling the sensor – an important advantage in space instruments, as it saves weight and reduces the risk of contamination build-up on the sensor.

On the other hand, the use of MCP intensifiers implies carrying along a high-voltage power supply, and it adds to the camera the drawbacks generally associated with MCP detectors, e.g., the limited resolution given by the multi-fibre bundles and corresponding flatfield structures. In addition, there may be distortions of the image related with the microchannel plates, the optical coupling between the intensifier and the image sensor, or the electric field between them. To minimize

Figure 25.2: An image intensifier tube with input window and output fibre block (made by ProxiVision GmbH, Germany).

such complications, the components must be carefully selected and well matched with each other.

General design of ICCDs and IAPSs

An intensified CCD or APS camera, in general, consists of a channel plate intensifier, a CCD or APS imaging chip with corresponding readout electronics, and an optical coupling between them. The general scheme is depicted in Figure 25.1.

The intensifier may be under vacuum, covered with a UV-transparent window, as shown in Figure 25.2. Or it may be open-faced (and therefore operable only under vacuum), depending on the working wavelength. Below 110 nm no window can be used. The photocathode plane actually represents the focal plane of the optical system. It may be defined by the front surface of the channel plate, or it may be a semi-transparent coating deposited on the inner side of the window. In an open-faced system, an additional photocathode coating may be deposited as a thick, opaque layer on the front face of the channel plate.

Depending on the gain factor needed, there may be one single MCP or a stack of two or three MCPs to produce electron pulses that are accelerated by a high voltage across a “proximity gap” onto the anode. The anode has a special coating. The main portion is a phosphor converting the electron pulse into a flash of visible light. In general, the sensitivity of the image sensor is high at this wavelength, such that a single channel plate-phosphor combination creates pulses strong enough for all types of readout schemes of the camera, however, for photon counting schemes a double stack of MCPs is preferred. In any case, the light at the phosphor must be transferred by optical means to the sensor. At this stage, the image can be magnified or de-magnified, to adapt to the sensor size, and it can even be attenuated, if needed, to adapt the output of the intensifier to the sensor's full-well capacity.

MCP intensifiers and photocathodes

The intensifiers used for ICCD/IAPS are the same MCP tubes as described in Chapter **??** (Timothy 2010). The only difference is the anode containing the phosphor coating described further below. In brief, the intensifier tube consists of a stack of ceramic frames with metal rings that apply the high voltage to the front and back side of the MCPs (<1 kV per MCP) for electron amplification and of the phosphor anode. An electric field of several kilovolt per milimetre is required for the photo-conversion and to avoid charge spreading in the proximity gap, the space between the MCP output and the anode. The input side of the intensifier may be the bare MCP or it may have a photocathode coating of the appropriate material to increase the detection efficiency by enhancing secondary electron creation (photo effect) in the working wavelength range. In the VUV spectral range the photocathodes are mostly made of alkali halides, e.g., CsI, KBr, CsBr, KI, RbBr, etc. (Siegmund 1999), materials with a large band gap (between valence and conduction bands) to suppress emission at longer wavelengths. These materials are also sufficiently stable under normal environmental conditions if high humidity can be avoided. For wavelengths longer than 110 nm, materials that are not stable under normal conditions, like multi-alkali combinations, can be used with a tube sealed under vacuum.

The phosphor screen anode

The electron pulses leaving the MCP output are accelerated by a high potential onto a proximity-focused phosphor screen deposited on a fibre optic face plate that is used as the intensifier output window. The value of the electric field (up to 6 kV/mm) depends on the size of the gap and determines the amount of transverse spreading of the charge cloud and the intensity of the phosphor flash. The amount of transverse charge spreading that is acceptable depends on the resolution of the sensor reading the image: it may be much larger when single-photon events are being detected with position-encoding (centroiding) the charge cloud after detection. An open intensifier is shown in Figure 25.3. Without MCPs inserted, the fibre optic bundle coated with a phosphor screen can be seen. The choice of the phosphor material depends on the spectrum of the luminous emission in relation to the wavelength with the highest efficiency of the sensor, the conversion efficiency of the phosphor material, and the response (decay) time of the light flash.

Typical phosphor screens have a broad spectral output in the near-UV, blue, or green spectral range with conversion efficiencies between 10^2 and 10^3 photons per electron (depending on the accelerating voltage). The decay times (to 1/10 of the maximum intensity) of common phosphors may be between 100 ns and 10 ms. The decay time of the luminescence should be related to the normal readout time of the image sensor. While CCDs in general use a shutter for timing the exposure, and the photon events are captured during the exposure time and then transferred to the readout amplifiers, CMOS-APS sensors run shutterless by reading out line by line and the exposure time of each line may be chosen much shorter than the

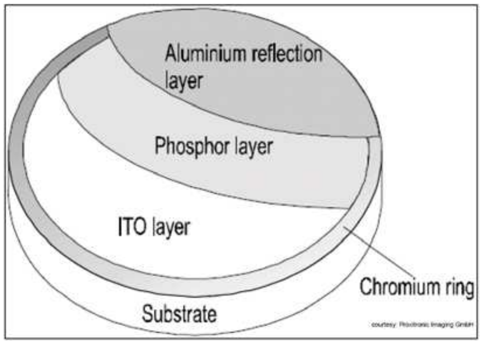
Figure 25.3: Intensifier housing with fibre optic output window. Left: inside-view with the phosphor screen and the pads for placing the 25 mm circular MCPs. Right: the fibre-optic output window at the back side of the tube.

readout time of the whole image. In this operational mode the lines are exposed sequentially and if the phosphor decay time is comparable to the line exposure time, the events spreading over several lines will not be detected correctly. In this case the decay time should be large compared to the line exposure time. On the other hand, if the exposure time is long (for example, longer than 0.1 s for a 1024×1024 pixel sensor), then the phosphor decay time is much shorter and no such interference occurs.

To maintain a homogeneous and stable electric field inside the proximity gap, the MCP output face and the phosphor screen must have conductive coatings. A thin metal layer (e.g., 50 nm of aluminium) on top of the phosphor may serve several purposes: it provides the homogeneous conductive coating, it increases the efficiency by reflecting the luminescence light back towards the sensor, and it prevents visible light from passing through the intensifier, thus making it visible-blind. Figure 25.4 shows the schematic design of an intensifier output window.

Coupling schemes

The image produced on the phosphor screen must be relayed to the imaging sensor device (CCD or APS) by an optical transfer. The simplest way (but rarely used) is to place the sensor in close proximity to the phosphor screen. Another way is to use an optical lens to transfer the image onto the plane of the sensor. In this case, only a transparent window is used as substrate for the screen and the sensor may as well have a protective window. One advantage of this optical transfer is the option of using the magnification of the lens for adaptation of the image scale to the size of the sensor. This scheme has been used successfully in instruments flown on space missions.



courtesy: Proxitronic Imaging GmbH

Figure 25.4: Design of the phosphor-coated output window of an intensifier.

Figure 25.5: Fibre optic tapers as advertised by the manufacturer (Schott North America, Inc.).

A more direct way of image transfer can be achieved by fibre optic coupling where the phosphor screen is applied to a fibre optic face plate. A fibre optic face plate is a coherent multi-fibre plate, which acts as a zero-depth window, transferring an image pixel by pixel (fibre by fibre) from one face of the plate to the other. Standard fibre sizes are between (3 and 25) µm. This fibre optic coupler can be glued directly onto the image sensor, providing 1:1 imaging from the intensifier to the sensor, or they can be made as a taper, magnifying (or reducing) within a range of magnifications given by the manufacturer. The common magnification range is up to 4:1 and sizes up to 75 mm diameter at the large end can be made. The geometric distortion of the image by such a taper is negligible compared to the distortion introduced by the intensifier. Figure 25.5 shows some fibre optic tapers that are commercially available.

A prerequisite for the direct coupling of the sensor with the fibre optic is that the sensor comes with a removable cover window. Although removing the window from the sensor is possible in principle, it is a difficult process. The fibre optic coupler can be glued directly onto the active area of the sensor by optical cement. However, in

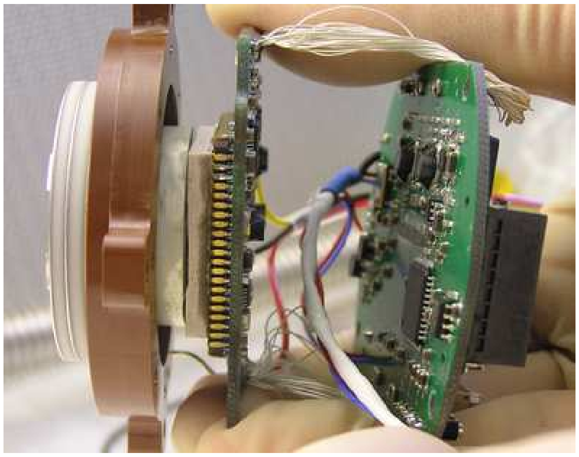


Figure 25.6: An engineering model of a camera with intensifier and sensor with readout system.

most circumstances the sensor has to be able to go through extreme temperature cycles, which makes a hard coupling impractical because of stress developed by mismatch of the thermal expansion coefficients (CTE) of the different materials. This can be solved by leaving a small gap of approximately 5 µm between the sensor and the coupler. A loss of contrast resulting from this gap can be avoided by filling the gap with oil of high refractive index. Of course, this coupling must then be supported mechanically and sealed around the interface by epoxy.

It may be important to adjust the orientation of the sensor with respect to the intensifier within tight tolerances. In such a case, it is more practical to first couple the sensor to another fibre optic face plate or taper, as described, which can afterwards be connected with the intensifier output window. During this process it is possible to operate the camera, to verify that no artefacts, like bubbles or schlieren, are being introduced by the coupling with the sensor. If this additional faceplate shall be avoided, then the direct coupling of the intensifier with the sensor has to be performed blindly. Figure 25.6 shows, as an example, the engineering model of an IAPS camera where this coupling scheme has been used. It is a camera of the Rapid Acquisition Imaging Spectrograph Experiment (RAISE), an instrument (Hassler et al 2004) to be launched by a NASA sounding rocket for a spectroscopic observation of the Sun.

Sensors and their readout schemes

The image produced by the intensifier on the phosphor screen is detected by an imaging array sensitive to the light of the phosphor. Imaging sensors that have been used with intensifiers are charge coupled devices, charge injection devices (CID), or active pixel sensors. As we have seen in Chapter **??** (Waltham 2010), their performance characteristics differ widely, and they will not be further discussed here. The readout scheme depends as well on the sensor type (CCD, CID, or APS) and on the operational scheme supported by the design of the sensor, and this determines the majority of its performance characteristics.

General performance characteristics and limitations

The characteristic of the imaging sensor determines most of the performance of the camera. There are, however, performance limitations that are generally inherent in this particular camera system. The most important limitation is related to the dynamic range of the entire camera, which may be due to the intensifier or the sensor (or both). However, the combination of intensifier with the imaging sensor provides us with a variety of design flexibilities to adapt the camera to a range of incoming photon fluxes, corresponding to the vast dynamic range of about eight orders of magnitude.

The light spots produced on the phosphor screen are generally larger than a sensor pixel, and the size and intensity varies strongly depending on the operating voltage of the intensifier. The amplification of the photon-electron-photon conversion in the intensifier may be so high that a single photon can produce a light spot that fills the full-well charge capacity of the image sensor. This obviously leads to a *local dynamic range* limitation. The dynamic range is, first of all, determined by the resolution (depth) of the sensor electronic digitization. For an optimal adaptation of the intensifier with the image sensor, a conversion of approximately 1:1 of the detected incoming photon to the digital unit (DN) of the sensor is useful. This requires that, for high photon input rates the intensifier has to be operated at very low gain. In order to adjust the intensifier such that saturation is avoided within a given exposure time, it may be necessary to reduce the MCP high voltage to a very low gain setting. Since the phosphor also has a high conversion efficiency (typically 100 photons per electron) it may be useful, in order to reduce the brightness of the light pulse, to implement an attenuator within the fibre optic coupler behind the phosphor screen. In this way, the charge created per photon in the image sensor (converted to DN per photon) can be adjusted without compromising the quantum detection efficiency.

For low photon input rates, on the other hand, the high amplification of the intensifier provides the possibility to operate the camera in photon-counting mode. In this mode the MCPs are used at a higher gain, producing a spot of light for each photon event that is much larger than the sensor pixel size. If the spot of light is large enough, the event positions may be determined within the electronic readout system by finding the centre of gravity of the charge signal level of affected pixels. The event locations are then passed on to the memory and binned into an image. Such a centroiding scheme achieves a much better accuracy than the pixel resolution of the sensor (Vallerga et al 1995). In addition, before finding the centroid of each event, the signals can be discriminated against dark noise and single-pixel noise events caused by, e.g., cosmic rays or “hot” pixels. As a result, the camera is free of dark noise and can be used at extremely low input signals. At the same time, since dark noise is discriminated, the sensor can be operated without the need of cryogenic cooling. The performance of the photon counting system is limited by the input photon flux. With sensors of very fast read-out rates

(CCDs and CMOS-APS sensors with 256 × 256 pixels exist with frame rates in the kHz range) the photon counting readout can be used up to fairly high input photon flux before deadtime of the electronic system or event overlap limits the performance. When centroiding is used, to avoid this overlap the input event rate must be well below 100 events/pixel/s.

Past and future intensified cameras for space missions

Soon after CCDs became available and space-qualified for scientific camera systems, efforts started to use them with microchannel plate intensifiers to increase the sensitivity in certain wavelength ranges. The first intensified cameras were developed in the late 1970s for the *Spacelab 1* mission. Further developments of ICCD cameras for space missions followed during the 1980s (Torr et al 1986). Due to the high efficiency of CCDs in the visible, they can be operated with intensifiers at very low gain resulting in a high count rate capability. Such a camera was built for the Coronal Diagnostic Spectrometer (CDS) (Thompson 1999), which has been operating almost continuously since 1996 on the *SOHO* spacecraft. The camera uses a single-MCP intensifier for the spectral bands 31 nm to 38 nm and 51 nm to 63 nm. Although the electrons are accelerated onto the phosphor anode on a fibre optic plate, a single lens focuses the image from the fibre optic window onto the CCD (1024 × 1024 pixel format). The camera is operated in "normal" mode (not photon counting) with passive cooling to reduce the dark noise.

An ICCD camera (with 2048 × 2048 pixel format) was built for the Tunable X-ray Imager (TXI) rocket experiment for the wavelength range of 17.1 nm to 21.1 nm that was flown in June 2001 (Golub et al 2002). The camera used a phosphor coated fibre optic taper *in front of* the MCP intensifier and another phosphor coated fibre optic plate as anode for coupling with the CCD. The intensifier, in this case, amplified the image of the phosphor and operated as a shutter by switching the high voltage of the MCPs.

A camera with curved MCPs was built for the Wideband Imaging Camera (Mende et al 2000) of the Imager for Magnetopause-to-Aurora Global Exploration (*IMAGE*) mission of NASA. The instrument is sensitive in the spectral region from 140 nm to 190 nm with a caesium iodide photocathode. The MCP is curved to accommodate the focal surface of the concentric optics of the camera. The phosphor anode of the intensifier is deposited on a concave side of the fibre optic output window, which is then coupled to the CCD with a fibre optic taper.

In conjunction with the fast readout of the image sensor, the intensifier enables the counting and position centroiding of each photon event, making this type of camera favourable for observations with low photon flux. Thus, cameras have been developed that can operate in normal (current integrating) mode and in photon-counting mode (Vallerga et al 2008).

Intensified CCD cameras have been built for the UV Monitoring Telescope of ESA's *XMM-Newton* mission (Mason et al 2001) and a similar camera for the *Swift* mission (Gehrels 2005) in the Ultraviolet and Spectroscopic Telescope (UVOT) instrument. Both cameras cover a very large spectral range from 170 nm to 600 nm using an S20 photocathode on the inside of the entrance window and a fibre optic taper coupling with the CCD.

In an attempt to avoid the shortcoming of CCDs, mainly the transfer of change along pixel rows, and aiming at a high-speed readout system, an intensifier was coupled with a CID (Charge Induction Device) that allows the addressing of individual pixels and the fast readout of sub-arrays. Such a camera was built for the Optical Monitor on the *XMM-Newton* mission (Morrissey et al 1998).

With the same reasoning, CMOS-APS sensors are now more often chosen as the image sensor for space cameras. Since these devices avoid charge transfer, they are more resistant to degradation by space radiation. In addition, the random accessibility of the image area and the flexible readout modes (snapshot or rolling shutter) that avoid the need for a mechanical shutter, make this type of sensor attractive for space applications. Since their sensitivity in the VUV is still low compared to microchannel plate detectors, they will, in this wavelength range, preferably be used with intensifiers. With the availability of space-qualified APS sensor devices (up to 1024 × 1024 pixel format), cameras with intensifiers are now being built for future missions. The first camera of this type was flown successfully in April 2006 and November 2007 on the Solar EUV Normal-Incidence Spectrometer (EUNIS) rocket experiment (Thomas and Davila 2001). This camera uses three APS sensors (with 9 µm pixel size) connected with three fibre optic couplers to one fibre optic output window of the intensifier. In this way, a large spectral range in the focal plane can be covered by the large area of the MCP intensifier, to be imaged by the small size of three active pixel sensors. Another IAPS camera was flown in 2010 on the NASA rocket spectrograph RAISE (Hassler et al 2004). For this instrument, two cameras have been designed for high count rates with a single MCP operating at relatively low gain and a STAR-1000 APS sensor (Cypress Inc.) with 1024 × 1024 pixels that can be read out at a cadence of 10 Hz. To enhance the sensitivity in the large wavelength range of the spectrograph (between 60 nm and 156 nm), the MCP of one camera has been coated with potassium bromide and the other with caesium iodide.

A new generation of CMOS-APS sensors is presently being developed for the ESA/NASA *Solar Orbiter* mission (Marsch et al 2005) that is planned for launch in 2017. Intensified open-faced APS cameras for the EUV spectral range are under development for the Spectral Imaging of the Coronal Environment (SPICE) spectrograph (Hassler et al 2011) and for the spectrographic channel of the Multi Element Telescope for Imaging and Spectroscopy (METIS) instrument (Antonucci et al 2008). These cameras have 1024 × 1024 image sensors that have already been space qualified, coupled by fibre optics with an MCP intensifier. For the Lyman-Alpha channel (Schühle et al 2011) of the Extreme Ultraviolet Imager (EUI) on *Solar Orbiter* a camera is being developed with narrow-band sensitivity near 121 nm using an intensifier closed with a magnesium fluoride window. The new sensor developed under the EUI project with 2048 × 2048 pixels is coupled with an intensifier by a fibre optic taper, adapting the intensifier useful diameter of 40 mm to the square size of 20.5 mm × 20.5 mm of the sensor.

Bibliography

Antonucci E, Andretta V, Cesare S (plus 14 authors) (2008) METIS, the Multi Element Telescope for Imaging and Spectroscopy: An Instrument Proposed for the *Solar Orbiter* Mission. Proc International Conference on Space Optics (ICSO 2008)

Gehrels N (2004) The *Swift* X-ray burst mission. New Astron Rev 48:431–435

Golub L, Deluca E, Hamilton P (plus four authors) (2002) A photometric imaging solar telescope, tunable in the extreme ultraviolet, utilizing multilayer X-ray optics. Rev Sci Instrum 73:1908–1913

Hassler DM, DeForest CE, Slater D (plus four authors) (2004) Future observations with RAISE, 35th COSPAR Scientific Assembly, Paris, France:2280

Hassler DM, DeForest C, Wilkinson E (and the SPICE Team) (2011) Investigations to Determine the Origin of the Solar Wind with SPICE and *Solar Orbiter*. American Astronomical Society, SPD meeting 42, Bull American Astronom Society 43

Marsch E, Marsden R, Harrison RA (plus two authors) (2005) *Solar Orbiter*-mission profile, main goals and present status. Adv Space Res 36:1360–1366

Mason KO, Breeveld A, Much R (plus 16 authors) (2001) The *XMM-Newton* Optical/UV Monitor Telescope. Astron Astrophys 365 1:L36–L44

Mende SB, Heetderks HD, Frey HU (plus 12 authors) (2003) Far ultraviolet imaging from the *IMAGE* spacecraft: 2 Wideband FUV imaging. Space Sci Rev 91:271–285

Morrissey P, Norton T, Kimble R (1998) A photon counting intensified CID detector for space astronomy. Proc SPIE 3356:1036–1045

Schühle U, Halain JP, Meining S, Teriaca L (2011) The Lyman-alpha telescope of the extreme ultraviolet imager on *Solar Orbiter*. Proc SPIE 81:81480K-1-81480K-11

Siegmund OHW (1999) Microchannel plate detector technologies for next generation UV instruments. ASP Conf Ser 164:374–391

Thomas RT, Davila JM (2001) EUNIS: a Solar EUV Normal-Incidence Spectrometer. Proc SPIE 4498:161–172

Thompson WT (1999) UV detectors aboard *SOHO*. Proc SPIE 3764:196–208

Timothy JG (2010) Microchannel plates for photon detection and imaging in space. ISSI SR-009:**??**–**??**

Torr MR, Torr GT, Baum R, Spielmaker R (1986) Intensified-CCD focal plane detector for space applications: a second generation. Appl Opt 25:2768–2777

Vallerga J, Jelinsky P, Siegmund OHW (1995) Initial results from a photon counting intensified CCD development. Proc SPIE 2518:410–421

Vallerga J, McPhate J, Tremsin A, Siegmund O (2008) Optically sensitive MCP image tube with a Medipix2 ASIC readout. Proc SPIE 7021:702115-1-702115-11

Waltham N (2010) CCD and CMOS sensors. ISSI SR-009:**??**–**??**