

## 7. MEASUREMENT OF INTENSITIES

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  $\sim 40$  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  $\sim 5$  kV is used.

The resolution of a fluorescent screen is typically in the range 20–50  $\mu\text{m}$  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  $\sim 1$ –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  $\sim 100$  keV is high and so, in practice, a single electron may release  $\sim 10$  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  $\sim 1$ .

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  $\sim 30$   $\mu\text{m}$  is typical. The film size used in electron microscopy has an area of  $\sim 50$   $\text{cm}^2$  so that a single recording contains  $\sim 5 \times 10^6$  pixels. This represents a very high storage capability