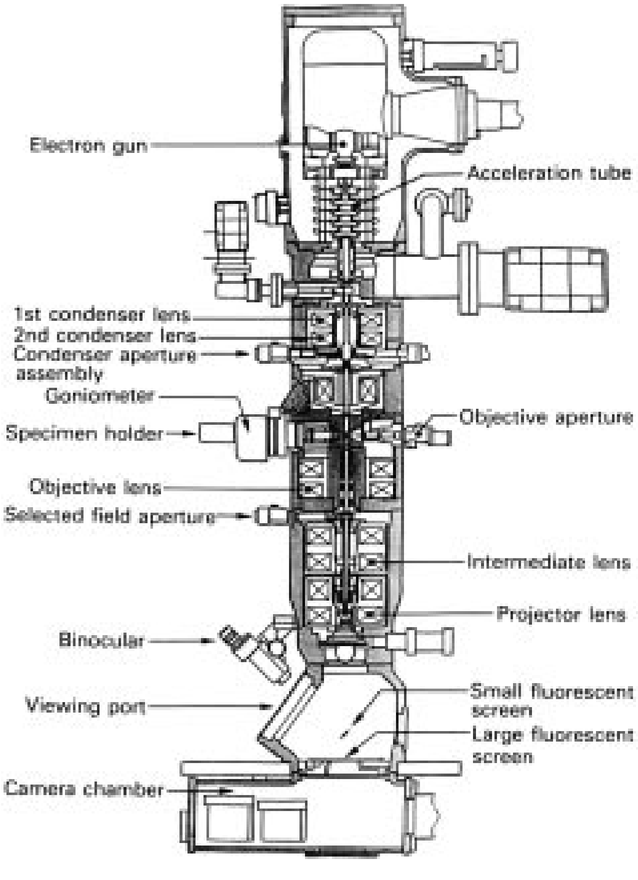
2. The TEM and its Optics



2.1 Introduction to the Transmission Electron Microscope

The transmission electron microscope (TEM) has become the premier tool for the microstructural characterization of materials. In practice, the diffraction patterns measured by x-ray methods are more quantitative than electron diffraction patterns, but electrons have an important advantage over x-rays – electrons can be focused easily. The optics of electron microscopes can be used to make images of the electron intensity emerging from the sample. For example, variations in the intensity of electron diffraction across a thin specimen, called "diffraction contrast," is useful for making images of defects such as dislocations, interfaces, and second phase particles. Beyond diffraction contrast microscopy, which measures the *intensity* of diffracted waves, in "high-resolution" transmission electron microscopy (HRTEM or HREM) the *phase* of the diffracted electron wave is preserved and interferes constructively or destructively with the phase of the transmitted wave. This technique of "phase-contrast imaging" is used to form images of columns of atoms. TEM is such a powerful tool for the characterization of materials that some microstructural features are defined largely in terms of their TEM images.

Besides diffraction and spatial imaging, the high-energy electrons in TEM cause electronic excitations of the atoms in the specimen. Two important spectroscopic techniques make use of these excitations.

- In energy-dispersive x-ray spectrometry (EDS), an x-ray spectrum is acquired from small regions of the specimen illuminated with a focused electron beam, usually using a solid-state detector as described in Sect. 1.4.1. Characteristic x-rays from each element are used to determine the concentrations of the different elements in the specimen.
- In electron energy-loss spectrometry (EELS), energy losses of the electrons are measured after the high-energy electrons have traversed the specimen. Energy loss mechanisms such as plasmon excitations and core electron excitations provide distinct and useful features in EELS spectra.

A block diagram of a TEM is shown in Fig. 2.1. A modern TEM may have the capability of imaging the variations in diffraction across the specimen (diffraction contrast imaging), imaging the phase contrast of the specimen (high-resolution imaging), obtaining diffraction patterns from selected areas of the specimen, and performing EELS and EDS spectroscopy measurements with a small, focused electron beam. A skilled microscopist can switch between these modes in seconds or minutes, allowing questions about the microstructure to be both posed and answered in short order during a session on the TEM.

In scanning transmission electron microscopy (STEM), a narrow (∼2–20 Å), focused beam of electrons is moved in a television-style raster pattern across the specimen. In synchronization with the raster scan, various data from the specimen are acquired, such as emitted x-rays, secondary electrons, or backscattered electrons. Transmitted electrons are detected with a moveable detector at the bottom of the microscope column. The STEM mode of operation is especially useful for spectroscopy work, since it permits the acquisition of a "chemical map" of the sample. For example, we could make an image of the distribution of Fe in a sample if we were to measure, in synchronization with the raster pattern, either the emission of Fe $K\alpha$ x-rays (with