Experimental Study of Flood Gun

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Abstract. Using the flood gun is a common and effective way to eliminate the charge buildup, which is mainly used in electron optics based devices such as CD-SEM, X-Ray Photoelectron Spectroscopy (XPS), Auger Electron Spectroscopy (AES), Secondary Ion Mass Spectrometry (SIMS), Electron Probe Micro Analysis (EPMA) and Ion Implanter. The characteristics of the beam play a decisive role in eliminating the effect of charge buildup, which directly determines the effect of using the related equipment. It is difficult to measure accurately and comprehensively the performance of the beam by using the current testing methods for the flood gun. In this paper, a method for measuring beam spot by using a Faraday cup aperture is proposed, and a test system is set up based on this method. Experiments on this test system have successfully achieved accurate and comprehensive measurement of the beam spot performance. The in-depth analysis of the beam spot performance has a guiding significance for the optimization of structural design and installation of the flood gun. At the same time, it contributes to the prediction of the experiment.

1. Introduction
With the development of electronic technology, various types of electron optical equipments have appeared, and they have played an increasingly important role in scientific research and practical work. At present, the main problem encountered by such devices when characterizing samples is: due to the poor conductivity of the sample material, the imbalance between the input and output electron fluxes results in charge accumulation. The accumulation of charge will form a spatial electric field on the surface and inside of the sample, which will change the trajectory of the electrons, which will adversely affect the use of the devices. Specifically for CD-SEM, it usually causes defects such as abnormal contrast of images and image distortion [1]. For XPS and SIMS, it will lead to the shift of the peak position and make it difficult to identify the elements accurately. Processing defects will occur in Ion Implanter. In order to reduce the above-mentioned effects caused by charge buildup, it is often necessary to neutralize the excess charge on the surface of the sample by using a flood gun [2-4].

The electron beam of the flood gun requires a large cross spot diameter and a uniform beam density distribution. It has long lifetime when working in a medium vacuum condition [5]. On one side, the low-energy electrons generated by the flood gun do not excite the original state of the material, which can avoid damage to the sample. On the other side, eliminate the occurrence of charge buildup [6]. The electron beam with a large cross spot and a uniform beam density distribution can increase the efficiency of the charge neutralization process and improve the effect of the neutralization.
At present, some researchers have successfully developed low-energy electron guns with different performances [7-11], but due to the limitation of test methods, they cannot fully demonstrate the characteristics of the beam. J. Arol Simpson and C. E. Kuyatt, the National Bureau of Standards in the United States, mainly showed the design concept and simulation results of the low-energy electron gun, and only tested the emission beam[7]. Peter W. Erdman and Edward C. Zipf, University of Pittsburgh, studied the trend of the beam current with acceleration voltage at different distances between grid and cathode [8]. Xue Dongdong, Dalian Jiaotong University, used the maximum beam spot diameter as the characterization result during the performance test of the electron gun[9]. A series of low-energy electron guns developed by America Kimball Physics[10] and Germany Staib Instrument[11].

However, the related research is incomplete, lack of in-depth research on the performance of the flood gun, especially the lack of detailed beam spot test and the variation of beam spot size with the operating parameters of the electron gun source. Aiming at this problem, this paper proposes a method of measuring beam spot using a Faraday cup and builds a test system based on this method. Through this system, a comprehensive and accurate measurement of the beam spot is achieved.

2. Experimental object
The flood gun is the core component that generates the electron beam. It consists of the cathode, grid and anode. Cathode is used to emit electrons. The role of Grid is controlling the actual emitting area of the cathode and pre-focus the electron beam. Anode is used to accelerate the electrons. It can be seen from Figure 1. that the flood gun designed by Institute of Electrical Engineering has a small size, which is convenient for integration in large high-resolution precision equipment such as high-flux electron microscopes.

![Figure 1. Picture of the flood gun.](image)

Considering that the flood gun requires lower electron energy, thermal emission is adopted. Thermal emission is to heat the cathode so that the electrons have sufficient kinetic energy to overcome the potential barrier, so that the electrons located in the appropriate direction escape from the metal surface to form an electron beam. Beam density of metal thermal emission conforms to Richardson's formula

$$j = AT^2 \exp\left(-\frac{\phi}{kT}\right)$$

In the formula, A is the cathode emission constant, Tc is the cathode emission temperature, the unit is K, \(\phi\) is the work function of the cathode, the unit is eV, and k is the Boltzmann constant.

The potential between the anode and the cathode is used to form an electric field, which gives electrons an acceleration toward the anode to form the electron beam. The grid can control the focus and emission of the electron beam. When the potential between the grid and the anode is positive, the grid will diverge the electron beam until the beam saturation value is reached. When the potential is negative, the electron beam grid will focus the electron beam until the electron beam is cut off.

3. Analysis of experimental methods
The main properties of the electron beam are the beam current and the beam spot diameter. Besides, another characteristic that should be noticed is the uniformity of the beam spot. Using the Faraday cups
is the method mostly adopted to measure the beam current. [12]. The main methods to measure the beam spot diameter are: CCD observation method [13] and occlusion scan method [14].

The principle of CCD observation method is shown in Figure 2. A high-sensitivity CCD detector is placed under the fluorescent screen. When the electron gun is irradiated on the fluorescent screen, fluorescence is generated. The fluorescence is detected and collected by the CCD detector, and the electrical signal is transmitted to the computer for imaging by photoelectric conversion. The approximate spot size and uniformity of the flood gun can be obtained by comparing the image acquisition area and the brightness of each pixel on the area.

![Figure 2. Schematic diagram of CCD observation method.](image)

The test principle of the occlusion scan method is shown in Figure 3. The diameter of the beam spot is determined by the number of electrons entering the Faraday cup. First ensure that all the electron beams enter the Faraday cup, and connect the Faraday cup to the oscilloscope; then move the silicon above the Faraday cup at a constant speed. The silicon will gradually block the electron beam during the movement of the silicon, resulting in receiving the number of electrons is reduced. When the Faraday cup cannot receive electrons, the detection current is zero. When the silicon is completely removed, the Faraday cup re-detects the maximum beam.

![Figure 3. Schematic diagram of the occlusion scanning method.](image)
Assuming the distribution of beam spot is uniform, the theoretical image obtained is shown in Figure 4. Given that the length of silicon is \( L \) and the beam spot diameter is \( d \), the size of the beam spot diameter can be calculated according to formula (2) by using \( t_1 \) and \( t_2 \) obtained by the oscilloscope.

\[
d = \frac{t_1 \times L}{t_1 + t_2}
\]

Figure 4. Theoretical image of occlusion scanning method.

Because the flood gun generates low-energy electrons (the energy is generally below 500eV or even lower), the common fluorescent screens on the market are difficult to work normally under the circumstances (usually the minimum working energy is around keV). Besides, the CCD observation method has some difficulties in quantitatively calculating the beam spot size and analyzing the uniformity. In the process of using the occlusion scanning method, due to the interaction between the electron beam and the solid, an interference signal mainly composed of secondary electrons will be generated, which will greatly affect the accuracy during the measurement.

In order to measure the characteristics of the beam spot accurately, a new method, the Faraday cup aperture scanning method, is proposed in this paper. The principle of the method is shown in Figure 5. First, select a Faraday cup with an aperture which the diameter is smaller than the diameter of the beam spot to be measured. Fix the Faraday cup on the stage and place it under the flood gun for receiving electrons, shown in Figure 6. In order to ensure that the excess electron beam is transmitted into the ground so as not to affect the measurement, a grounded metal shield, which has a same diameter aperture with the Faraday cup, is installed above the Faraday cup. Then move the stage at a constant speed to achieve the relative movement of the beam spot and the Faraday cup aperture, and guarantee that the movement range of the Faraday cup aperture will completely cover the beam spot area. The aperture will always receive electrons during the moving process, and the electrons will flow into the picoammeter which outputs the results in the form of the current signal to the computer. Subsequent analysis and comparison of the current values received at each location can generate an electron beam distribution characteristic map, and then the beam spot diameter and distribution characteristics of the flood gun can be obtained. This method can quantitatively, comprehensively and accurately measure beam shape and analyse beam spot characteristics in depth.

Figure 5. Schematic diagram of Faraday cup aperture scanning method.
4. Construction of experimental test system

According to the proposed principle of the Faraday cup aperture scanning method, based on the existing measurement experience and project requirements of the research group, the electron beam performance test system is built up, the overall structure of the system is shown in Figure 7. The system is mainly composed of vacuum subsystem, electron gun and its control subsystem, stage subsystem, and data acquisition subsystem.

The vacuum subsystem is mainly composed of mechanical pump, molecular pump, vacuum chamber, etc.; the electron gun and its control subsystem are mainly composed of the flood gun and its power supply; the stage subsystem is mainly composed of precision displacement stage. The stage has three axes. The X-axis and Y-axis use the micronix MMC-110, the Z-axis uses the MMC-200. The data acquisition subsystem is mainly composed of a Faraday cup, picoammeter and computer. Among them, the Faraday cup uses the product of Kimball Company FC-72A. The diameter of the Faraday cup aperture is 2mm, and the structure is shown in Figure 7. The picoammeter uses a dual channel picoammeter Model 6482 by Keithley Company.

5. Results

5.1. Beam spot diameter and distribution characteristics

First, warm up the electron gun until it is stable. Move the stage in the x-y plane and the Faraday cup follows it. During this process, the picoammeter continuously measures the current value and sends it to the computer. The analysis of the data in the computer can determine the irradiation range of the electron beam, that is, the beam spot size and the uniformity of the distribution. During the experiment, the pressure was around 1.9x10^-4pa, the cathode current was 1.8A, the acceleration voltage was 1000eV, and the grid voltage was -1V (based on the acceleration). At this time, the flood gun power supply showed an emission current of 41.7μA, which was obtained on a working plane 50mm below the electron gun. The two-dimensional distribution is shown in Figure 8. (The outermost contour is the
profile of the beam spot, and the value of the contour increases inwardly which means closer to the centre more beam density.)

![Figure 8. Two-dimensional distribution characteristics of beam spot.](image)

5.2. Beam characteristics as a function of acceleration voltage
At the same time, using the Faraday cup aperture scanning X-axis and Y-axis can find the relationship between beam spot characteristics and acceleration voltage. Under the circumstances that the filament current is 1.7A, grid voltage is 0V, the X-axis is taken as an example for illustration below Figure 9. It can be seen that as the acceleration voltage increases, the current value received by the Faraday cup aperture becomes larger, indicating that the beam current density is increasing. If the effective diameter of the beam spot is defined as above the ten percent of the maximum received value, it can be concluded that as the acceleration voltage level increases, the size of the beam spot does not change significantly.

![Figure 9. Beam characteristics varies as the acceleration voltage](image)

5.3. Beam characteristics as a function of grid voltage
According to the method mentioned in 5.2, the variation rule of the beam spot diameter in the X-axis and Y-axis with the grid voltage can be obtained. Under the circumstances that the filament current is 1.7A, acceleration voltage is 1000V, the X-axis is used as an example for description below. It can be seen from Figure 10. that as the grid voltage increases, the current value received by the Faraday cup aperture becomes larger, and at the same time the size of the beam spot also becomes significantly larger.
5.4. The trend of beam divergence angle varies with the grid voltage

The Z-axis stage can be used to measure the beam spot size of the electron beam at different Z-positions. The focus position and divergence angle of the electron beam can be determined through geometric optics. The principle is shown in Figure 11. The beam spot diameter \(d_2\) (mm) is obtained on the original working plane, and the working plane is raised by 10 mm on this basis. At this time, a new beam spot diameter \(d_1\) (mm) can be measured. Assuming that the working distance at the beginning is \(S\), according to the principle of similar triangles, formula (3) can be obtained.

\[
\frac{S-10}{S} = \frac{0.5d_1}{0.5d_2}
\]  

(3)

Based on (3), we can get the equation (4)

\[
S = \frac{10 \times d_2}{d_1 - d_2}
\]  

(4)

Further, the angle \(\theta\) between the outermost electron and the central axis can be calculated by equation (5), and this angle is also recorded as the divergence angle of the beam spot.

\[
\theta = \tan^{-1}\left(\frac{0.5 \times d_2}{S}\right) = \tan^{-1}\left(\frac{d_2 - d_1}{20}\right)
\]  

(5)

The beam divergence angles under different grid voltage conditions were obtained according to the above method, and the results are shown in Figure 12. If the grid voltage is negative (based on acceleration voltage), it can be seen that the electron beam is suppressed and the divergence angle \(\theta\) of the X axis and the Y axis is almost the same. Under the condition that the positive voltage is applied to the grid, the divergence angle difference between the X axis and the Y axis is small, and it gradually enlarges as the grid voltage increases. The analysis here may be caused by the asymmetry of the cathode installation. When the electron beam is in a suppressed state, the effect of the asymmetry of the installation is negligible; when the electron beam is in a divergent state, the effect of the asymmetry of...
the installation is enlarged, which will lead to the enlargement of the difference in the divergence angle between the X-axis and the Y axis.

6. Conclusion
Aiming at the problem that the electron beam characteristics cannot be quantitatively and accurately measured when the flood gun is used, a method to measure the beam spot using a Faraday cup aperture is proposed, and a test system is built based on the method. Experimental study of the flood gun is performed. Besides, this method can collect a large amount of data. Through processing and analysing the data, important parameters such as beam spot diameter, beam spot distribution characteristics, beam divergence angle, etc. can be obtained to achieve a comprehensive, accurate and in-depth analysis of the beam. The in-depth analysis of the beam spot performance has a guiding function to optimize the structural design and installation of the flood gun. At the same time, it contributes to the prediction of the experiment results.

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Figure 12. Trend of divergence angle as a function of grid voltage.
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