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7.2. Detectors for electrons

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7.2.1. Introduction

It is convenient to divide instruments used to form electron-diffraction patterns and images into two categories. In the first, all electron beams are static in the sense that neither the beams incident on nor emergent from the specimen are varied in position or orientation during the detection and recording process. Such is the case, for example, in a conventional transmission electron microscope (CTEM) where diffraction patterns and images must be recorded using a parallel or flux-density detector. By contrast, instruments in the second category employ a scanning system to vary the position or orientation of the electron beams before or after the specimen. Thus, in a scanning transmission electron microscope (STEM), diffracton patterns may be formed by rocking a beam about a point on the specimen or by positioning a stationary probe at the selected point and deflecting the beams as they emerge from the specimen. Under these conditions, the electrons are detected by a small total flux detector located on the optic axis of the instrument and the diffraction pattern (or image) is built up in a time-sequential or serial manner.

Whilst many of the properties required of total flux and flux-density detectors differ significantly, all detectors must satisfy certain criteria. A means of characterizing detectors is given in Section 7.2.2 together with a brief description of which particular features are desirable in each of the two categories. Specific detectors suitable for parallel recording are considered in Section 7.2.3, where a description is given both of their operation and of the extent to which they fulfil the criteria outlined in the preceding section. Finally, in Section 7.2.4, similar details are given for detectors suitable for serial recording purposes.

7.2.2. Characterization of detectors

Electron-diffraction patterns and images are inherently noisy due to the random arrival of electrons at the detector plane. The number of electrons N arriving in a specified time interval at the detector (or a particular detector element in the case of a flux-density detector) fluctuates in such a way that the variance of the signal σ_N^2 is equal to $\langle N\rangle$ where $\langle N\rangle$ denotes the expectation value of N. This is in accord with Poisson statistics and it follows that the signal-to-noise ratio of the incident signal $(\mathrm{SNR})_i$ may be increased indefinitely, in principle, by simply increasing the recording time until a sufficiently large number of electrons has arrived at the detector.

An ideal electron detector would be one in which the signal-to-noise ratio of the output signal was also equal to the limit imposed by Poisson statistics. Such a detector would impose no additional noise onto the signal and there would be no further loss of information. In practice, this is unattainable, and it is convenient to define a detective quantum efficiency (DQE) to provide a quantitative description of the signal degradation or information loss directly attributable to the detector. If an input signal S_i (variance σ_i^2) gives rise to an output signal S_o (variance σ_o^2), the DQE is defined as

$$\mathrm{DQE} = (\mathrm{d}S_o/\mathrm{d}S_i)^2\sigma_i^2/\sigma_o^2, \qquad (7.2.2.1)$$

where $\mathrm{d}S_o/\mathrm{d}S_i$ is the gradient of the output/input characteristic. For detectors with a linear response, (7.2.2.1) may be simplified and it is convenient to express the DQE as

$$\mathrm{DQE} = (\mathrm{SNR})_o^2/(\mathrm{SNR})_i^2, \qquad (7.2.2.2)$$

where the subscripts i and o again denote input and output. In all cases, the DQE is necessarily less than unity and factors that frequently limit the performance of detectors have been discussed in a general way as well as for specific cases by Herrmann (1984), Chapman & Morrison (1984), and Chapman, Craven & Scott (1989).

Although the DQE provides a useful quantitative figure of merit for a detector, alone it does not provide enough information to determine whether a particular detector will be suitable for a chosen application. To ascertain this, it is necessary to consider the following attributes of individual detectors:

(*a*) dynamic range;
(*b*) fraction of the dynamic range over which the detector response is (approximately) linear;
(*c*) ease of access to the output signal;
(*d*) suitability for use over a wide range of electron energies;
(*e*) speed of response;
(*f*) resolution;
(*g*) information-storage capability;
(*h*) single shot or repeated use;
(*i*) susceptibility to radiation damage;
(*j*) simplicity of construction;
(*k*) ease of use;
(*l*) cost.

For all detection and recording systems, a high DQE over a wide signal range is desirable. This is particularly so when diffraction patterns from single crystals are being studied as the intensity of diffraction spots in a single pattern can vary over many orders of magnitude. In addition, it is advantageous if an unvarying and simple relation exists between the output and input signals over the complete range of the latter. Thereafter, important attributes for parallel and serial systems can differ markedly.

Parallel detectors should have high spatial resolution and a large information-storage capacity. The latter requirement ensures that extensive and complex diffraction paterns and images may be studied at one time while the two requirements together ensure that the overall size of the detector is minimized. This is generally advantageous when optimizing overall instrumental performance. Broadly speaking, two options exist. The first is to employ a relatively complex system that may be used repeatedly and that allows easy access to a quantitative output signal, but that is inevitably expensive and complex in construction (see *e.g.* Subsection 7.2.3.3); the second is to use a simple, cheap system such as film (Subsection 7.2.3.2), which must be replaced each time a new image is to be recorded. The choice between the two options depends largely on the experiment to be undertaken and may involve such factors as whether the required information can be obtained from, for example, the symmetry or separation of spots or lines in a diffraction pattern or whether quantitative intensities across the entire field are needed. Also relevant is the delay that is acceptable between initiating a recording and obtaining the information in the form required. By contrast, the actual speed of response of the detector itself is rarely the limiting factor.

In serial electron detection systems, however, the speed of response of the detector can be crucial. The detector is generally a single undivided element with a fast enough response to ensure

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