United States Patent

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[31] **P 19 37 482.4**

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[54] **ION LENS TO PROVIDE A FOCUSED ION, OR ION AND ELECTRON BEAM AT A TARGET, PARTICULARLY FOR ION MICROPROBE APPARATUS**
12 Claims, 4 Drawing Figs.

[52] **U.S. Cl.** ..... **250/49.5 P,** 250/41.9 ME, 250/49.5 D, 250/49.5 PE, 250/49.5 C

[51] **Int. Cl.** **H01j 37/14,** H01j 37/12

[50] **Field of Search** ..... 250/41.9 ME, 49.9 SB, 41.9 SA, 41.9 SE, 49.5 PE, 49.5 P, 49.5 C, 49.5 D; 335/210, 213

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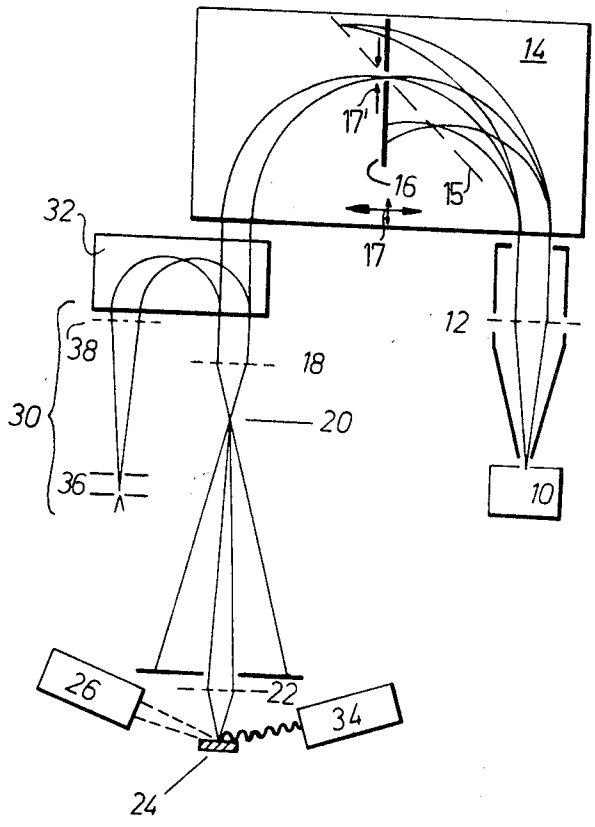
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ABSTRACT: An ion lens (**12**) is located between an ion source (**10**) and the magnetic sector field of an ion microprobe apparatus, the ion lens having its input focal plane in the region in which the ion beam emitted by the ion source has its smallest cross section, the magnetic sector field being a uniform homogeneous 180° magnetic field in which the ions emitted from the ion lens (**12**) as parallel bundles are first deflected by 90°, then passed through an aperture for selection of ions of predetermined mass, and again deflected by 90°, to be emitted as parallel bundles of ions of preselected mass. The microprobe may be combined with an electron beam generator which emits a parallel beam of electrons to a second uniform 180° magnetic field, which places the electron beam coaxially with the ion beam. The ion beam passes through a portion of this second magnetic field in a region which is of insufficient field strength to deflect the ion beam, to provide for simultaneous, or selective irradiation of the same spot on a test sample by ions or electrons. Lenses for simultaneous focusing of ions and electrons (FIG. **2**) includes a pair of pole shoes with a magnetic field therebetween and a nonmagnetic electrode located between the pole shoes and energized with respect to the pole shoes to provide for combined magnetic and electrical action on the ion, and/or electron beam.



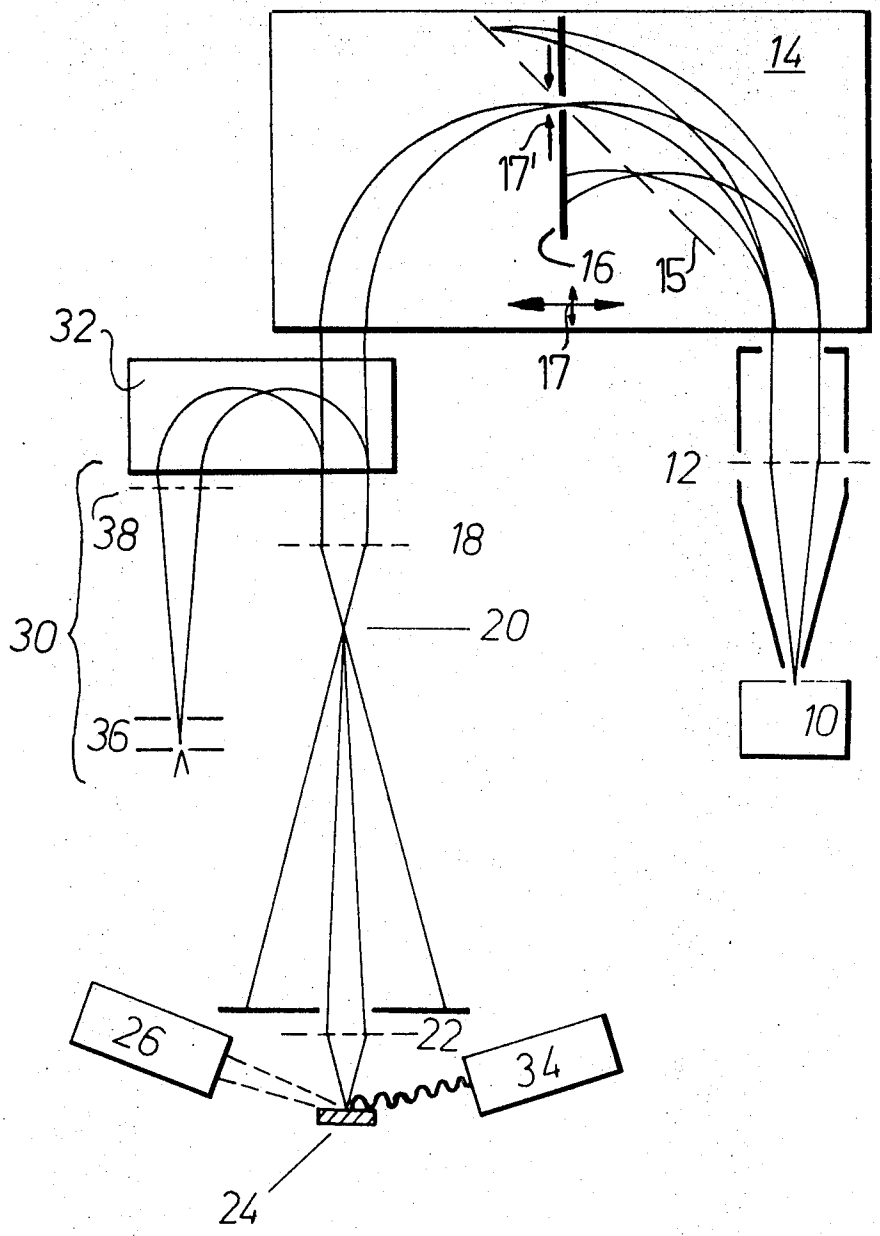


Fig. 1

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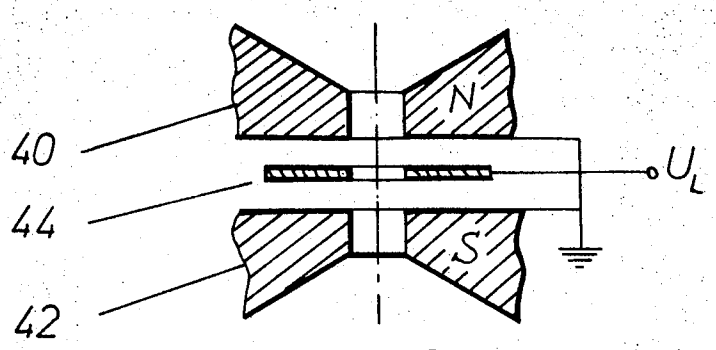


Fig. 2

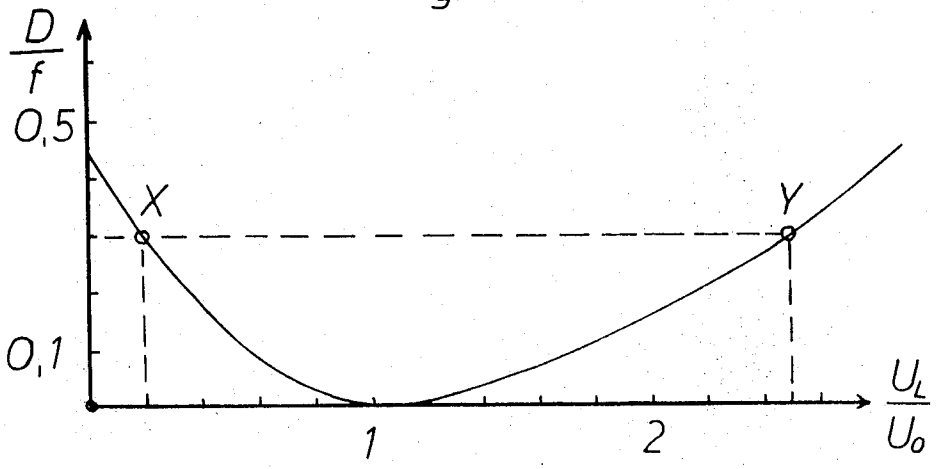


Fig. 3

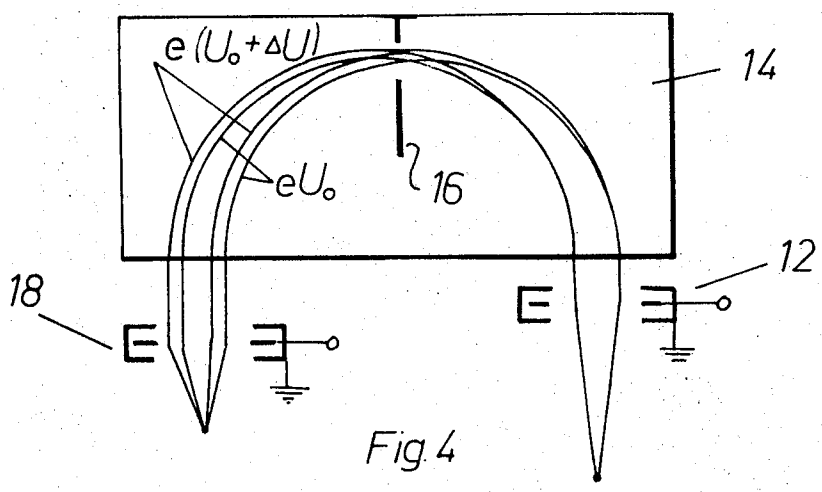


Fig. 4

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ION LENS TO PROVIDE A FOCUSED ION, OR ION AND ELECTRON BEAM AT A TARGET, PARTICULARLY FOR ION MICROPROBE APPARATUS

The present invention relates to ion lenses, for example for use in ion microprobe to provide a focused ion, or ion and electron beam to a target apparatus, more particularly for mass analyzers having a magnetic sector field in which ions of a desired mass are separated out from the ions in an ion beam generated by a source.

Ion microprobe beams are used in apparatus in which a small limited region of a test object is analyzed by means of particle radiation—see, for example, H. Liebl "Ion Microprobe Mass Analyzer" J. Appl. Phys. 38, 5277 (1967). Microprobe analyzers utilizing electron beams are so constructed that a sharply focused electron beam is directed to the test object and that the resulting emitted X-radiation is analyzed in an X-ray spectrometer—see, for example, H. Malissa "Elektronenstrahlmikroanalyse" Handbuch der mikrochemischen Methoden IV, Springer-Verlag 1966, or L.S. Birks "Electron Probe Microanalysis", Interscience Publ. New York 1963. In ion microprobe mass analyzers, a fine, accurately focused ion beam is directed to the test object and secondary ions derived from the region of impingement of the ion beams are then analyzed by means of a mass spectrometer. For a more complete discussion, reference is made to the aforementioned "Liebl" reference in the Journal of Applied Physics.

Ion microprobe mass analyzers utilize a magnetic sector field to sort out ions of a desired mass from all the ions generated by the ion source. A condenser lens, as well as an objective lens is provided to obtain an impingement spot of small extent. Secondary ions obtained from the impingement spot can then be analyzed. In known ion microprobe mass analyzers, a crossover region exists at the focal plane on the input side of the magnetic sector field. This crossover region is the zone of smallest cross-sectional area of the beam generated by the ion source. The object of the arrangement is to provide a completely pure beam of primary ions, in which only ions of a single mass are present. Ions of a predetermined desired energy eU_o are then obtained as parallel beams from the magnetic field. Ions having a different energy, that is the energy of which varies by an amount of $e\Delta U$ from the desired energy, likewise exit as parallel bundles of ion beams from the magnetic field. These bundles of beams however, form a small angle γ in the deflection plane with the bundle of ions of the desired energy. Mathematically expressed:

$$\gamma=N_2\Delta U/2U_o \qquad (1)$$

wherein N_2 is the momentum dispersion factor of the magnetic field. The ions leaving the magnetic field are focused by a condenser lens, which may consist of an electrostatic lens having focal length f, in its focal plane. Such a lens may be a three-element lens, the outer two elements of which are electrically connected and usually grounded, and the central electrode is placed at a different potential. The focusing point for the ions of energy $e(U_o+\Delta U)$ is displaced with respect to the focusing point for ions having energy eU_o transverse to the axis of the lens in the deflection plane by an amount

$$y=f\gamma=f(N_2\Delta U/2U_o) \qquad (2).$$

The cross section of the image of the ion source at the point of impingement is thus not circular, even if the imaging is straightforward and undistorted, since the momentum dispersion of the magnetic field is present, and, depending on the spread of energy of the ions, this imaging point is more or less elongated.

The lack of uniformity of energy of the ions is one factor which distorts the imaging point of the ion beam. Additionally, there are two further factors which tend to make the image of the crossover region elongated, or may cause it to drift or move. Instability of the acceleration voltage U and of the magnetic field strength H will have this effect. Instability is here deemed to include also ripple. Instability of the acceleration voltage, as well as of the magnetic field strength changes the direction of the parallel bundle or rays issuing from the magnetic field by an angle γ which is given by the equation (1), and in which ΔU now denotes the variation of the acceleration potential; with respect to the magnetic field, the angle is given by:

$$\gamma=N_2(\Delta H/H_0) \qquad (3)$$

in which ΔH indicates variation of the desired magnetic field strength H_o.

The known ion microprobe thus results in an imaging spot having an undesirably large cross-sectional area, since the intermediate image of the crossover region is imaged by the objective lens on the test object.

It is an object of the present invention to avoid the above-discussed disadvantage.

Known microprobe mass analyzers usually permit investigation only either by an ion beam or by an electron beam. It would greatly simplify spectrographic investigation, and open new fields of investigation, if it would be possible to irradiate a test object in the same apparatus both with an electron beam and an ion beam.

It is an additional object of the present invention to provide an apparatus in which test objects can be selectively irradiated by electron beams or ion beams.

Investigations have shown that a magnetic field need be used which has a dispersion coefficient $N_2=o$. In such a field the ion beam is split up in such a manner that ions of different momenta which enter the field along a common straight line will leave the field along different, parallel paths. To make the above equation (2) applicable, it is necessary that a virtual ion source, as seen from the condenser lens, is located at infinity. In other words, ions having a similar energy and leaving the ion source at a small angle, in space, must leave the magnetic field as parallel bundles. These two conditions can be combined into a single one, namely that the magnetic field must be so arranged that all ions which are derived from a specific point of the ion source, and which have a comparatively small relative energy width, leave the ion source at a small angular region, in space, will exit from the magnetic field as parallel bundles of rays. Since the condenser lens focuses this bundle or rays to a point at its focal point (neglecting chromatic lens aberrations) no mass separation occurs at the focal point. In order to obtain a mass separation, which is the reason for the presence of the magnetic field, a mass spectrum must first be generated within the magnetic field and a resolving aperture (for example a slit) must be arranged therein.

A combination of a homogeneous 180° magnetic field with an electrostatis lens fulfills these requirements, if the ion source falls within the focal plane of the electrostatis lens. The electrostatis lens then causes the ion beams derived from the ion source to become parallel. After deflection by 90°, a mass spectrum is generated within the magnetic field. Ions of the desired mass pass a slit located there and leave the magnetic field again as parallel beams. A subsequent condenser lens then images the ion source in its focal plane which, even though there is nonuniformity of energy of the ions, is completely round and which does not spread or move laterally upon instability of the acceleration potential or the magnetic field.

SUBJECT MATTER OF THE PRESENT INVENTION

Briefly, an ion lens is located between the ion source and the magnetic sector field which has its entering focal plane located in the region in which the ion beam derived from the source has its smallest cross-sectional area. A homogeneous magnetic sector field which is a 180° field is next provided, in which the ions enter as parallel bundles. After deflection about 90°, an aperture is provided which permits passage only of those ions having a desired mass, thus selecting the mass of the beam leaving the magnetic sector field. A further rotation by 90° by the field then causes the selected ions within a beam to leave the magnetic field as a parallel bundle.

In order to provide for selective irradiation by electron, or ion beams, and in accordance with a feature of the invention, a second 180° magnetic field is located between the first 180° magnetic field and the condenser lens, the ion bundle from the first 180° magnetic field passing through the second one. The second magnetic field is uniform. Only a weak field, in the order of a few hundred Gauss, is needed to deflect the electron beam. This field is too small to noticeably deflect the ion beam. An electron beam generating the system is so arranged with respect to the second 180° magnetic field that electron beams entering the second 180° magnetic field will be emitted, after deflection by 180°, as parallel bundles coaxially with the path of the ion bundles, and will enter the condenser lens.

The condenser lens, and preferably also the objective lens, are electrostatis lenses having a pair of magnetic pole shoes, apertured to receive the particle beams to be focused (that is, the electron beam and the ion beam). Between the pole shoes is an insulated, nonmagnetic aperture electrode. Magnets are provided to generate a magnetic field between the pole shoes, and an electric field is generated between both pole shoes on the one hand, and the aperture electrode on the other.

The lens in accordance with the present invention may be used not only for ion microprobes but also for other applications which operate alternatively, or simultaneously, with electron and ion beams.

The invention will be described by way of example with reference to the accompanying drawings, wherein:

FIG. 1 is a schematic representation of a microprobe system operable simultaneously, or selectively, with an ion beam or an electron beam;

FIG. 2 is a schematic representation of a portion of the lens, preferably used as condenser lens and objective lens in the system of FIG. 1;

FIG. 3 is a graph illustrating the property of the lens in accordance with FIG. 2;

and FIG. 4 is a graphic representation of the path of the ion beam in a portion of the apparatus of the present invention.

The microprobe mass analyzer illustrated in FIG. 1 may be used selectively, or simultaneously, to irradiate a test sample with an ion beam or with an electron beam. An ion source **10**, for example a Duoplasmatron may be used; such a source is described in Review of Scientific Instruments, Vol. 33, 1340 (1962). Ion source **10**, or rather the ion beam generated thereby, will have one zone of minimum cross section. This zone is in the focal plane of the receiving side of an electrostatis lens **12**, so that the ions will leave lens **12** as parallel bundles. This parallel ion bundle is then introduced into a homogeneous 180° magnetic field **14**, which, after deflecting the ions by 90°, generates the mass spectrum. The ions which has the desired mass are passed through a nonmagnetic slit, or aperture **16** located within the magnetic field, and after a further deflection by 90° they again will form a parallel bundle and will exit from magnet field **14**. The ion bundle is then focused by a condenser **18** at an image plane **20**, where the ion source is imaged. The image on plane **20** is, in turn, imaged by an objective lens **22** on the test sample **24**. The ion beam will sputter small particles from the test sample and generate secondary ions, which can be analyzed by mass spectrometer **26**.

As described insofar, the arrangement is operable as an ion microprobe mass analyzer.

The maximum permissible energy spread of the ions delivered by the ion source can be derived from the requirement that an aperture **16** a complete mass separation must occur. Only ions of the desired mass M should pass through aperture **16**. If, additionally, ions of an adjacent mass M+ΔM would pass through aperture **16**, the ions of different mass would be focused by condenser lens **18** at the same point as the ions of the desired mass and thus the ion beam impinging on the test sample would be nonuniform with respect to mass.

The mass resolution A of a magnetic field is mathematically determined:

$$1/A=\Delta M/M=\Delta U/U_o \qquad (4)$$

To obtain complete mass separation, the following requirement must be met:

$$\Delta U/U_o<1/A \qquad (5).$$

Ions derived from the Duoplasmatron ion source have an energy spread of at the most 10 ev. Thus the relative energy spread $\Delta U/U_o$ is approximately 1:1,000 at a typical acceleration voltage of 10 kv. On the other hand, a mass resolution capability of at the most 250 is necessary, considering all the elements, so that the above requirement can be met without difficulty. The acceptable fluctuations of ΔU or ΔH respectively, of the acceleration voltage U_o or the magnetic field strength H_o, are determined from the requirement that at the position at which the ions, having the desired mass, are focused, the ion beam may not deviate to such an extent that the bundle of those ions which are desired is limited by the aperture **16** (see FIG. 4) since otherwise intensity variations of the ions' current may result. Variations in accelerating voltage can be analyzed similarly to the analysis in connection with energy spread. Mathematically

$$\Delta U/U_o<1/A \qquad (6)$$

in which ΔU is now the variation in accelerating voltage U_o. Similarly, permitted variations ΔH of the magnetic field H_o can be expressed:

$$\Delta H/H_o<1/2A \qquad (7).$$

Factor 1/2 is derived from the square root relationship of field strength and mass.

A voltage source for accelerating voltage and for the magnetic field current thus needs to be stabilized only to about 0.1 percent, which is no particular problem. In a known ion mass analyzer, the impingement spot, at an acceleration voltage of 10 kv., is however twice as long as wide due to energy spread. In order to keep the side excursions of the impingement spot within reasonable limits, accelerating voltage and magnetic field must be stabilized to 0.01 percent which, however, is electronically complicated and expensive.

The mass analyzer in accordance with the present invention, in spite of energy spread, will yield an impingement spot of ions which is circular and even in spite of regulation of the supply voltage and current 10 times worse than that of known devices, no lateral excursion of the spot will occur.

The apparatus in accordance with the present invention may be used selectively either with an electron beam or with an ion beam. An additional electron source **30**, which is an electron generating system **36**, such as a known simple triode system, and an electrostatic or magnetic lens **38**, delivers an electron beam to a further magnetic field **32** rotating the beam by 180°. The required field strength, to rotate the electron beam by 180°, is only a few hundred Gauss, which is too little to affect the ion beam substantially or to cause noticeable deflection thereof. An X-ray spectrometer **34** is provided to analyze the impingement area for X-rays. The focal plane of the entrance side of the electrostatic or magnetic focusing lens **38** is coincident with the crossover region of the source **36**. The 180° rotating magnetic field provides an exit path to the electron beam which is coaxial with the axis of the condenser lens **18** for the ion beam and thus coaxial with the ion beam, for application to objective lens **22**, which simultaneously functions to focus the electron beam as well as the ion beam. The ion beam leaving magnetic field **14** is not substantially influenced by magnetic field **32**.

The construction of a combined electron microprobe and ion microprobe analyzer requires lenses which can be simultaneously, or selectively used to pass both electrons and ions and focus electron beams and ion beams. It is known that electrostatic lenses can focus selectively ions, as well as electrons, and, simultaneously, negative ions and electrons of equal

energy. A more versatile lens, useful in the apparatus of FIG. 1 and preferably utilized for lenses 18, 22 in the system is illustrated in FIG. 2.

The lens of FIG. 2 can function as a usual magnetic lens for electrons, and additionally as an electrostatic lens for ions; it may, additionally, be used simultaneously for electrons and for positive ions of comparable energy. A magnetic lens formed by a pair of pole shoes 40, 42, suitably magnetized or subjected to a magnetic field (permanent magnets, electro magnets and the like, and not specially shown). An aperture electrode 44 of nonmagnetic, electrically conductive material is located between the pole shoes and coaxially therewith. Electrode 44 is insulated from pole shoes 40, 42, and is subjected to a voltage U_L which differs from the potential of the pole shoes themselves which, preferably, are connected to a reference potential such as ground. The electrode 44, together with pole shoes 40, 42 forms an electrostatic lens.

The operation of the lens of FIG. 2 can be adjusted to focus positive ions and electrons simultaneously. First, the required positive potential to focus the positive ions is placed at the center, or aperture electrode 44, the other terminal being connected to both pole shoes 40, 42, for example ground. FIG. 3 is a graph illustrating the refractive power D/f of an electrostatic lens with respect to the ratio of lens voltage U_L as measured against ion source potential to accelerating voltage U_o of the ions. For literature reference, see V.K. Zworykin et al., "Electron Optics and the Electron Microscope," New York 1945 and 1948. To focus the ions, a predetermined working point X will be established; as can be seen, point X is at the left branch of the curve, where the relationship $U_1/U_o<1$; in the example given, $U_L/U_o=0.2$. The refractive power $D/f=0.3$. A similar refractive power of $D/f=0.3$ occurs at the right branch of the curve, where $U_L/U_o>1$. This is valid now for electrons, in which $U_L/U_o=2.5$, that is for electrons having an energy $eU_o=eU_L/2.5$. Thus, positive ions of energy 10 kev. and electrons of energy 4 kev. are focused, the operation for the ions being at the left branch of the curve and for electrons at the right branch. If the energy of the electrons is increased, the working point will move on the right branch of the curve to the left from point Y, until for energy of infinity $U_L/U_o=1$. For electrons of this energy region, the refractive power of the lens is thus less than for the ions of 10 kev. energy. In this region, the refractive power of the lens for the electrons can be increased by addition of a magnetic field generated between pole shoes 40, 42, acting as magnetic lens, until it is the same as for the ions, so that simultaneous focusing of ions and electrons can be achieved. The ions are not essentially influenced by a magnetic field of the strength required to focus the electrons. If required, the focus of the ions can be adjusted somewhat by the lens voltage.

In order to have the ion beam of the desired mass leave the magnetic field 14 coaxially with lens 18, the diaphragm 16 should be positioned in the middle between the axes of lenses 12 and 18, where the crossover for the desired ions occurs. The aperture itself should be a slit of variable width perpendicular to the pole faces, positioned at a distance from the common entrance and exit boundary plane that is half the distance between the axes of lenses 12 and 18. The dashed line 15 within the magnetic field 14 indicates the position of the mass spectrum. The ions not transmitted through the slit are intercepted by diaphragm 16. Movement of the aperture 16 transverse of the field or parallel to the mass spectrum (line 15), can be obtained by any devices well known in the art, and is schematically indicated by arrow 17. Change in the aperture size is indicated by arrows 17'.

Housings, evacuating apparatus, and other auxiliary devices well known in the art have been omitted from the showing of the drawing, to simplify the presentation. Such apparatus, itself, is well known in the art and for further details of structures and apparatus, known by themselves, reference is made to the literature referred to in the specification above.

The target 24 may be a test sample, or a work piece if the microprobe is used in analytical apparatus. The use is not so limited, however, since the apparatus could also be used for implantation work, for example doping of semiconductors, ion beam machining, or other applications.

I claim:

1. An apparatus adapted to receive a divergent beam of ions emerging with various energies from an ion source, and directing a focused beam of ions of a selected mass onto a small spot on a target (24), said apparatus comprising:
- a first electrostatic lens (12) receiving said ions from said source (10) and delivering a parallel ion beam;
- a magnetic deflection field means receiving said parallel beam, deflecting said beam by 90° and forming, at an image location (15), images of said ion source, each image corresponding to a selected ion mass, further deflecting the ions emerging from a selected image for another 90° and producing thereby a second parallel beam which emerges from said magnetic deflection field means;
- an aperture means (16) located at the image location and passing only ions which form the selected image; and
- a second electrostatic lens (18) receiving said second parallel beam and focusing said beam into a second image (20) of said source, so that said second image (20) may be either the small spot on the target or the spot, available to be focused by a further lens means (22) onto said target.

2. Apparatus according to claim 1, including an electronic lens (22) parallel to said target, the position of the lens with respect to said target being adjustable.

3. Apparatus according to claim 1, wherein the aperture opening of said aperture means (16) is adjustable.

4. Apparatus according to claim 1, additionally focusing an electron beam further comprising
- a second 180° magnetic field means (32) located in the path of said electron beam and deflecting said electron beam as a parallel beam into a path coaxial with the path of said ion beam, said second magnetic field deflecting means being located at a position between said magnetic deflection field (14) and said target (24).

5. Apparatus according to claim 4, wherein said second field is located to be additionally in the path of said ion beam.

6. Apparatus according to claim 5 wherein the second 180° magnetic field is of insufficient strength to substantially affect the path of the ion beam.

7. Apparatus according to claim 6, wherein said ion lens assembly (18) comprises (FIG. 2) a pair of pole shoes (40,42) having a magnetic field therebetween;
- a nonmagnetic electrode (44) located between said pole shoes and electrically insulated therefrom;
- and means applying an electric field between said electrode and said pole shoes.

8. Apparatus according to claim 4, wherein said ion lens assembly comprises a combined magnetic and electrostatic lens.

9. Apparatus according to claim 4, including a condenser lens assembly (22) located in the path of said ion beam and said coaxial electron beam and in advance of said target.

10. Apparatus according to claim 7, wherein said condenser lens assembly (22) comprises (FIG. 2) a pair of pole shoes (40,42) having a magnetic field applied therebetween;
- a nonmagnetic electrode (44) located between said pole shoes and insulated electrically therefrom;
- and means applying an electric field between said electrode and said pole shoes.

11. Apparatus according to claim 4 including a mass spectrograph (26) sensitive to secondary ions and means (34) analyzing X-rays emitted by said target upon irradiation by said beam.

12. Apparatus according to claim 1 including analyzing means (26) determining the generation of secondary ions by the target upon irradiation by the beam of selected ions.

* * * * *