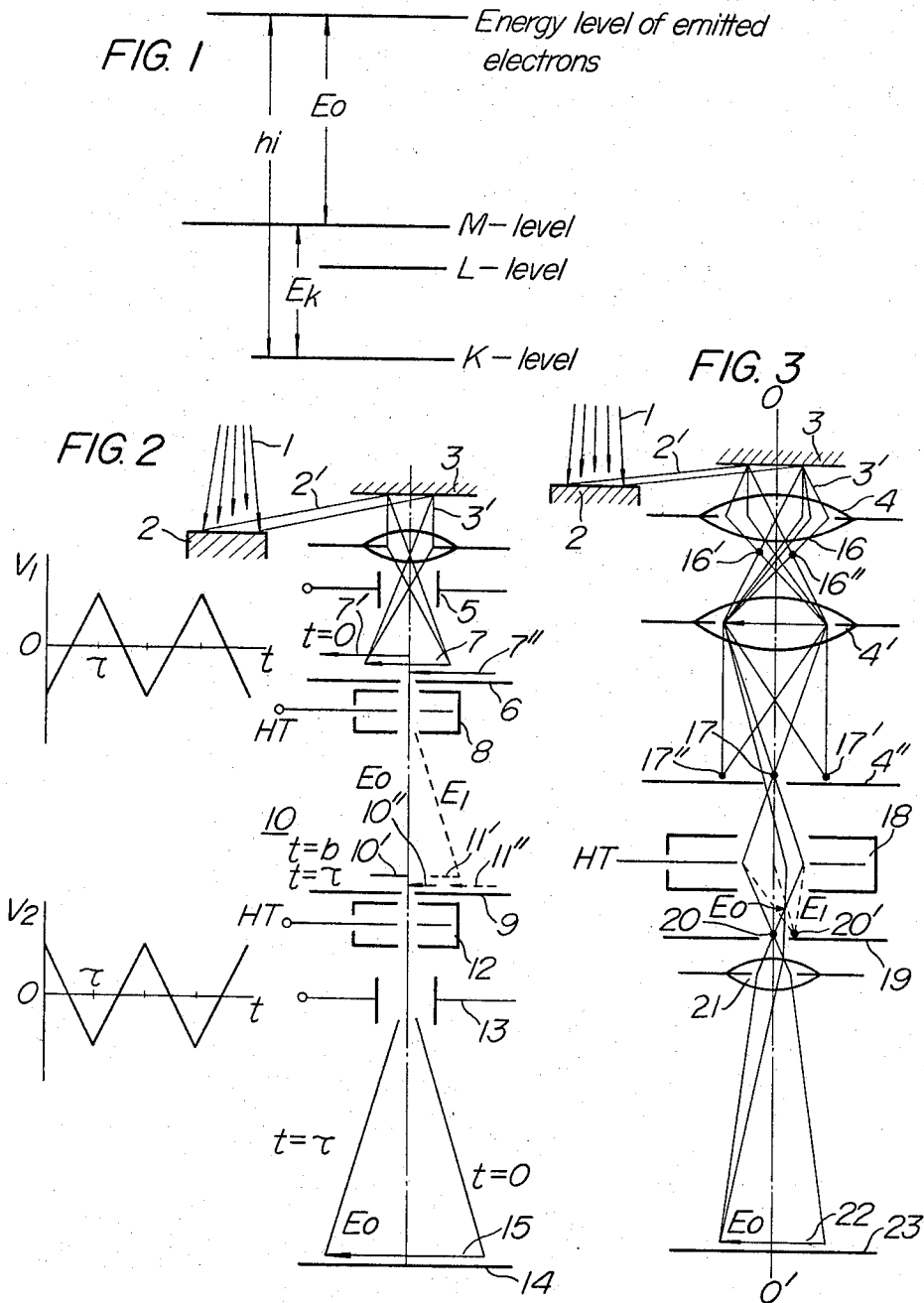


March 19, 1968

HIROSHI WATANABE

3,374,346

SPECTROSCOPIC ELECTRON MICROSCOPE WHEREIN A SPECIMEN IS
IRRADIATED WITH X-RAYS AND THE ELECTRONS EMITTED
ARE ENERGY ANALYZED
Filed July 12, 1965



INVENTOR

Hiroshi Watanabe

Paul M. Craig, Jr.

ATTORNEY

BY

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SPECTROSCOPIC ELECTRON MICROSCOPE WHEREIN A SPECIMEN IS IRRADIATED WITH X-RAYS AND THE ELECTRONS EMITTED ARE ENERGY ANALYZED

Hiroshi Watanabe, Kokubunji-shi, Japan, assignor to
Hitachi, Ltd., Tokyo, Japan

Filed July 12, 1965, Ser. No. 470,991

Claims priority, application Japan, July 15, 1964,
39/40,591

3 Claims. (Cl. 250—49.5)

This invention is concerned with spectroscopic electron microscopes.

Heretofore, X-ray fluorescence spectrometers have often been used in analyzing specimens of unknown composition and in which the specimen is irradiated with X-rays and the secondary X-rays thus generated are analyzed for wavelengths. The use of such devices, however, is limited to elements of atomic numbers of the order of ^{12}Mg or heavier since lighter elements produce characteristic X-rays of such long wavelengths as to make their spectroscopy practically infeasible. Thus, in the past, microanalysis of elements lighter than ^{12}Mg has been impossible employing any nondestructive technique of X-ray analysis. Even with elements heavier than ^{12}Mg , X-ray microanalyzers exhibit only a resolution of the order of 1μ . In addition, they involve a deficiency that the specimen surface is inevitably contaminated as it is directly irradiated by an electron beam.

Under these circumstances, the present invention is intended to provide a novel spectroscopic electron microscope which is free from any of the difficulties previously met and to attain this objective proposes to obtain an image of the X-ray-irradiated portion of the specimen by use of electron rays of a particular energy level selected from those emitted by the specimen when it is irradiated with X-rays of a predetermined wavelength.

The foregoing and other objects, features and advantages of the present invention will become apparent from the following description when taken in conjunction with the accompanying drawings, in which:

FIG. 1 is an energy diagram illustrating the principles of the invention;

FIG. 2 is a schematic diagram of an electron microscope embodying the invention; and

FIG. 3 schematically illustrates another embodiment of the invention.

Referring first to FIG. 1, the principles of the present invention will be described in detail. It has been found that any unknown specimen can be determined by energy analysis of the K-, L- or M-electrons ejected out of their orbits in the atoms which constitute the X-ray-irradiated portion of the specimen, and further by determining the difference of the energy of the ejected electrons from the energy $h\nu$ of the impinging X-rays, which corresponds to the energy of K-, L- or M-electrons as held in the atoms. Now suppose that a specimen of aluminum is irradiated with X-rays having an energy of $h\nu$. In this case, the orbits of the K- and L-levels are filled with electrons while the M-level orbit has a vacancy including only three electrons. Thus, the electrons of the M-level form the outer shell electrons. Let it now be assumed that K-electrons are ejected by X-radiation. Then the electrons will run through the free space with an energy corresponding to that indicated by E_0 in FIG. 1. It will thus be apparent that the specimen can readily be identified as aluminum by accurately measuring the value E_0 by means of an energy analyzer and referring to the table of E_K in FIG. 1.

Further, by selecting from the electrons ejected by the specimen only those having the particular energy value

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for formation of a desired microscopic image, it will be appreciated that the distribution of the specimen components can be clearly observed as a contrast between light and shade in the image.

Reference will next be made to FIG. 2, which illustrates an electron microscope embodying the principles of the present invention.

In FIG. 2, reference numeral 1 indicates an electron beam emitted by the electron gun (not shown) of the electron microscope; 2 indicates an anticathode target formed of Cu, W or other pure metal selected according to the purpose; 2' indicates characteristic X-rays formed at the target 2 and impinging against a specimen 3 under examination; 3' indicates an electron beam of K-, L-, M- or other level emitting from the specimen 3; 4 indicates an objective lens; 5 indicates a first deflector means for scanning the electron beam 3'; 6 indicates a first stop or aperture diaphragm in having a slit or tiny aperture; 7 indicates an image of the specimen formed by the objective lens 4; 8 indicates an electron-energy analyzing lens; 9 indicates a second stop having a slit or tiny aperture; 10 and 11 indicate analyzed electron images; 12 indicates a cylindrical electron lens; 13 indicates a second deflector for scanning; 14 indicates an image plane; and 15 indicates the final image of the specimen.

The electron beam 3' emitting from the specimen when it is irradiated by X-rays of a predetermined wavelength apparently includes scattered electrons having different energy values E_0, E_1, E_2 , etc. Assume that the first deflector 5 is subjected to a first deflecting voltage V_1 such as shown in the left portion of FIG. 2 for the purpose of deflecting the specimen image 7 formed in the plane of the first stop 6. Then, the image 7 is displaced into a position indicated at 7', for example, at the instant of $t=0$ and into position 7'' at the instant of $t=\tau$, representing half of the period of the deflecting voltage. Accordingly, the electron ray passing through the slit of the first stop 6 at the instant of $t=0$ includes electrons forming one end of the image (i.e., the tail end of the arrow indicating the image) while the electron ray passing through the slit at the instant of $t=\tau$ includes electrons forming the other end of the image (i.e. the head end of the arrow). Thus, it is noted that the electrons corresponding to the respective image points and passing through the slit of the first stop 6 form a pattern of energy distribution including values E_0, E_1, E_2 , etc., which can be analyzed by means of the analyzing lens 8. In this embodiment, the analyzing lens 8 takes the form of an electrostatic unipotential lens having a rectangular aperture and use is made of the extra-ordinarily large chromatic aberration of such lens for energy analysis of the electron ray. It is to be understood, however, that the analyzing lens 8 may take any other form of electron prism which is effective to disperse the electrons in accordance with their energy differences. Apparently, the same purpose may be served by a pair of electron deflector plates. Incidentally, even though the analyzing lens 8 has a substantially high resolution, it is difficult to obtain a deflection of the order enough to identify the specimen image as a whole and also the energy deviation of the electron ray cannot be so large. This is the reason why the first deflector 5 is used to divide the specimen image 7 into minute sections and the energies of the image-forming electrons are analyzed separately for each of the individual image sections. In this manner, it will be understood that any specimen image can be converted by energy analysis into an image formed solely by electrons of the same energy level irrespective of the size of the specimen image. Further, by such energy analysis of each of the electron rays, which correspond to the re-

spective image points, it is possible to select from the electron rays having an energy distribution including E_1 , E_2 , etc. only those having any desired energy value and the specimen can thus be identified by finding the value E_K , as described hereinbefore.

Again referring to FIG. 2, it is to be noted that, at the instant of $t=0$ in the diagram of the first deflecting voltage V_1 , elastically scattered electrons of energy E_0 , included in the electron ray forming the tail portion of the specimen image now positioned at $7'$, are exclusively allowed to precede through the slit of the second stop 9 , as indicated at $10'$ and inelastically scattered electrons of energy E_1 included in such electron ray are thrown onto the second stop 9 around the slit therein as indicated at $11'$. Similarly, at the instant of $t=\tau$, electrons of energy E_0 included in the electron ray this time forming the head portion of the specimen image at $7''$ are projected as indicated at $10''$ but those of energy E_1 are projected as indicated at $11''$. Thus, only rays of elastically scattered electrons, having one and the same energy value E_0 , are allowed to pass through the slit of the second stop 9 . In this manner, even with a specimen image of a substantial size, it is possible to select from the electron rays corresponding to the respective image points only those scattered elastically and having an energy value E_0 for passage through the aperture in the second slit. The electron rays of the same energy E_0 , having passed through the second stop 9 , are deflected to form a desired final image 15 of the specimen under examination on the image plane 14 by the second deflector 13 , to which a second deflecting voltage V_2 is applied which is opposite in polarity to the first deflecting voltage V_1 , as shown in the left portion of FIG. 2. It will readily be appreciated that the final image of the specimen is extraordinarily high in quality since it is formed solely by elastically scattered electrons having the same energy value E_0 . The cylindrical electron lens 12 arranged beneath the second stop 9 serves to correct any substantial astigmatism of the analyzing lens 8 for the purpose of further enhancing the quality of the image 15 . When it is desired to obtain a higher magnification, an appropriate magnifying lens system not shown may be used in combination to further magnify the image 15 .

With the embodiment described above, it will readily be understood that a specimen image formed of monoenergetic electrons having any desired energy value other than E_0 can be obtained by properly adjusting the energy-analyzing power of the analyzing lens 8 or the position of the slit of the second stop 9 or both to allow passage of electron rays of the energy value only.

Reference will next be made to FIG. 3, which illustrates another embodiment of the present invention. In this figure, reference numerals 16 , $16'$, $16''$, . . . indicate an electron diffraction pattern obtained in the back focal plane of the objective lens 4 ; $4'$ indicates a first auxiliary lens; $4''$ indicates a first stop or aperture diaphragm adjustable in position; 17 , $17'$, $17''$, . . . indicate enlarged diffraction spots formed in the plane of the first stop $4''$; 18 indicates an analyzing lens; 19 indicates a second stop or aperture diaphragm also adjustable in position; 20 , $20'$, $20''$, . . . indicate analyzed images formed in the plane of the second stop 19 by energy analysis of the analyzing lens 18 ; 21 indicates a magnifying or second auxiliary lens; 22 indicates an imaging plane; and 23 indicates a final image.

As described in connection with the first embodiment of the present invention, the electron beam emitting from the specimen 3 includes electrons having different energy values E_0 , E_1 , E_2 , etc. Accordingly, the electron rays forming the respective image points 17 , $17'$, $17''$, . . . of the electron diffraction pattern, which is formed in the plane of the first stop $4''$ as a magnified projection of the electron diffraction pattern 16 , $16'$, $16''$, . . . obtained in the back focal plane of the objective lens through the auxiliary lens 15 , have an energy distribution

including energy values of E_0 , E_1 , E_2 , etc. Suppose that the aperture position of the first stop $4''$ is adjusted, for example, to allow passage therethrough of those electrons which form the central diffraction spot 17 , as illustrated. Such electrons are energy-analyzed by means of the analyzing lens 18 to form in the plane of the second stop images 20 , $20'$, $20''$, . . . corresponding to the respective energy values E_0 , E_1 , E_2 , . . . in the form of a discontinuous spectrum. It will be noted that, of all the electrons thus analyzed, those having the energy value of E_0 are elastically scattered electrons and all the rest are inelastically scattered. The analyzing lens 18 in this embodiment is in the form of an electrostatic unipotential lens which and thus exhibits an extraordinarily large chromatic aberration, which is utilized for energy analysis. The analyzing lens 18 , however, may apparently take any other form of electron prism which is effective to disperse the electrons in accordance with the energy difference therebetween. For example, the same purpose may be served by a pair of electron deflector plates, as described hereinbefore in connection with the preceding embodiment of the invention.

In any case, the images formed in the plane of the second stop 19 in different positions corresponding to the respective energy values are each formed by electrons which are monoenergetic having the same energy value. It is possible, therefore, to obtain on the imaging plane 22 a final image 23 of high quality, which is formed solely by elastically scattered electrons of energy value E_0 and magnified by the magnifying lens 21 , by adjusting the aperture position of the second stop 19 so as to allow passage therethrough of only the elastically scattered electrons of energy E_0 , for example, forming the diffraction spot 16 , as illustrated. Now, take the electron rays $1'$ which deviate from the beam 1 travelling parallel to the axis $O-O'$ of the microscope by only a slight angle, which with ordinary electron microscopes ranges from 10^{-3} to 10^{-4} radian. Since an image of any particular point of the specimen, which in the figure is shown as the headpoint of the arrow, is apparently formed at the points of intersection of electron rays emitting from the point of the specimen, such image is formed in the vicinity of the intermediate or first auxiliary lens 15 and then of the analyzing lens and finally is formed in the imaging plane 22 through the intermediary of the projection or second auxiliary lens 21 .

Now, any one of the diffraction spots, for example, the central spot 16 includes all the electron rays emitting from the different points of the specimen and travelling parallel to the axis $O-O'$. Thus, of all the informations carried on a specimen of limited extent, the information carried by the electron rays emitting in the direction of the axis $O-O'$ of the microscope is all included in the central spot 16 . Accordingly, with the electron microscope, a bright field image can be obtained by placing the objective aperture diaphragm in the position of the central spot 16 while a dark field image can be obtained by placing the diaphragm in the position of each of the other spots $16'$, $16''$,

In the above example, the energy analysis of the diffraction spots 16 , $16'$, $16''$, . . . is useful in that it enables energy selection of the final image as obtained on the electron microscope. That is, it is possible to obtain a mono-energetic image on an electron microscope by energy analysis of the diffraction spots each formed therein as a gathering of electron rays, as described hereinbefore. For example, the electron rays passing through the aperture of the second stop 19 , for example, positioned as illustrated are monoenergetic having the energy value of E_0 and include only electrons emitting from the different points of the specimen in parallel with the axis of the microscopic system. Thus, it will be apparent that by employing such electron rays, a microscopic image of bright field can be obtained which is monoenergetic including electrons of the same energy of

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E_0 . Of course, electron rays slightly inclined to the microscopic axis and having the energy value of E_0 are also allowed to pass the aperture of the second stop 19, which is limited in magnitude, thereby contributing to the focusing of a final image in the electron microscope.

In this manner, of all the electron rays emitting from the different points of the specimen in parallel to the microscopic axis or at a slight inclination thereto, only those having the energy value of E_0 are allowed to pass through the aperture of the second stop 19 and are projected on the final imaging plane 22 through the magnifying lens 21. On this occasion, the electron rays emitting from the different points of the specimen are all focused to form respective points of the final image 23, and thus the latter is apparently formed only by electron rays having the energy value E_0 .

Next assume that the second stop 19 is displaced to the right as viewed in FIG. 3 or the operating point of the analyzing lens is slightly changed so that the aperture position of the second stop 19 is slightly varied relatively to the position of the analyzed image 20, 20', 20'', . . . thereby to allow only the spot formed by electrons having an energy value other than E_0 , for example, the spot 20 formed by electrons of energy E_1 , to be placed in the aperture of the second stop 19. It will be apparent that the image 23 thus obtained in the imaging plane of the electron microscope is one formed only by inelastically scattered electrons having the energy value of E_1 .

According to the present invention, it will be appreciated from the foregoing that microanalysis can be performed successfully not only with heavier elements but also with such lighter elements as cannot be analyzed by any X-ray microanalyzer or X-ray spectrograph for fluorescence analysis and that a resolution is obtainable which corresponds to that of any ordinary electron microscope. In addition, the distribution of the specimen components can be directly observed as the light-and-dark contrast of a final image formed in the electron microscope. A further practical advantage of the present invention is that, since the specimen is only irradiated with X-rays, there is no danger of its surface being contaminated as with the case of the X-ray microanalyzer and thus the component distribution of any minute specimen can be observed with higher accuracy.

What is claimed is:

1. A spectroscopic electron microscope comprising means for irradiating the specimen under examination with X-rays of a predetermined wavelength, an objective lens, and an axial arrangement between the objective lens and the imaging plane of the microscope of components including:

a first deflecting device for deflecting the electron image of the specimen formed by the objective lens, a first aperture diaphragm having a small aperture or slit and disposed in the imaging plane of the objective lens, means for energy analysis of the electrons passing in time sequence through said first aperture dia-

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phragm to form the respective points of said image of the specimen, a second aperture diaphragm adapted to allow passage of only those electrons having any desired energy value of all the electrons analyzed by said means for energy analysis, and a second deflecting device for deflecting the rays of monoenergetic electrons passing through said second aperture diaphragm toward their respective positions in the imaging plane of the microscope.

2. A spectroscopic electron microscope comprising means for irradiating the specimen under examination with X-rays of a predetermined wavelength, an objective lens and an axial arrangement between the objective lens and the imaging plane of the microscope of components including:

a first deflecting device for deflecting the electron image of the specimen formed by said objective lens, a first aperture diaphragm having a small aperture or slit and disposed in the imaging plane of said objective lens, means for energy analysis of the electrons passing through said first aperture diaphragm in time sequence according to the deflection period of said first deflecting device to form the respective points of said image of the specimen, a second diaphragm aperture adapted to allow passage of only those electrons having any desired energy value of all the electrons analyzed by said means for energy analysis, means for correcting the electron rays passing through said second aperture diaphragm for the astigmatism of said energy analysis means, and a second deflecting device for deflecting the electron rays thus corrected toward their respective positions in the imaging plane of the microscope.

3. A spectroscopic electron microscope comprising means for irradiating the specimen under examination with X-rays of a predetermined wavelength, an objective lens and an axial arrangement between said objective lens and the imaging plane of the microscope of components including:

a first auxiliary lens for forming a magnified projection of the electron diffraction spots of the specimen formed in the back focal plane of said objective lens, first selecting means for selectively allowing passage of the electrons forming the magnified diffraction spots, means for energy analysis of the electrons selected by said first selecting means, second selecting means for allowing passage of those electrons having any desired energy value of all the electrons analyzed by said energy analysis means, and a second auxiliary lens for forming a magnified projection of the electrons selected by said second selecting means.

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