A Scanning Transmission Electron Microscope Using a Field Emission Electron Gun

T. KOMODA, A. TONOMURA, A. OHKURA and Y. MINAMIKAWA

Central Research Laboratory Naka Works, Hitachi Ltd., Katsuta, Japan

The scanning transmission electron microscope (STEM) incorporated with a field emission electron gun is now giving many fruitful results such as single atom observation as reported by Crewe.[1-3] The STEM presents not only good performance in the observation of fine details of specimen, but it has excellent capabilities in the area of quantitative analysis of biological samples.[4,5] The authors have also begun to design a STEM together with a field emission gun in response to these promising reports.

DESIGN OF THE FIELD EMISSION GUN

The brightness of the field emission itself was measured as high as an average of 5×10^9 A/cm^2 sr for 100 kV electrons,[6] which is about 1000 times higher than that of the thermionic guns.

It is, however, reduced due to the aberrations made in the anode space in which the electrons are accelerated. In order to maintain the brightness, Butler-type electrodes[7] are essential in the field emission electron gun. We have computed the shape of the anode electrodes, which have aberrations as small as possible, modifying Butler's method.

We have assumed an axial potential distribution in the anode field containing one parameter " a " as follows:

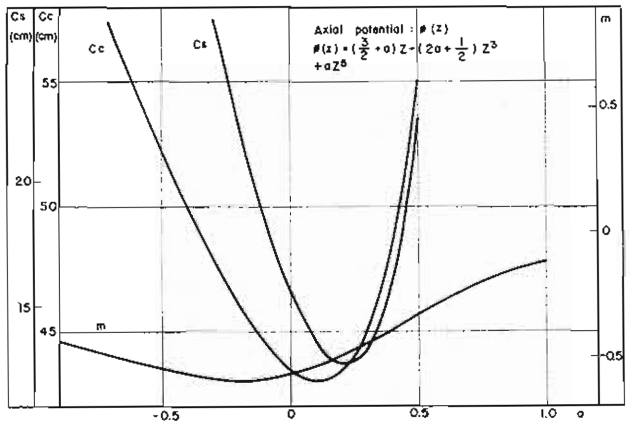

Fig. 1. Electron optical properties of the electrostatic field which is represented by axial potential distributions $\Phi(a)$.

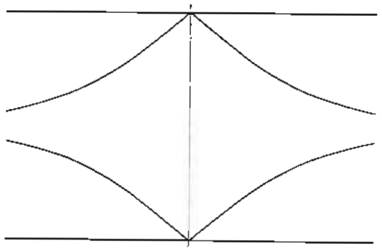

Fig. 2. An anode shape designed to minimize spherical aberration in the field.

$$\Phi(z)=\left(\frac{3}{2}+a\right)z-\left(2a+\frac{1}{2}\right)z^3+az^5$$

Lens properties, such as the spherical aberration C_s, chromatic aberration C_c, and magnification m are computed as a function of " a " using a hybrid computer. As shown in Fig. 1, the spherical aberration coefficient becomes minimum at the optimum value of " a " where the aberration is 30% smaller than Butler's. An anode shape has been designed on the basis of the optimum axial potential distribution. The shape is somewhat different from Butler's as shown in Fig. 2. Brightness of the field emission is reduced only 1/10 using this anode design. Hence, the final brightness is expected to be as high as 5×10^8 A/cm² sr at 100 kV.

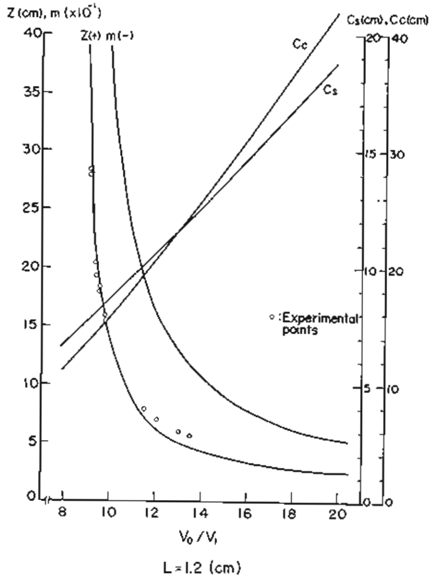

Fig. 3. Electron optical properties of the field emission gun as a function of ratio of the accelerating voltage V_0 and first anode voltage V_1.

PERFORMANCE OF THE FIELD EMISSION GUN

Optical properties of our field emission gun have been calculated as a function of the voltage ratio V_0/V_1, where V_0 stands for the accelerating voltage and V_1 the first anode voltage. An example is shown in Fig. 3 in which the distance between the tip and the first anode is given as 12 mm. Z illustrates the position of the focused point in the electron beam away from the top surface of the first anode. The experimental values of Z coincide well with calculated ones. The spot diameter of the focused beam is also calculated, as shown in Fig. 4, and the effective source size, spherical aberration, chromatic aberration, and diffraction effects are considered. A spot diameter smaller than 200 Å can easily be expected without any help from the other demagnifying lens.

Emission current fluctuation is one of the most serious problems in field emission work. It depends on the vacuum conditions around the tip and on the total intensity of beam current emitted from the tip. At present, a stable probe current of the order of 10^{-9} A is obtainable so long as the ambiant pressure is kept in the range of 10^{-10} torr and the total emission current within several μA.

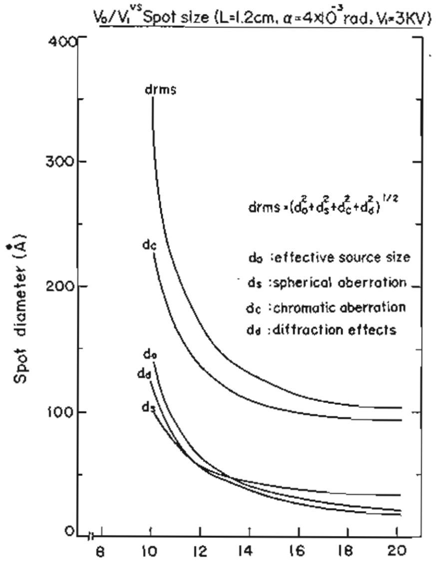

Fig. 4. Spot diameter of the electron beam focused with the field emission gun.

CONSTRUCTION OF AN ELECTRON OPTICAL COLUMN

Figures 5 and 6 show a schematic diagram and an outside view of an electron optical column of the STEM.

We put an additional magnetic lens between the electron gun and the objective lens in

* So far as the beam spot size is concerned, only one demagnifying lens, which has a short focal length, is necessary to make an electron probe as small as 5 Å in diameter.

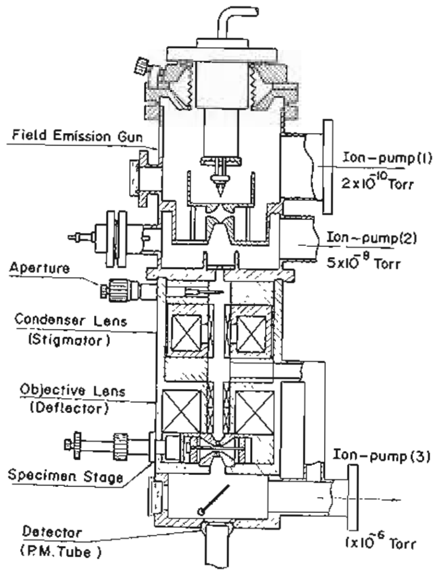

Fig. 5. Schematic diagram of an electron optical column of the STEM.

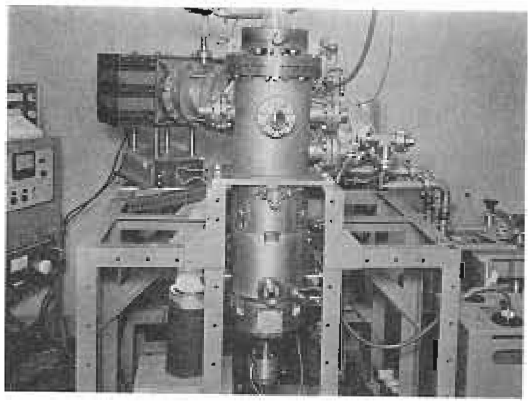

Fig. 6. An electron optical column of the STEM.

order to make the optical performance of the STEM more flexible*. The spot size as well as the intensity of the scanning electron probe can be controlled easily by means of the additional lens.

The microscope column is divided into three sections from the vacuum technical point of view, and they are differentially evacuated with three ion pumps individually. The pressure of the lens column is 10^{-6} torr, while the pressure in the gun chamber is on the low level of 10^{-10} torr. Since ordinary Viton O-rings are used for the vacuum shield in the lens column, the

operations of the microscope—specimen exchange, aperture control, etc.—are as easy as in the conventional transmission electron microscope.

Specimen contamination is one of the most serious problems in high resolution scanning electron microscopy because the specimen is irradiated with a very fine but extremely intense electron probe. To avoid the contamination effect, an anticontamination device is incorporated in the specimen chamber. A specimen holder which is put in the objective lens gap is sandwiched in between two cold plates cooled by liquid nitrogen. The cold plates keep the specimen from contamination and make possible observation of the same area of the specimen for 10 min at a magnification as high as one million times. If the device was not used, the image would fade out in a few tens of seconds due to contamination.

RESULTS

Some examples of electron micrographs taken with the STEM are shown in Figs. 7 and 8. The specimens are a thin section of a biological tissue and Ferritin particles respectively. The accelerating voltage was 40 kV. These pictures are almost equal to those taken with the conventional transmission electron microscope in the sense of resolution and also in contrast. Contrast, however, can be easily raised by an electronic technique in the STEM. Even without staining, thin-sectioned biological samples can be seen on the display tube screen directly. A high resolution better than 10 Å is shown in these pictures. Phase contrast images and Fresnel fringes are also observed with STEM, representing high coherence of the field emission electrons.

An electron energy spectrometer is now installed below the objective lens. Performance of the spectrometer and results of the chemical analysis of specimens will be presented elsewhere.

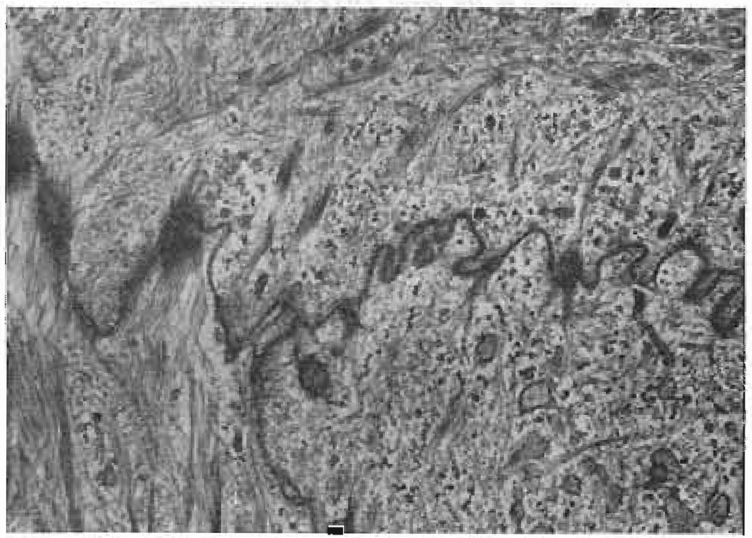

Fig. 7. Thin section of a biological tissue.

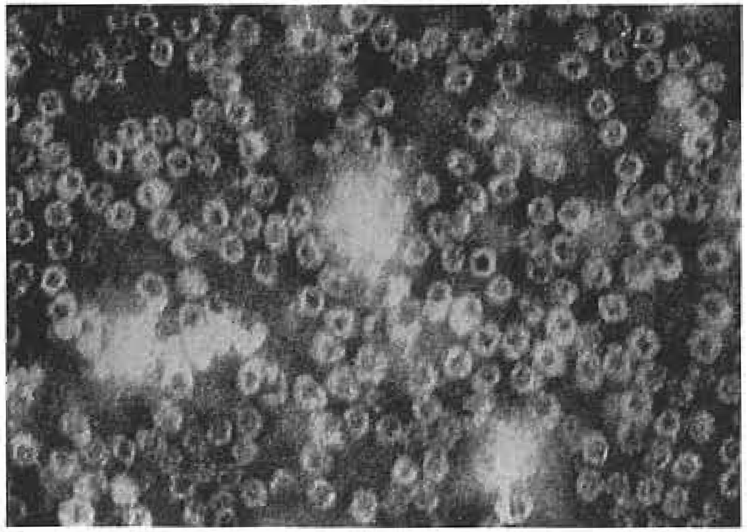

Fig. 8. Ferritin particles.

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