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comprehensive survey of the present status and the future potentialities of gas-filled position-sensitive detectors.

7.1.6.3. *Semiconductor detectors*

Semiconductor detectors are essentially solid-state ionization chambers in which the incoming photon generates electron–hole pairs instead of electron–ion pairs. Semiconductor detectors are sensitive to the entire electromagnetic spectrum from visible to X-rays, and they can also detect electrons directly. There are, therefore, three possible methods of constructing semiconductor X-ray detectors, each of which has its advantages and disadvantages.

(1) They can be exposed directly to the incoming X-rays.

(2) The X-ray photons can be made to produce visible light photons that are then detected in a light sensor.

(3) The X-rays can be made to produce electrons that are detected by the semiconductor detector.

In semiconductor one- or two-dimensional PSD's, the detector and the read-out circuitry are usually integrated on the same chip. In these devices, the pixel size and position are fixed once and for all so that they are geometrically completely stable. Integrated read-out circuitry has a low input capacity and thus an extremely low read-out noise.

All semiconductor X-ray PSD's are derived from imagers for visible light, which are of two basic types: photodiode arrays (PDA's) and charge-coupled devices (CCD's) (Lowrance, 1979; Allinson, 1982; Borso, 1982; Third European Symposium on Semiconductor Detectors, 1984).

In PDA's, the detection of a photon-generated charge takes place in a depletion layer that is formed either in a suitably biased *p–n* diode or in a metal-oxide-semiconductor (MOS) capacitor. The electron–hole pairs are separated by the field associated with the depletion layer. The individual diodes store charge during the integration period; this is read out into a common video output line *via* MOS multiplexing switches. This architecture is usually adopted for linear arrays where the switches can be arranged around the periphery of the diodes with a minimum amount of dead space between them and where they can be shielded from the incident X-rays. PDA's tend to suffer from a high fixed-pattern noise due to differences in the performance of individual MOS switches.

In CCD's (Howes & Morgan, 1979), the sensing elements are always MOS capacitors suitably biased to establish charge-storage volumes. During read out, the charge is transferred in a 'bucket-brigade' fashion from one MOS capacitor to the next until it reaches the output. In linear CCD's, this output is at one end of what is essentially an analogue shift register. Most two-dimensional CCD's are frame-transfer devices: at the end of the exposure, the charge is transferred line by line to an identical array of MOS elements; while the next 'frame' is exposed in the image array, the contents of the buffer array are transferred, one line at a time, to a single-line buffer from which they are shifted out element by element. Since the transfer circuitry in CCD's is interlaced with the detector elements, they are more difficult to shield and are more subject to radiation damage.

7.1.6.3.1. *X-ray-sensitive semiconductor PSD's*

For X-ray diffraction applications, the main disadvantage of semiconductor devices is that the universal trend in their manufacture is in the direction of miniaturization, leading to a very small pixel size. Thus, imaging devices with up to 2000×2000 pixels have been produced but the pixel size is typically $\sim 10\,\mu m$ for CCD's and $\sim 20\,\mu m$ for PDA's; in most X-ray diffraction applications, it would be difficult to scale down sample and source sizes to a point where the pattern size is

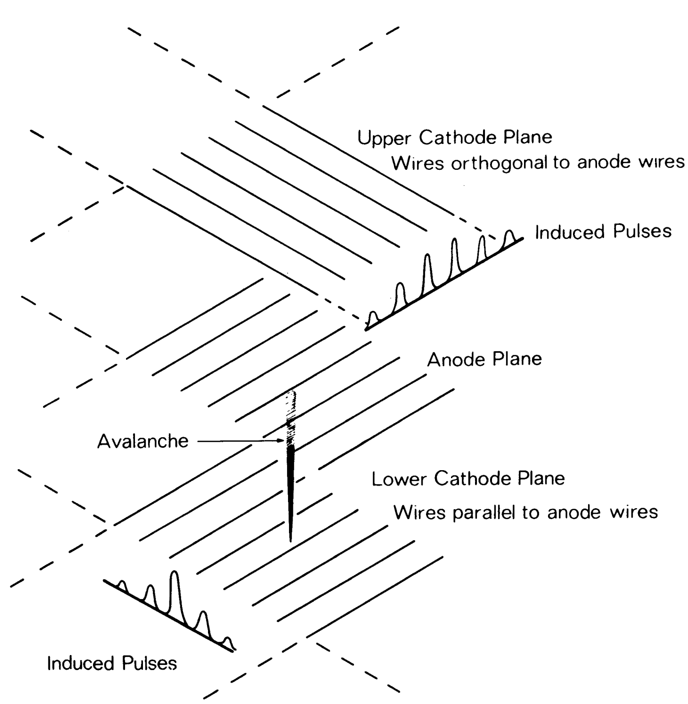

Fig. 7.1.6.5. Three-plane MWPC. Note the pseudo-quantization due to charge collection on one anode wire. The cathode wires may either be connected to a tapped delay line as in Fig. 7.1.6.4(*c*) or to individual amplifiers as in Fig. 7.1.6.4(*d*) (courtesy of A. R. Faruqi).

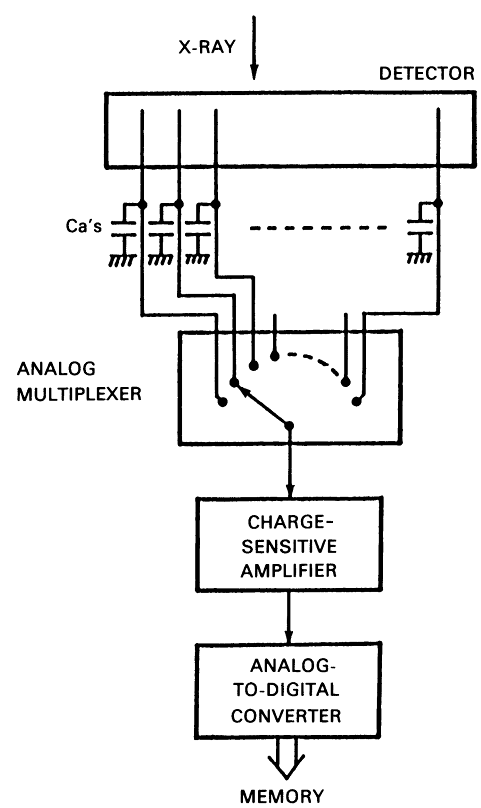

Fig. 7.1.6.6. Integrating LPSD. From Mochiki (1984); courtesy of K. Mochiki.

appropriate to a semiconductor imager, even though a 2000×2000 CCD with $27 \times 27\,\mu m$ pixels is available.

Semiconductor point counters cooled to 80 K are characterized by their very high energy resolution (better than 2% in the 8 keV region). Some counting PSD's potentially have a similar energy resolution. Two-dimensional X-ray-sensitive CCD's for X-ray astronomy research have been used as photon counters (Walton, Stern, Catura & Culhane, 1985; Lumb, Chowanietz & Wells, 1985) but they can only be used at very low counting rates. In integrating devices, the energy discrimination is lost. Silicon detectors for visible-light applications are made with depletion depths of the order of 10 µm. For the detection of 8 keV photons with more than 90% efficiency, depletion depths of 165 µm are necessary and these can be produced only from very high resistivity material (Howes & Morgan, 1979). Moreover, in commercial visible-light imagers, the depletion region is covered by circuitry or by an inactive layer that constitutes an absorbing window for X-ray detection. For the detection of X-rays or electrons, it is, therefore, customary to thin the device and to illuminate it from the back (see, for example, Meyer-Ilse, Wilhelm & Guttmann, 1993).

One-dimensional X-ray detectors utilizing PDA's, such as those made by the Reticon Corporation, have found a number of applications, especially in dispersive X-ray absorption spectroscopy (EXAFS) (Jucha, Bonin, Dartyge, Flank, Fontaine & Raoux, 1984).

A particular problem with silicon detectors is the damage caused by the incidence of X-rays or of energetic electrons. The effects can be minimized by masking all but the active part of their device and by operating it at low temperatures (Jucha *et al.*, 1984).

The use of the room-temperature semiconductor mercuric iodide in place of silicon seems promising (Patt, Delduca, Dolin & Ortale, 1986).

The X-ray diffraction applications of directly sensitive semiconductor PSD's are likely to remain limited. A previous conversion to visible light or to electrons offers the possibility of an optical or electron-optical demagnification onto the imager, as well as of avoiding some of the other problems discussed above (Deckman & Gruner, 1986).

7.1.6.3.2. *Light-sensitive semiconductor PSD's*

Standard light-sensitive semiconductor imaging devices can be used for X-ray detection if the X-rays are first converted to light by means of a phosphor. One 8 keV X-ray photon produces several hundred light photons in a good phosphor (see Table 7.1.6.2). Because of the low noise levels possible with cooled CCD's (~10 electrons r.m.s.), only 1 to 3% of these photons need to reach the device to produce a perfect X-ray detector. Unfortunately, even this is possible only with optics that do not demagnify to any considerable extent (see Subsection 7.1.6.5) and one is thus restricted to a small detector. However, CCDs are now available that can be butted along two or three edges and these make possible the construction of 'tiled' detectors that contain four or six of such CCD chips (Burke, Mountain, Harrison, Bautz, Doty, Ricker & Daniels, 1991; Fordham, Bellis, Bone & Norton, 1991; Allinson, 1994). Individual channels can be read simultaneously (Hopf & Rodricks, 1994), thus making possible a relatively rapid read out of a large number of pixels.

7.1.6.3.3. *Electron-sensitive PSD's*

In image intensifiers, an output image is produced on a phosphor screen by electrons with an energy of a few keV. A promising device with direct positional read out consists of a demagnifying intensifier in which the phosphor is replaced by a CCD. Various intensifiers have been described in which the electrons reaching the CCD have an energy of several keV so that the electron–hole generation is amplified (EBS process) (Lowrance, Zucchino, Renda & Long, 1979; Lemonnier, Richard, Piaget, Petit & Vittot, 1985). High-energy electrons are liable to cause radiation damage and similar precautions as for X-rays, such as thinning and back-illumination, are necessary. Experiments have been reported with less-damaging low-energy (200 eV) electrons produced in a microchannel plate (MCP) image intensifier (Dereniak, Roehrig, Salcido, Pommerrenig, Simms & Abrahams, 1985). Both approaches look promising but it is questionable whether a device with an X-ray phosphor input and of adequate size and resolution at an affordable price will emerge in the near future.

7.1.6.4. *Devices with an X-ray-sensitive photocathode*

Image converters and television cameras with X-ray-sensitive photocathodes have been reported. These cathodes must be thin, or they must have a low bulk density to allow the photoelectrons to escape (Bateman & Apsimon, 1979; Haubold, 1984).

Television tubes with a beryllium window and a 25 mm diameter lead oxide target are available and experimental 125 mm tubes have been described (Suzuki, Uchiyama & Ito, 1976).

X-ray-sensitive Saticon television camera tubes with an amorphous selenium–arsenic target (Chikawa, Sato & Fujimoto, 1984) have an active diameter of only 10 mm but a limiting resolution (MTF = 5%) of 6 µm. They have an absorption efficiency of 52% for Mo $K\alpha$ radiation and are used mainly for X-ray topography. Other X-ray-sensitive television camera tubes have been described by Matsushima, Koyama, Tanimoto & Tano (1987), Suzuki, Hayakawa, Usami, Hirano, Endoh & Okamura (1989) and Sato, Maruyama, Goto, Fujimoto, Shidara, Kawamura, Hirai, Sakai & Chikawa (1993). Such tubes are discussed further in Section 7.1.7.

7.1.6.5. *Television area detectors with external phosphor*

Much development has gone into quantitative measurements with area detectors in which the diffraction pattern is formed on an external phosphor fibre-optically coupled to a low-light-level television camera. Mostly the television camera embodies a demagnifying image intensifier coupled *via* demagnifying optics to a sensitive television camera tube (Arndt & Gilmore, 1979; Arndt, 1982; 1985; Arndt & In't Veld, 1988; Kalata, 1982, 1985; Gruner, Milch & Reynolds, 1982) or to a CCD or an array of CCD's (Strauss, Naday, Sherman, Kraimer & Westbrook, 1987; Strauss, Westbrook, Naday, Coleman, Westbrook, Travis, Sweet, Pflugrath & Stanton, 1990; Templer, Gruner & Eikenberry, 1988; Widom & Feng, 1989; Fuchs, Wu & Chu, 1990; Karellas, Liu, Harris & D'Orsi, 1992). Camera tubes were frequently read at commercial television rates (625 lines with a field repetition rate of 25 Hz or 525 lines with a field repetition rate of 30 Hz in Europe and in North America and Japan, respectively), leading to pixel rates of about 10 MHz. Successive images were then digitized and their sums stored in memory (see Fig. 7.1.6.7). Milch, Gruner & Reynolds (1982) developed a slow-scan method for a silicon-intensifier-target (SIT) tube. This latter method has been facilitated by the development of very large scale integration memory circuits, which have made it possible to construct economical image stores into which the camera can write at a slow rate and which can then be read at normal television rates for display purposes.

references