

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 $(\text{SNR})_i$ 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

$$\text{DQE} = (dS_o/dS_i)^2 \sigma_i^2 / \sigma_o^2, \quad (7.2.2.1)$$

where dS_o/dS_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

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

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 patterns 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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that recording times are sufficiently short to avoid problems arising from specimen drift or the build up of contamination during the recording. Clearly, a serial detector must also be well suited to repeated use and (reasonably) resistant to radiation damage. The output must be easily accessible and at least temporary storage must be available to allow an entire field to be examined. Although segmented detectors are sometimes used in serial detection systems (*e.g.* Burge & van Toorn, 1980), the number of individual elements is usually small and the spatial resolution of the detector is rarely a relevant consideration.

7.2.3. Parallel detectors

7.2.3.1. Fluorescent screens

The fluorescent screen offers the simplest means of rendering a spatially distributed electron signal visible to the eye. Screens are frequently made using ZnS powder to which small numbers of activator atoms have been added to make the wavelength at which maximum emission occurs match the maximum sensitivity of the eye. This occurs in the yellow-green region of the spectrum.

The light output from a fluorescent screen is proportional to electron current density over a wide range and, for a given current density, increases slowly with electron energy. For electrons of energy greater than ~ 40 keV (as are used in RHEED, CTEM, and HVEM), the output level is generally satisfactory under normal experimental conditions; however, when significantly lower electron energies are involved (as is the practice in LEED where energies are typically less than 1 keV), the electrons must be accelerated onto the screen to increase to a suitable level the number of photons emitted by each incident electron. In practice, an accelerating voltage of ~ 5 kV is used.

The resolution of a fluorescent screen is typically in the range 20–50 μm for powders, although significantly smaller values are achievable, particularly if single crystals are used instead. Powder phosphor screens can generally be made as large as required so that the field of view is limited by instrumental constraints rather than by any imposed by the detector itself. On removal of the electron signal, the light intensity decays in a two-stage process. The initial decrease is rapid with a time constant < 1 ms after which an afterglow lasting ~ 1 –5 s remains. Further details of commonly used fluorescent materials have been discussed by Garlick (1966) and Reimer (1984).

Fluorescent screens may be viewed in reflection or transmission, although the optimum thickness of material (for a given incident electron energy) differs significantly in the two cases. Reflection screens are widely used simply as viewing screens and are rarely used as a component in a recording system; by contrast, transmission screens are the first stage in many systems that combine detection and recording and will appear in this context in Subsections 7.2.3.3 and 7.2.3.4.

7.2.3.2. Photographic emulsions

Photographic emulsions provide the most frequently used means of recording spatially distributed electron signals. They are of little use alone in that the output signal is not available until the emulsion has been developed and fixed and so are normally used in conjunction with a viewing system such as that described above. A photographic emulsion is an example of an analogue storage medium and further equipment is required (see below) if quantitative electron intensity data are to be extracted from the developed emulsion.

In most instances, the electron image or diffraction pattern is allowed to impinge directly onto a desiccated photographic

emulsion stored inside the vacuum system. The probability that a silver halide grain will be rendered developable by an electron of energy ~ 100 keV is high and so, in practice, a single electron may release ~ 10 grains. This is in contrast to what is observed when photographic emulsions are exposed to light where several quanta must be absorbed by one grain to render it developable. For this reason, there is no illumination threshold when electrons are used and the law of reciprocity is applicable over a very wide electron intensity range. Fuller details of the theory of the interaction between electrons and photographic emulsions are given by Hamilton & Marchant (1967), Valentine (1966), Farnell & Flint (1975), and Zeitler (1992).

The alternative to directly exposing film within the vacuum system to the electron beam is to convert the electron signal into an equivalent photon signal, which is then recorded outside the vacuum system. Conversion may be achieved by use of a transmission fluorescent screen, and the photon signal may be led out of the vacuum system using a fibre-optic plate (Guetter & Menzel, 1978). In this way, the need to open the vacuum system every time new films are required is eliminated, but the noise properties of the overall system are generally inferior to those achievable using direct exposure.

The relation between the density D of the developed emulsion and the exposure q (expressed as a charge/unit area) has been widely studied theoretically and experimentally over a range of electron energies (Hamilton & Marchant, 1967; Valentine, 1966). To a good approximation, the characteristic takes the form

$$D = D_s[1 - \exp(-cq)] + D_o, \quad (7.2.3.1)$$

where D_o is the 'fog' level, D_s the saturation density, and c the speed of the emulsion (defined by the gradient of the characteristic dD/dq at $q = 0$). Given that saturation densities up to 6 are not uncommon and the fog can be kept small, it can be seen that the variation of D with q is approximately linear to densities of ~ 1 .

The DQE for a number of emulsions has been measured [for typical results see Herrmann (1984)] and, over a limited range of exposure, values between 0.7 and 0.8 may be achieved. Below and above the optimum exposure, the DQE falls. For low exposures, the effect of the background fog becomes important while saturation effects cause a fall in DQE at high exposures. These effects can be serious when, for example, diffraction patterns with a very high dynamic range are to be recorded and a number of different exposures must be used if maximum information is to be obtained.

Within bounds, the exposure at which the optimum DQE occurs can be varied by selecting different emulsions and also by varying development conditions. As faster emulsions tend to have larger grain sizes, the spatial resolution cannot be regarded as an independent or fixed parameter. For this reason, it is generally preferable when comparing different emulsions to plot the variation of DQE not with the number of electrons falling on unit area of emulsion but with the number of electrons falling on the pixel area. The latter quantity may be defined conveniently as the size of the point spread function of a single electron. Unfortunately, further complications ensue as the resolution of the emulsion depends not only on the grain size but also on the diameter of the electron diffusion cloud in the emulsion, a quantity that varies markedly with electron energy.

Using emulsions commonly employed for recording diffraction patterns and images with 100 keV electrons, a resolution of ~ 30 μm is typical. The film size used in electron microscopy has an area of ~ 50 cm^2 so that a single recording contains $\sim 5 \times 10^6$ pixels. This represents a very high storage capability