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at synchrotron sources, permits a new exposure to be made while scanning is performed. Self-contained systems offer the advantages of simplified operation and the possibility of calibrating the detector, since only a single sheet of material is used in a mechanically stable setup.

Storage phosphors are typically read out with 100 µm square pixels, resulting in 2000×2500 pixel images for the common size of sheet. Larger formats are available. The wide PSF of storage phosphors makes the effective pixel size considerably larger than the nominal value. Some scanners permit smaller pixels, but this is of limited utility because there is a readout noise component associated with each pixel and too small a pixel harms the signal-to-noise ratio without improving data. The most critical component of the storage-phosphor system is the mirror assembly that gathers the photostimulated emission during readout. There are very few emitted photons for each stored X-ray (at the photon energies used for diffraction), and only a small fraction of these are detected in the photomultiplier (in some cases less than one per stored X-ray). This step in the detection process is critical in maintaining high quantum efficiency. Although image plates have an inherently wide dynamic range, the practical value is always limited by the scanner analogue-to-digital converter.

Television detectors. Numerous integrating detector designs based on television sensor technologies have been published and, in one case, produced commercially (Milch *et al.*, 1982; Arndt, 1991). These detectors span a wide range of design complexity and performance. The primary element is a phosphor screen, which converts the incident X-ray pattern to a light image that is directly or indirectly coupled to the sensor, such as a Vidicon or CCD. Many of the designs employ image intensifiers to raise the signal strength of the visible image above the noise of the sensor system. Some designs employ cameras operated at video rates, with frames accumulated in the attached computer or on videotape. Other designs use cooled cameras operated in a slow-scan mode, which greatly reduces noise. The X-ray exposure is integrated in the camera, then read out once at the end of the integration period.

Most of these systems would be classified as complex, but several of them are working reliably today in laboratories with conventional X-ray sources. The image intensifiers improve the DQE of the systems, while sacrificing dynamic range and image sharpness. In addition, intensifiers are sensitive to magnetic fields, requiring great care in their use if proper detector calibration is to be maintained.

Considerable enhancement to the television-type detector is made possible by the low-noise imaging capabilities of CCDs, described in Chapter 7.2. In this case, high DQE can be maintained without intensification when the CCD is cooled and read with slow-scan electronics. As such, these detectors are much more robust and have improved imaging qualities.

7.1.4. Future detectors

Commercially available X-ray detectors have evolved from X-ray film and point diffractometry to area gas-proportional counters, to image plates, and now to CCD detectors. Two new X-ray detector technologies are on the horizon. One is based on the large-area amorphous semiconductors and thin-film transistor arrays which are being intensively developed by many large companies for medical radiography (reviewed by Moy, 1999). The radiographic need is to be able to cover very large areas (*e.g.* 0.5 m^2) with a high-spatial-resolution detector that is sensitive to hard X-rays. A number of these detectors are at the moment (1999) poised for introduction, but they are specialized for radiographic applications and are poorly suited for relatively long, low-noise integration of low-energy X-rays. It remains to be seen whether the technology will succeed and whether it can be modified for quantitative crystallographic applications.

A second technology being developed specifically for quantitative X-ray diffraction is based on solid-state pixel array detectors (PADs) (Iles *et al.*, 1996; Datte *et al.*, 1999; Barna *et al.*, 1997; Rossi *et al.*, 1999). In a PAD, X-rays are stopped directly in a semiconductor and the resulting signal is processed by electronics integrated into each pixel. Direct conversion of X-rays into electrical signals in a high-grade semiconductor has many advantages: many signal electrons are produced for each X-ray, and the conversion medium is very linear, has low noise and is well understood. Since each pixel has its own electronics, there is enormous flexibility in performing local signal processing. In principle, PADs have tremendous advantages of sensitivity, flexibility, noise and stability. The challenge will be to make PADs of a size and format useful for crystallography, while still being sufficiently affordable to be commercially viable.

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