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Monochromators in electron microscopy

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ABSTRACT

Monochromators used in electron microscopes have been reviewed. There are three steps in its progress. At the first step, monochromator is used in retarding mode. Wien filter monochromator and analyzer are floating on the high voltage connected to the gun high voltage. It provides very high energy resolution of about 10 meV at 60 kV accelerating voltage. In the second step, various gun monochromators; the Wien filter (fringe field monochromator, single focus monochromator and double focus monochromator) and electrostatic omega type are proposed and some of which are commercialized. The double Wien filter and the electrostatic omega monochromators have functions of astigmatic focus on the slit plane and the compensation of the dispersion at the last focus.

As the third step, the earth potential monochromator is proposed. Only highly stabilized beam can go through the earth potential monochromator slit, whose magnetic field is stabilized around the 10^{-8}, even if the beam stability from the gun is not so high. This function will be useful in the future high spatial resolution electron microscopy.

1. Introduction

Monochromators have a long history in surface science to get a few ten to meV energy resolution [1]. The accelerating voltage of energy analyzers in surface science is relatively low compared to the analyzers in material science, in which higher accelerating voltage is usually used; it is easy to get high energy resolution. Difficulties in low energy instrumentation are to avoid the external magnetic field disturbances and the production of the ultra high vacuum environment.

The first monochromator for bulk materials under transmission mode was built by Schröder and Geiger [2]. The accelerating voltage was 20 kV and it was improved to 30 kV by Essig [3]. They used the same retarding Wien filters both of the monochromator and the analyzer. Their machine has no microscope function and the energy resolution reached a few meV. Both of monochromator and analyzer are used in the retarding mode up to 10 eV or less to get the high energy resolution. Three high voltages: the electron gun, the monochromator and the analyzer are all supplied from a common high voltage power supply.

Tanaka planed to install the same kind of Wien filters on TEM (transmission electron microscope) to combine meV energy resolution and μm spatial resolution. I myself have involved in JEOL to design and construction of the machine and Terauchi et al. [4] has succeeded in getting 12 meV energy resolutions at 60 kV after quite difficult alignment of the microscope optical axis. These two machines have directed to be the Wien filter as a standard instrument of the monochromator in electron microscopes.

In Tanaka's monochromator, electrons are first accelerated to 60 kV and then retarded to 20 V before the monochromator. The beam is accelerated again to 60 kV after the monochromator and transmits the specimen at 60 kV. The beam again decelerated to 20 V before entering to the analyzer and accelerated again to 60 kV before entering the image forming lenses. The machine is very tall (about 4 m) and the operation of the machine needs very high skills. No one followed to construct the same kind of machines, and the machine is keeping the highest energy resolution electron microscope even at present within the working machines.

A new idea of gun monochromator has been proposed by Mook and Kruit [5]. The monochromator made of a thin Wien filter was built as a fringe field monochromator inside the gun [6]. They thought that the necessary energy dispersion is the same as the probe size of a field emission gun (FEG), which is about 10 nm. If we can make a slit with nanometer width, the necessary energy dispersion of the monochromator is only 10 nm. Aberrations of the energy filter will be negligibly small if the filter is weakly excited to generate a small dispersion. They used a very thin Wien filter inside the gun. The fringe field Wien filter monochromator is first installed in IBM [7] and is now working in Shimadzu [8] to improve the spatial resolution of SEM (scanning electron microscope).

FEI Company has succeeded in constructing a single Wien filter monochromator inside the gun [9]. This is a simple construction and has succeeded in commercial distribution [10]. There are two differences with the fringe field monochromator. First one is that the slit is not set inside the electron gun but at the earth potential

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after accelerating electrons. This is a big advantage from the point of the practical construction of the machine. The second point is that the Wien filter works under the full excitation to make a focus by itself and the dispersion is of micron order. The shape of the Wien filter itself is not published in literatures but from the viewgraphs shown in conferences, it looks similar to the fringe field monochromator [6].

JEOL has made a double focus Wien filter [11], in which the first crossover has an astigmatic focus to avoid the Boersch effect. Double focus monochromator can compensate the residual dispersion within the slit width and can avoid the decrease of the brightness.

Multi focus gun monochromators, which have the same advantage of the double focus Wien filter about the point of the brightness, are announced from Kahl and Rose [12] and Huber and Plies [13]. Both monochromators are made of electrostatic omega filter. Although the former has complicated electrode shape [14], the latter consists of a combination of hemi-spherical electrostatic analyzers. The former one is announced commercially from CEOS and Zeiss [15]. The advantages of the electrostatic omega filter are the same as the double focus Wien filter for avoiding the reduction of the brightness and the astigmatic focus in the slit plane. An original merit is it's free from coils. It is technically a difficult work to use coils in the ultra high vacuum electron gun. However, the drawback of the omega filter is its complication of the electron trajectories. It is not possible to make any mechanical adjustments from outside because it is on the high voltage.

Symmetrical double focus Wien monochromator has been constructed by JEOL [16] based on the numerical simulation made by Martínez and Tuno [17] and on the analytical theory by Ioanoviciu et al. [18]. The theory has been improved to give the multipole excitation conditions in giving the negative spherical and negative chromatic aberration conditions useful to design a Wien type aberration corrector [19]. The theory can be seen in the aberration chapter by Hawkes in the second edition of ''Handbook of Charged particle optics'' edited by Orloff [20].

Future monochromators must be placed on the earth potential level. Both of the monochromator and the analyzer can be set on the same ground level and the requirement to the stability of the high voltage is released. For the accelerating voltage of 200 kV, it is necessary to get the energy resolution of $0.1/200000=5\times10^{-7}$. This resolution has not been obtained in usual energy filters. The highest energy resolution obtained by the omega filter is 1 eV at 1 MV in an ultra-high voltage microscope [21]. The resolution is 1/1,000,000, which is 1×10^{-6}. If we use the large omega filter, which has a height of about 1 m, on a usual microscope of 100–300 kV, we can obtain nearly the satisfactory resolution.

I have proposed a monochromator on the earth potential with using an S-filter [22], which has $6\sim10$ μm/eV dispersion at 300 kV, to the Joint project between Chemistry and Material science in Cambridge University between 1999 and 2001. However the machine has not been constructed and there are no publications about its microscope.

Krivanek et al's idea [23] for the earth potential monochromator is to insert quadrupoles in the drift region between the sector magnets of an alpha filter. It is necessary to increase the dispersion only for the dispersion direction to improve the dispersion. Quadrupoles are useful to improve the dispersion only on the direction of the dispersion.

Another important application of the monochromator is to reduce the chromatic aberration to get a higher spatial resolution. The spatial resolution of 0.08 nm has been attained by the spherical aberration correction with using a usual field emission electron source (FEG). Further decrease of electron source energy width with using a nano-tip cathode, Sawada et al. [24] has succeeded a resolution of 0.05 nm.

After the field emission electron gun (FEG) has been widely used, the energy width of the source has been improved to 0.7 eV (thermal field emitter) and 0.3 eV (cold emitter). In recently, several new cathodes and cathode materials such as a single atom electron source [25] and a spin polarized electron source [26], all of which have 0.1 eV energy widths, have been proposed. However, there are no cathodes which have energy width less than 0.1 eV. In order to examine energy resolution less than 0.1 eV, it is still necessary to use a monochromator.

On the other hand, the use of monochromator/analyzer in SEM has been tried sometime. SEM is in-between analytical TEM and surface analysis equipments such as Auger, Esca, and analytical LEEM/PEEM. In the surface analysis, electrostatic analyzers are mainly used. Monochromator of SEM [27] is now applied to improve the spatial resolution.

2. A Wien filter used as a retarding monochromator

A Wien filter and its coil for the magnet similar to the Tanaka's machine in its final form [4] are shown in Fig. 1(a) and (b), respectively. This is an 8-pole Wien filter with large four poles in the horizontal and the vertical directions and another four small poles to the diagonal directions. Two diagonal poles are bent to the upper side and the other two to the down side. Two coils are used to bundle those three poles each other. With these bending poles, only two coils are enough for eight poles. The reduced number of coils is useful for a monochromator in high vacuum. Those two coils are serially connected and only one current supply is used to excite a homogeneous magnetic field. Three voltages are necessary to generate homogeneous and quadrupole electrostatic field components. It is important to reduce the number of power supplies, because all of those are floating on the high voltage.

Fig. 1(c)–(e) shows dipole electrostatic (E_1), quadrupole electrostatic (E_2) and dipole magnetic (B_1) field components generated by the Wien filter shown in Fig. 1(a), respectively. In the case of generating the quadrupole component, the applied voltage to the top and bottom poles is twice bigger than that of the left and right horizontal poles, because the width of the pole faces are about a half of the latter. By applying such the different voltages, pure E_2 term is generated at least near the center. Fig. 2(a)–(c) shows the filter shape along the optical axis (z), electron ray trajectory along the z-axis and the spot diagram at the exit plane, respectively. The accelerating voltage of the system is 5 kV, the diameter of the incident beam 2 μm and the half divergence angle of the incident beam is 5 mrad. Two beams with 5000 and 4999 eV are drawn. Although the beam path is not symmetrical in the horizontal axis, it does not deviate from the axis. This means that the Wien condition (straight beam condition) is satisfied even in the fringing region. Although the energy difference of 1 eV cannot be seen in the ray trajectory, it is separated in the output beam shown in Fig. 2(c). Four circular beams with radius 0.25, 0.5, 0.75 and 1 μm are drawn. The beam of the radius 1 μm contacts each other, but the other beams are separated. Even in the 1 μm beam, it might be separated at the top of the spectrum. Because 1 eV beam is separated at 5 keV beam, 10 meV can be separated at the accelerating voltage of 50 eV, if the increase of the divergence angle by the retardation is not so large.

3. Gun monochromators

3.1. Fringe field monochromator

Fig. 3(a)–(c) shows electrostatic field distribution on the round lens part and Wien filter part of the fringing field monochromator