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R. F. K. HERZOG

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MASS SPECTROMETER

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FIG. 1

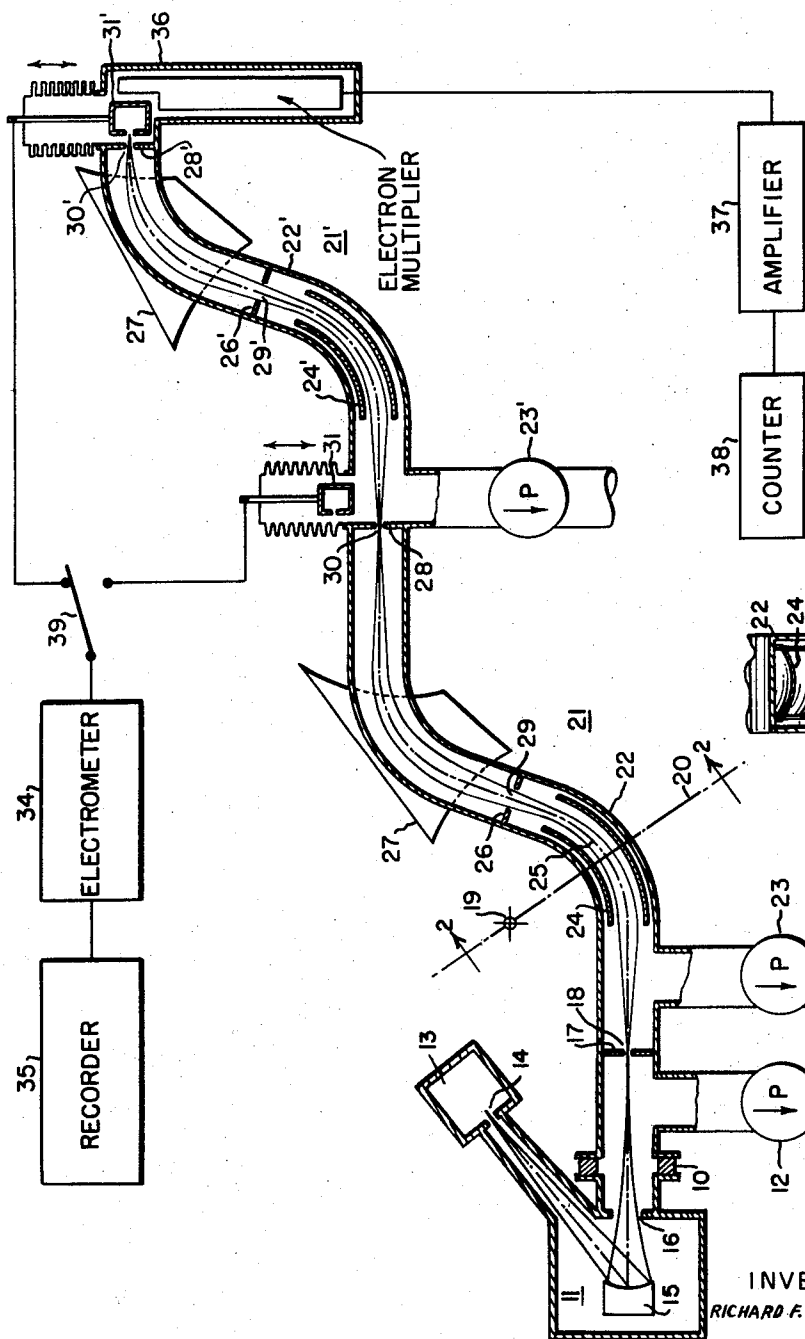


FIG. 2

INVENTOR
RICHARD F. K. HERZOG

BY. KENWAY, JENNEY, WITTER & HILDRETH

ATTORNEYS

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2,947,868

MASS SPECTROMETER

Richard F. K. Herzog, Lexington, Mass., assignor to Geophysics Corporation of America, Boston, Mass., a corporation of Massachusetts

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23 Claims. (Cl. 250—41.9)

The invention relates to a new and improved mass spectrometer, in particular to a mass spectrometer of high sensitivity for the analysis of minute trace impurities in solids.

Extensive research on the properties of materials in the solid state has revealed the importance of minute amounts of impurities which may be present in these materials. Concentrations of impurities as small as one part in 10^9 or 10^{10} may exert a very large influence on the properties of a material, particularly on its electrical properties. Presently available mass spectrometers are generally incapable of providing reliable measurements of the presence of such small amounts of impurities. This is due in large part to their limited sensitivity and resolution, as well as to the practical difficulties encountered in measuring extremely small current intensities.

The sensitivity of an instrument is primarily a function of the existence of "background" which may be considered analogous to noise in conventional electrical measurements. Background can be considered as falling into one of two types, i.e. general or continuous background and line background. Thus, in a plot of current intensity (number of ions per second) against atomic mass, the general background will appear as a more or less continuous quantity of varying amplitude superimposed on the general plot. The line background, on the other hand, will appear as separate lines opposite the respective atomic weights of the impurities which are present in addition to the particular trace impurity analyzed. The latter, of course, also appears as a line opposite its atomic weight.

The general background is produced in large part by ions which have collided with molecules of the residual gas in the spectrometer enclosure, as well as by ions which have been reflected from the walls of the enclosure. This type of background can be reduced by improving the vacuum within the spectrometer and by traps and baffles which either prevent ions from hitting the walls or which catch reflected ions before they can reach the collector.

The line background is produced primarily by impurities released from the walls and gaskets of the instrument, particularly those of the ion source. It may also derive from the residual gas in the ionization chamber. This background can be reduced by thoroughly de-gassing the instrument at high temperatures and by eliminating all organic materials such as occur in gaskets, insulators, stopcock grease and vacuum pump fluid. A considerable improvement can be brought about by employing mercury diffusion pumps in place of the more conventional oil diffusion pumps. The mercury background is limited to a few mass numbers and therefore produces very little interference with the detection of the impurities under investigation. On the other hand, the line background of oil diffusion pumps covers many mass numbers and characteristically varies strongly from one mass number to another. Such a condition is undesirable since it produces uncertainty in the detection limit of the different impurities analyzed.

The prior art discloses many examples of instruments

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which employ techniques aimed at improving the performance of standard mass spectrometers. In general, these measures are directed at improving the sensitivity and the resolution of the instrument. Thus, Thomson's well-known parabola spectograph was improved in two ways: (1) by A.J. Dempster who employed a single magnetic field transverse to the ion beam for the purpose of obtaining optical focusing by means of beam deflection; ("A New Method of Positive Ray Analysis," Physical Review, vol. 11, page 316, 1918); and (2) by F. W. Aston who added a transverse electric field in order to obtain velocity focusing, ("A Positive Ray Spectrograph," Philosophical Magazine, vol. 38, page 70, 1919). Velocity focusing compensates for the unequal energies of the ions in the spectrometer which may be due to the finite size of the source or due to collisions of the ions with residual gas molecules. Another expedient which has been employed to improve spectrometer performance is the use of special fields to obtain anastigmatic focusing. ("Mass Spectrograph with Anastigmatic Focusing," Zeitschrift für Naturforschung, vol. 8a, page 191, 1953.)

It has also been proposed to combine two electric fields and one magnetic field in order to improve the resolution of mass spectrometers. ("Increase of the Resolving Power of Mass Spectrographs," Physikalische Zeitschrift, vol. 39, page 463, 1938.) Two-stage mass spectrometers, wherein each stage employs a single magnetic field, have been used for special purposes. (Handbook of Mass Spectroscopy, by Inghram and Haydn, Publication 311, page 24. National Research Council. Published 1954.) In one application of this instrument the general background was reduced by the pre-selection of one ion species with an attendant increase in the sensitivity of measurement. One of the disadvantages of this 2-stage instrument, which is attributed to Inghram and Hess, is that the second stage must be at a considerably higher potential than the first stage because of the additional acceleration potential applied to the ion beam in the second stage. Such an arrangement represents a serious limitation which impairs the general utility and the flexibility of the instrument. Another purpose for which the above instrument has been successfully used is the investigation of collision processes. In this case, the deflection field of the first stage was used to select a special type of bombarding ion ("monochrometer") and the deflection field of the second stage was used to analyze the collision products ("spectrometer").

None of the foregoing techniques has been entirely successful to provide an instrument which is capable of carrying out reliable measurements of minute amounts of impurities. An instrument which is adapted for such measurements must not only have an extremely high sensitivity coupled with a coefficient of transmission that approaches unity, but must further provide good resolution and a wide dynamic range.

Accordingly, it is the primary object of this invention to provide an improved mass spectrometer which overcomes the disadvantages of prior art instruments and which is adapted to carry out reliable measurements of minute amounts of impurities to aid in the analysis of trace impurities in solids.

This and other objects of the invention, together with the novel features and advantages thereof, will become apparent from the following detailed specification with reference to the accompanying drawing, in which:

Fig. 1 illustrates a preferred embodiment of the invention; and

Fig. 2 is a cross-sectional view of the apparatus of Fig. 1 taken along line 2—2.

In brief, the invention herein comprises a multi-stage, high-resolution mass spectrometer which has a coefficient of transmission that approaches unity. Optical as well as

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velocity focusing is carried out in each stage by the use of transverse magnetic and electric fields separated by a slitted diaphragm in order to limit the energy spread. The stages preceding the final stage serve to reduce the background in the final stage by pre-selecting the desired ion species. They are further operative to focus a two-dimensional image of the diaphragm slit which initiates the first stage, at the locus of the initial diaphragm slit of the final stage. With this instrument, very high sensitivity measurements can be carried out without compromising either the high resolution or the wide dynamic range required.

Fig. 1 illustrates a preferred embodiment of the invention herein. A pump 12 provides a medium vacuum region of about 10^{-5} mm. of mercury in an enclosed chamber 11. Ions from an argon ion source 13 pass through the opening of a diaphragm 14 to form an intense argon beam which is accelerated to an energy of about 20 kev. The argon ion beam is directed at a sample 15 whose trace impurities are to be analyzed and produces sputtering and ionization. Ions of the sample which are released as a result of the bombardment by the argon beam are drawn from the sample by a small electric field and pass through opening 16 to form an ion beam. An acceleration potential of the order to 10 to 20 kev. is applied across an insulator 10 in the direction of the beam to accelerate the ions. The apparatus required to apply the aforesaid electric field and acceleration potential is conventional and well known in the art and has been omitted from the drawing for the sake of clarity. A diaphragm 17, which has a discriminating slit 18, separates the medium vacuum region from the first stage which is generally indicated by the reference numeral 21. A pump 23 maintains the stage 21, which is defined by an envelope 22, at a vacuum pressure of the order of 10^{-7} mm. Hg. The stage is sealed with metal gaskets in order to reduce the general background and to permit thorough degassing of the system at high temperatures. A toroid condenser 24, adapted to apply an electric field transverse to the ion beam, is positioned as shown in the drawing with respect to the beam path. This path is indicated by the optical beam axis 25 which generally coincides with the true beam axis. The condenser consists of a pair of spaced, concentrically curved, conductive surfaces. The radius of the condenser surfaces in the plane of the drawing, i.e. about the point 19 on the broken line 20, differs from the radius of curvature in a plane normal thereto, i.e., a plane whose trace in the plane of the drawing is indicated by the line 20. This is shown more clearly in Fig. 2. A diaphragm 26 which has a discriminating slit 29 is disposed in the envelope 22 subsequent to the toroid condenser. A pair of identically shaped, parallel pole pieces 27 is stationed subsequent to the diaphragm 26 along the path of the ion beam. In the preferred embodiment shown, the pole pieces are spaced from each other in a direction normal to the plane of the drawing so that the envelope 22 is disposed between them. With this arrangement the necessity for withdrawing the pole pieces during the degassing procedure is obviated. A diaphragm 28 terminates the stage 21. A discriminating slit 30 in the diaphragm communicates with the subsequent stage 21'. An ion collector 31 which consists of a conventional Faraday cage, is shown in its withdrawn position but may be positioned in the path of the ion beam behind the slit 30 as indicated by the double-ended arrow in the drawing. It is connected to one terminal of the switch 39.

The stage 21' is substantially identical in construction to stage 21, corresponding parts having been labeled with prime reference numerals. A pump 23' maintains a vacuum pressure of the order of 10^{-9} mm. Hg in stage 21' in order to reduce the continuous background as far as possible. A ion collector 31' is positioned subsequent to a diaphragm 28' which terminates the stage 21'.

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The ion collector 31' is also retractable as indicated by the double-ended arrow in the drawing and is connected to the other terminal of the switch 39. The switch is coupled to a vibrating reed electrometer 34 which, in turn, is connected to a recorder 35. An electron multiplier 36 is positioned to receive ions through the discriminating slit of diaphragm 28' when the ion collector 31' is in its withdrawn position. The electron multiplier is connected to an amplifier 37 which, in turn, is connected to a counter 38.

In operation, the ions from the argon source 13 bombard the sample 15 to cause sputtering and ionization at the surface thereof. The ions released from the sample are drawn away by the application of the small electric field and are accelerated toward diaphragm 17 by the application of an acceleration potential in this direction. The two-dimensional discriminating slit 18 of the diaphragm 17 serves as the object of the ion-optical lens system and thereby determines the shape of the ion beam in subsequent spectrometer stages.

A transverse deflecting force, i.e. a force normal to the optical beam axis 25, is applied to the ion beam which passes between the plates of toroid condenser 24. This deflecting force is produced by the electric field which is applied between the plates. It is operative through an angle centered about the plane of the drawing which depends on the curvature of the condenser plates. The effect of the electric deflecting force on the beam in the plane of the drawing is to bend the beam in an upward direction. Depending on the energy of the respective ions, the radius of the curvature of the respective ion paths differs between the plates of the condenser. The curvature of the toroid condenser surfaces in the plane which is normal to the plane of the drawing and which is represented by the trace 20, cooperates with the curvature in the plane of the drawing to concentrate the ion beam in all directions and prevents the ions from striking the walls of the envelope 22. This action is different from that which takes place in more conventional mass spectrometers wherein the deflecting fields act only as cylindrical lenses. As such, they concentrate the ion beam in only one direction and permit it to strike the walls of the envelope due to beam divergence in other directions. In contradistinction, the toroid condenser in the present invention concentrates the beam in all directions. This concentrating effect becomes particularly important in the narrow space between the pole pieces 27.

The actual amount of optical focusing which takes place in the toroid condenser alone is relatively small. As can be seen from the drawing, a certain amount of dispersion actually takes place after the beam leaves the toroid condenser. The ion beam is also subjected to a certain amount of velocity dispersion in the condenser alone. The primary function of the toroid condenser is to cooperate with the subsequently disposed magnetic field to bring about velocity focusing of ions of the same mass and of different energies. As a result of this cooperation a transmission coefficient with approaches unity for the stage is obtained. The transmission coefficient may be defined as the ratio between the number of ions passing through slit 30 to the number of ions entering slit 18 when the fields are adjusted for the passage of a given ion species. By the proper use of a toroid condenser in cooperation with suitably shaped pole pieces the effective lens opening is enlarged by approximately two orders of magnitude. This is equivalent to doubling the beam intensity without the loss of any resolution. Where trace impurities of the order of 1×10^{-9} or 1×10^{-10} are to be detected, the ability to double the beam intensity represents a very important advance over the prior art.

An improvement in the resolution as well as in the dynamic range of each stage is achieved by the use of discriminating slits between the deflecting fields, such as the slit 29 of diaphragm 26. The dynamic range can

be defined as the ratio of the largest and smallest intensity peaks which can be measured. The diaphragm 26 rejects all ions which have an excessive energy deviation and which have been in collision with the walls or with residual gas molecules. As a result, only such ions are admitted to the magnetic deflecting field as can be focused by the latter to produce a sharp image at slit 30. The action of slit 30 in diaphragm 28 is similar to that of slit 29. Its primary function is to reject ions which have been in collision in the magnetic field. The improved resolution and dynamic range obtained contributes materially to the increased sensitivity of the instrument.

The transverse magnetic field set up by the spaced pole pieces 27 in a direction normal to the optical beam axis 25 applies a deflecting force in the plane of the drawing to the ion beam which is opposite in direction to that applied by the toroid condenser. The pole pieces are shaped so as to provide the maximum beam width for the minimum image distortion, as well as to account for the effects of the fringing magnetic fields. In addition to its function in cooperation with the toroid condenser to bring about velocity focusing of the ion beam, the magnetic deflecting field is shaped to bring about optical focusing at the discriminating slit 30 of the ion beam received from the toroid condenser. It will be understood in this context, that the beam deflecting forces of the shaped magnetic field are not only applied to the plane of the drawing. A deflecting force normal to the plane of the drawing is exerted on all ions, which fail to enter the magnetic field in a direction normal to a tangent to its edge.

The action of the mass spectrometer which forms the subject matter of this invention is, to a certain extent, analogous to the action of an optical lens system. The properties of such a system can be more readily improved by combining a large number of single lenses than by attempting to incorporate all the desired corrections in a single lens. Indeed, it is frequently impossible to obtain the desired characteristics within the practical limitations of a single lens. The same situation holds true for a mass spectrometer wherein the action of the individual deflecting fields for the purpose of this discussion, may be considered as being analogous to that of the lenses in the optical system. In the case of an optical lens system the sensitivity of the instrument depends on the largest opening of the discriminating slits which may be used while retaining sufficient resolution. Since a wider aperture requires better correction of any spherical aberrations, a larger number of lenses is generally called for. Similarly, in the case of the mass spectrometer, the larger the effective aperture, the greater is the number of deflecting fields required. Since, in order to measure minute trace impurities, the maximum intensity consistent with high resolution is required, a large effective aperture is necessary.

The overall effect resulting from the cooperation of the toroid condenser 24, the slit 29 and the magnetic pole pieces 27 of the stage 21, is to act as an ion-optical lens system which produces a sharp, two-dimensional image of the initial discriminating slit 18 at the locus of the terminating discriminating slit 30. The action which takes place in the stage 21 thus serves a dual function. While keeping the stage 21' as clean as possible of the background-producing ions by admitting only properly selected ions, it simultaneously permits an extremely high vacuum to be maintained in the stage 21'. This condition again tends to reduce the background at the output and thus results in an improved sensitivity.

The collector 31, which is positioned immediately behind the slit 30, is used only for purposes of adjustment in order to obtain the proper output from the stage 21. During this measurement the collector 31 is connected to the electrometer 34 by means of the switch 39. After suitable adjustments have been made, the switch 39 is

returned to the position shown in the drawing. The collector 31 is withdrawn and the beam is permitted to enter the stage 21' where substantially the same process is repeated as was described in connection with stage 21. The ion collector 31' is also retractable and is used only for the purpose of measuring the principal constituents of the sample. When in use, the ion current actuates the vibrating reed electrometer which in turn produces a measurement at the recorder 35. Magnitudes of the order of 10^{-10} amperes can be measured in this way. For the purpose of obtaining a measurement of the minor constituents of the sample a counting technique is employed with the aid of the electron multiplier 36. The output of the multiplier is amplified and is applied to the counter 38. With this technique the smallest ion current which can be measured with fairly good statistical accuracy (about 10%) after a counting time of the order of two minutes, is approximately one ion per second, or 10^{-19} amperes.

It will be readily understood that the use of more than one instrument stage brings about a material improvement in the sensitivity of measurement. Thus, if the continuous background in each stage superimposed on the trace element under analysis is 10^{-5} of the main peak (the latter being defined as the intensity level at the atomic mass of the main constituent), a combination of two stages reduces this background to about 10^{-10} of the main peak. The addition of more stages will bring about a further reduction of the background. Due to the extremely small ion current which is to be measured, it is important that the transmission coefficient of each stage approaches unity. If this condition is not met, the loss of amplitude of the output current of a multi-stage instrument may conceivably offset the reduction in the general background.

Numerous modifications may be made in the multi-stage mass spectrometer disclosed herein without departing from the scope of the invention. It will be readily understood that the transverse deflecting fields applied by the toroid condenser and by the magnetic pole pieces respectively, need not necessarily deflect the beam in opposite directions. For example, beam curvature in the same sense may be effected to cause the beam to double back on itself.

It is not necessary for the envelope of each stage to conform to the beam path as shown in the drawing. Any convenient shape may be adopted, provided it can be kept at the proper vacuum pressure.

Neither the magnetic fields nor the electric fields are confined to the precise configuration disclosure herein. The determination of these fields will depend, in all instances, on the particular requirements of the measurement to be made.

Various ion sources may be used, provided only that a substantially mono-energetic, parallel beam of high and constant intensity is obtained. Thus, the sample may be evaporated in a small oven wherein ionization is brought about by electron impact or by a hot filament. The latter method is applicable for samples of low and medium melting points. Alternatively, a high frequency spark may be passed between two electrodes of the sample. This method produces a strong beam, even from samples having a high melting point. However, the intensity of the beam is subject to severe fluctuation which, under certain conditions, may make precise quantitative analysis difficult. The embodiment illustrated in Fig. 1 employs the method of sputtering by ion bombardment. In this technique the ion current is relatively constant since it does not depend to any great extent on the melting point of the sample. As such, this method has many advantages for use in mass spectrometers.

It will be seen from the foregoing disclosure that the multi-stage mass spectrometer which forms the subject matter of the invention herein combines the multiple

advantages of relatively high output current, a coefficient of transmission which is substantially unity, high resolution and wide dynamic range. An extremely high sensitivity is thus obtained which makes possible the precise and reliable measurement of minute trace impurities in solids which have defied reliable analysis heretofore.

Although a specific embodiment of the invention has been described and illustrated, the foregoing disclosure is for the purpose of illustration only. It will be understood that numerous modifications, departures and equivalents will now occur to those skilled in the art, all of which fall within the true spirit and scope of the invention.

I claim:

1. A mass spectrometer for operating on an ion beam, comprising at least two pairs of deflecting fields spaced along the path of said beam, each of said deflecting fields being adapted to apply transverse deflecting forces to said beam, means preceding said deflecting fields for applying an acceleration potential to said beam, and means positioned intermediate successively positioned deflecting fields to permit beam transmission through a predetermined opening only.

2. A mass spectrometer for operating on an ion beam, comprising at least two pairs of deflecting fields spaced along the path of said beam, said fields being adapted to concentrate said beam in a plane transverse thereto, and means preceding said deflecting fields for applying an acceleration potential to said beam.

3. A mass spectrometer for operating on an ion beam, comprising at least two pairs of transverse fields spaced along the path of said beam, said fields being adapted to concentrate said beam in a plane transverse thereto, and means positioned intermediate successive pairs of said fields to limit beam transmission to a predetermined opening.

4. A mass spectrometer for operating on an ion beam, comprising at least two pairs of transverse fields spaced along the path of said beam, said fields being adapted to concentrate said beam in a plane transverse thereto, and means positioned intermediate successive ones of said fields to limit beam transmission to a predetermined opening.

5. A mass spectrometer for operating on an ion beam, comprising a plurality of magnetic and electric deflecting fields spaced in alternation to determine the path of said beam, said fields being adapted to concentrate said beam in a plane transverse thereto.

6. A mass spectrometer for operating on an ion beam, comprising a plurality of magnetic and electric deflecting fields spaced in alternation to determine the path of said beam, said fields being adapted to concentrate said beam in a plane transverse thereto, and means positioned intermediate successive ones of said deflecting fields to confine beam transmission to a predetermined opening.

7. A mass spectrometer for operating on an ion beam, comprising at least two pairs of deflecting fields spaced along the path of said beam, each of said pairs including one magnetic and one electric field adapted to apply transverse deflecting forces to said beam.

8. A mass spectrometer for operating on an ion beam, comprising at least two pairs of deflecting fields spaced along the path of said beam, each of said pairs including one magnetic and one electric field adapted to apply deflecting forces transverse to said beam, and means positioned intermediate successive ones of said deflecting fields to permit beam transmission through a predetermined opening only.

9. A mass spectrometer for operating on an ion beam, comprising means for applying an acceleration potential to said beam, a plurality of sequentially disposed stages following said last recited means, a first discriminating slit separating said last recited means from the first one of said stages, each of said stages comprising velocity focusing means and optical focusing means and being termi-

nated by a discriminating slit, said focusing means being adapted to produce a two-dimensional image of said first discriminating slit at the locus of the discriminating slit which terminates the last stage.

10. A mass spectrometer for operating on an ion beam, comprising a plurality of sequentially disposed stages, means including a discriminating slit adapted to terminate each stage and couple it to the subsequent stage of said spectrometer, initial coupling means including an initial discriminating slit preceding said first stage, each of said stages including a shaped magnetic field adapted to apply transverse magnetic deflecting forces to bring about optical focusing of the ion beam entering said magnetic field, said magnetic deflecting forces being applied substantially parallel to a first plane to all ions entering said magnetic field within a predetermined angle of incidence, said magnetic deflecting forces being additionally applied in a plane normal to said first plane to all ions entering said magnetic field outside of said predetermined angle of incidence, each of said spectrometer stages further including an electric field adapted to apply transverse deflecting forces to said beam, said electric deflecting forces being applied throughout a predetermined angle centered about said first plane, said electric field being adapted to cooperate with said magnetic field to bring about velocity focusing of said beam, whereby a two-dimensional image of said initial discriminating slit is focused at the locus of the terminating discriminating slit of each stage.

11. The apparatus of claim 10 wherein said electric field of each stage precedes said magnetic field, and further comprising means including a discriminating slit disposed intermediate the respective deflecting fields of each stage, said last-recited discriminating slit admitting only that portion of said beam to said magnetic field which can be focused by the latter.

12. The apparatus of claim 10 wherein said spectrometer is housed in an envelope, each of said discriminating slits being disposed in a diaphragm, said diaphragms separating successive stages within said envelope from each other while permitting communication through said discriminating slits, and means for maintaining successive stages of said spectrometer at an increasingly higher vacuum.

13. A mass spectrometer for analyzing the trace impurities of an ion beam derived from a sample in the solid state, comprising a plurality of stages each defined by an envelope and separating diaphragms, each of said diaphragms comprising a discriminating slit adapted to pass a predetermined portion of the impinging ion beam, means for maintaining successive spectrometer stages at increasingly higher vacuum pressures, means for pre-selecting the ions of the desired trace impurity against the background in the spectrometer section prior to the final stage, said pre-selecting means including optical and velocity ion focusing means, said focusing means being adapted to produce an image of the initial discriminating slit of the first one of said spectrometer stages at the locus of the initial discriminating slit of said final stage, said final stage including electric and magnetic fields to apply transverse deflecting forces to said beam, said deflecting forces being adapted to produce anastigmatic velocity focusing and optical focusing of said beam, a diaphragm disposed intermediate said fields, said last-recited diaphragm including a discriminating slit adapted to admit only those ions to said magnetic field capable of being focused by the latter, whereby the two-dimensional image of the initial discriminating slit of said first stage appears at the locus of the terminating slit of said final stage substantially free from said background.

14. The apparatus of claim 13 and further comprising means for applying an acceleration potential to said ion beam prior to said first stage only, and means for measuring the ions passing through the terminal slit of said final stage.

15. A multi-stage mass spectrometer for operating on an ion beam which emanates from an initial discriminating slit coupled to the first stage, successively disposed stages being coupled to each other by means of respective discriminating slits, each of said stages comprising means for providing a magnetic deflecting field preceding the terminating discriminating slit thereof, said magnetic deflecting field being shaped to produce optical focusing of the entering ion beam by the application of transverse magnetic deflecting forces, said magnetic deflecting forces being substantially confined to a first plane when the angle of incidence of said beam with respect to said magnetic field falls within a predetermined range, said magnetic field being adapted to apply magnetic deflecting forces in a plane normal to said first plane when the beam angle of incidence falls outside said range, said last-recited means comprising a pair of parallel magnetic pole pieces spaced from each other in a direction normal to said first plane to contain said ion beam therebetween, said magnetic field being applied between said spaced pole pieces, means for providing an electric field disposed intermediate the initial coupling slit of said stage and said magnetic field to apply transverse electric deflecting forces to said beam, said electric deflecting forces being substantially confined to an angle centered about said first plane, said last-recited means comprising a toroid condenser consisting of a pair of spaced, concentric curved surfaces disposed to contain said ion beam therebetween, said electric field being applied between said spaced surfaces, said electric field being adapted in cooperation with said shaped magnetic field to produce velocity focusing of said ion beam, whereby a two-dimensional image of said initial discriminating slit is focused at the locus of the terminating discriminating slit of the final spectrometer stage.

16. The apparatus of claim 15 wherein respective analyzer stages of said mass spectrometer are maintained at substantially the same potential, and further comprising a discriminating slit interposed between respective deflecting fields of each stage.

17. The apparatus of claim 16 and further comprising means for maintaining successive ones of said spectrometer stages at increasingly higher vacuum.

18. The apparatus of claim 15 and further comprising means for positioning an ion collector subsequent to the terminal coupling slit of each stage, each of said ion collectors being adapted to be withdrawn from the path of said beam, and means for measuring the ions obtained at each of said collectors.

19. A multi-stage mass spectrometer for operating on an ion beam, each of said stages comprising a first deflecting field adapted to apply transverse beam deflecting forces in an angle centered about a first plane, a second deflecting field for providing optical focusing of the entering beam, said second deflecting field being adapted to apply transverse beam deflecting forces substantially in said first plane upon beam incidence within a predetermined angular range, said second deflecting field being additionally adapted to apply transverse beam deflecting forces substantially perpendicular to said first plane upon beam incidence outside said angular range.

20. A multi-stage mass spectrometer for operating on an ion beam, each of said stages comprising a first deflecting field adapted to apply transverse beam deflecting forces in an angular range centered about a first plane, a second deflecting field for providing optical focusing of the entering beam, said second deflecting field being adapted to apply transverse beam deflecting forces substantially in said first plane upon beam incidence within a predetermined angular range, said second deflecting field being additionally adapted to apply transverse beam deflecting forces substantially perpendicular to said first plane upon beam incidence outside said angular range, the focal lengths of said first deflecting field being different in mutually perpendicular directions, and a discriminating slit coupling successively disposed stages.

21. A multi-stage mass spectrometer for operating on an ion beam, respective stages being maintained at substantially the same potential, each of said stages comprising a first deflecting field adapted to apply transverse beam deflecting forces in an angle centered about a first plane, a second deflecting field for providing optical focusing of the entering beam, said second deflecting field being adapted to apply transverse beam deflecting forces substantially in said first plane upon beam incidence within a predetermined angular range, said second deflecting field being additionally adapted to apply transverse beam deflecting forces substantially perpendicular to said first plane upon beam incidence outside said angular range, the focal lengths of said first deflecting field being different in mutually perpendicular directions, and a discriminating slit coupling each pair of successively disposed stages.

22. A multi-stage mass spectrometer for operating on an ion beam, respective stages being maintained at substantially the same potential, each of said stages comprising a first deflecting field adapted to apply transverse beam deflecting forces in an angle centered about a first plane, a second deflecting field for providing optical focusing of the entering beam, said second deflecting field being adapted to apply transverse beam deflecting forces substantially in said first plane upon beam incidence within a predetermined angular range, said second deflecting field being additionally adapted to apply transverse beam deflecting forces substantially perpendicular to said first plane upon beam incidence outside said angular range, the focal lengths of said first deflecting field being different in mutually perpendicular directions, a discriminating slit coupling successively disposed stages, said successively disposed stages being maintained at an increasingly higher vacuum.

23. A multi-stage mass spectrometer adapted for the analysis of minute trace impurities in solids, comprising a first chamber containing the sample to be analyzed, means for evacuating said chamber to maintain a predetermined vacuum pressure therein, means disposed in said chamber for producing ions of said sample, means for applying an accelerating potential to said ions to produce an ion beam, each of said stages comprising an envelope portion separated from the subsequent stage by a diaphragm, each of said diaphragms having a discriminating slit which communicates with the subsequent stage, means for evacuating each of said stages to a predetermined vacuum pressure, said last-recited means being adapted to maintain increasingly lower vacuum pressures in the successive stages of said spectrometer, a diaphragm separating said first enclosed space from the first stage, said diaphragm having a discriminating slit disposed in the path of said ion beam, each of said stages comprising a toroid condenser consisting of a pair of spaced, concentric curved surfaces, each of said surfaces having different radii of curvature in mutually perpendicular first and second planes, means for applying an electric field between said surfaces, said electric field being adapted to apply transverse deflecting forces to said beam in an angle centered about the first one of said mutually perpendicular planes, each of said stages further comprising a pair of shaped, spaced magnetic pole pieces parallel to said first plane, means for applying a shaped magnetic field between said pole pieces, said magnetic field being adapted to apply transverse deflecting forces to said beam in said first plane when the beam angle of incidence is substantially 90°, said magnetic field being additionally adapted to apply transverse beam deflecting forces in a plane normal to said first plane when the beam angle of incidence is not 90°, said fields being adapted to deflect said beam in said first plane substantially through mutually opposite angles, said electric field being adapted to bring about velocity focusing of said beam in cooperation with said shaped magnetic field, said magnetic field being

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adapted to bring about optical focusing of the entering beam to produce a two-dimensional image of the initial slit of each stage at the terminal slit thereof, a diaphragm having a discriminating slit disposed in the path of said beam intermediate said toroid condenser and said pair of pole pieces, said last-recited discriminating slit being adapted to admit only that beam portion to said magnetic field which is adapted to be focused, a retractable ion

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collector adapted to be disposed in the path of said beam immediately following the diaphragm terminating each of said stages, and measuring means adapted to be connected to the ion collector of each of said stages.

References Cited in the file of this patent

"Advances in Electronics and Electron Physics," vol. VIII, by Academic Press, Inc., New York, 1956 edition.

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 2,947,868

August 2, 1960

Richard F. K. Herzog

It is hereby certified that error appears in the printed specification of the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 3, line 25, for "to", first occurrence, read -- of --; column 4, line 58, for "with" read -- which --; column 7, line 59, for "on" read -- one --.

Signed and sealed this 4th day of April 1961.

(SEAL)

Attest: ERNEST W. SWIDER

~~XXXXXXXXXX~~
Attesting Officer

ARTHUR W. CROCKER
Acting Commissioner of Patents