

[54] X-RAY SOURCE

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Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 146,741, May 25, 1971, abandoned.

[52] **U.S. Cl.**..... 313/55, 313/330

[51] **Int. Cl.** **H01j 35/08**

[58] **Field of Search**..... 313/55, 330

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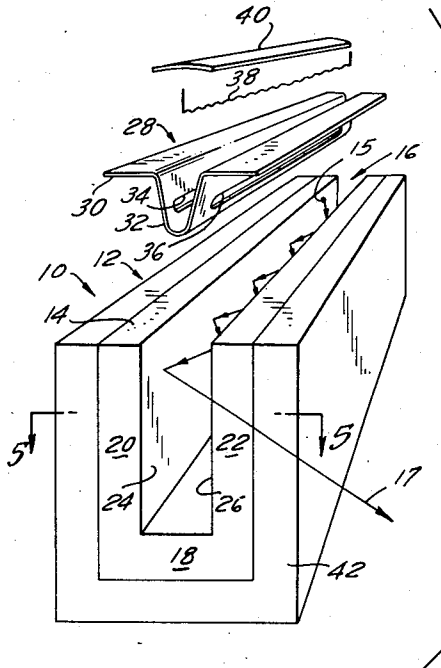
Attorney, Agent, or Firm—Patrick J. Walsh

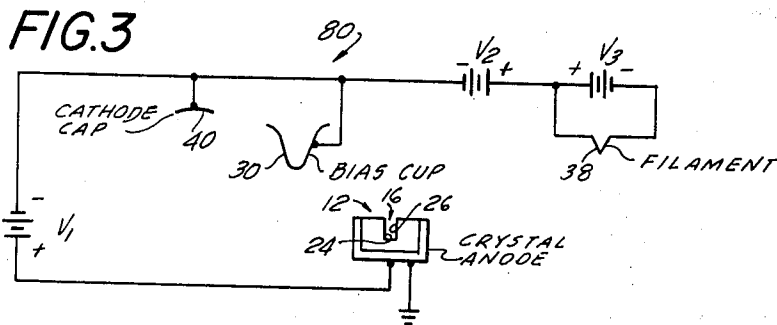
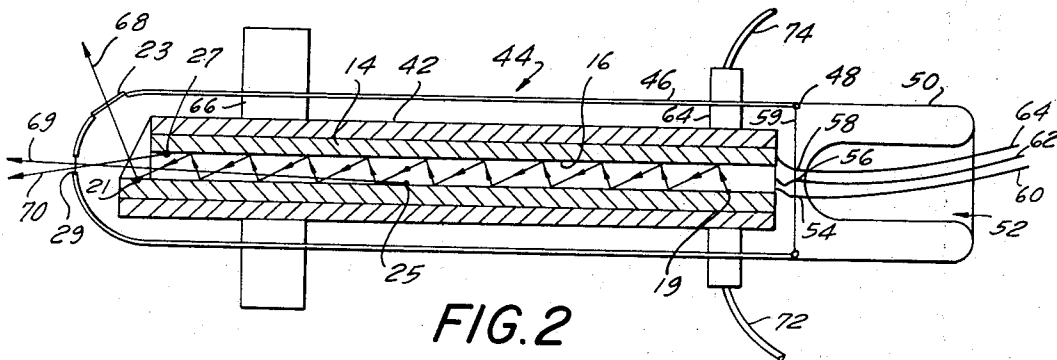
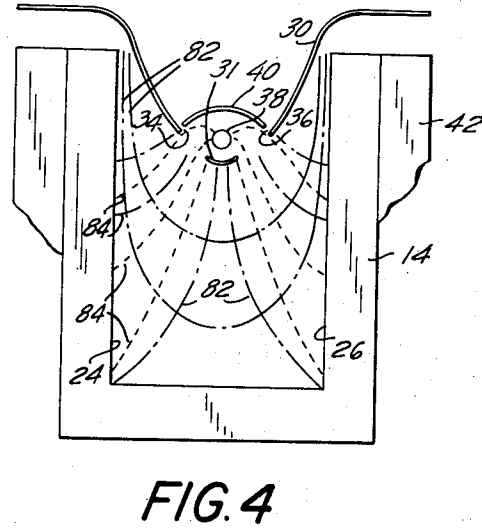
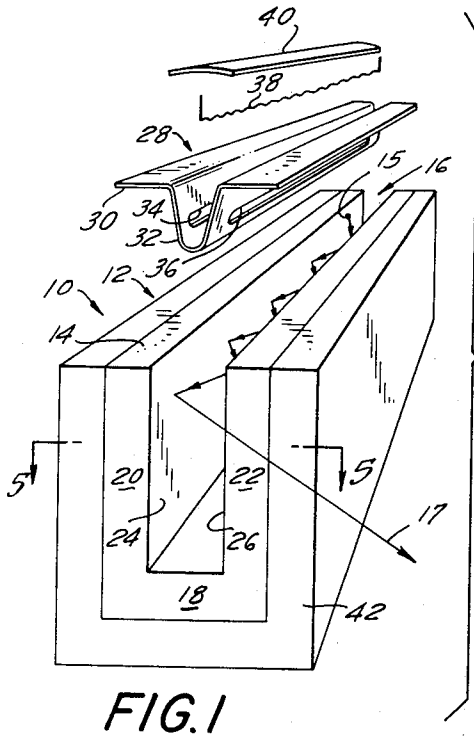
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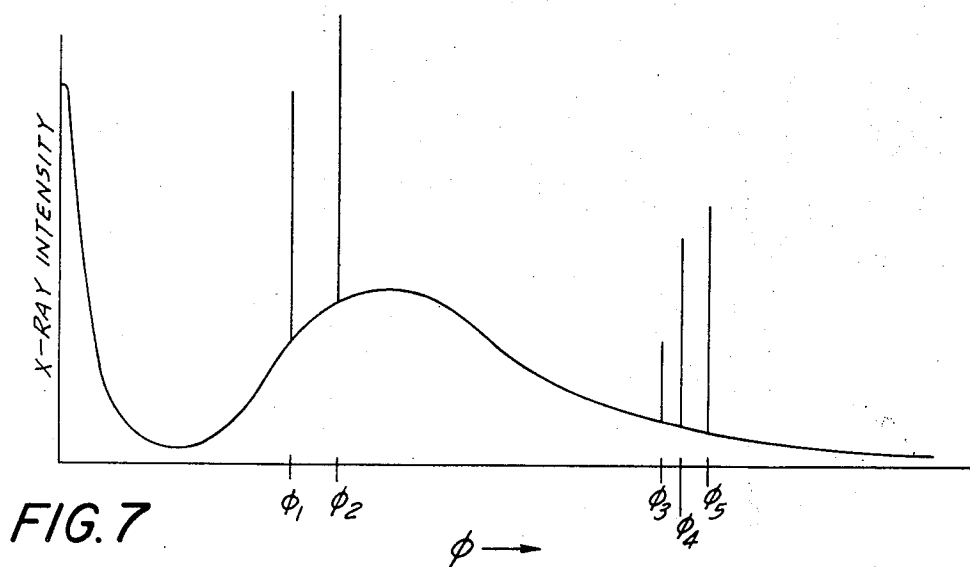
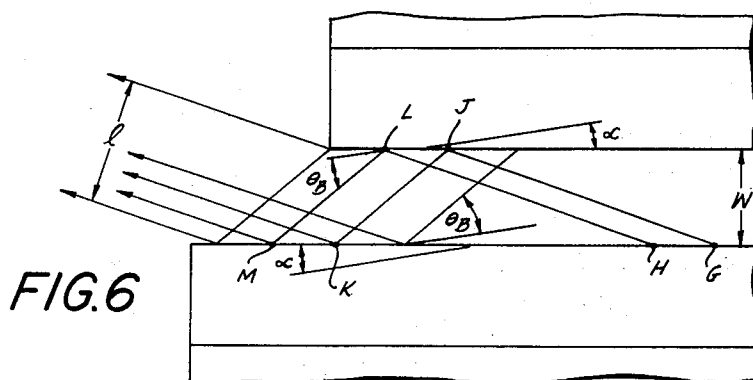
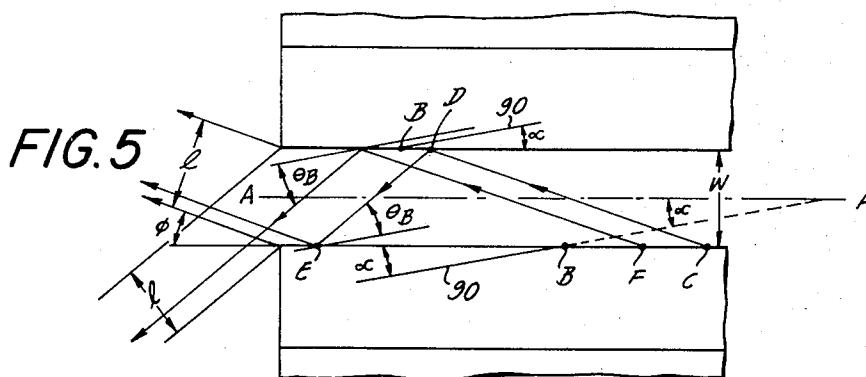
ABSTRACT

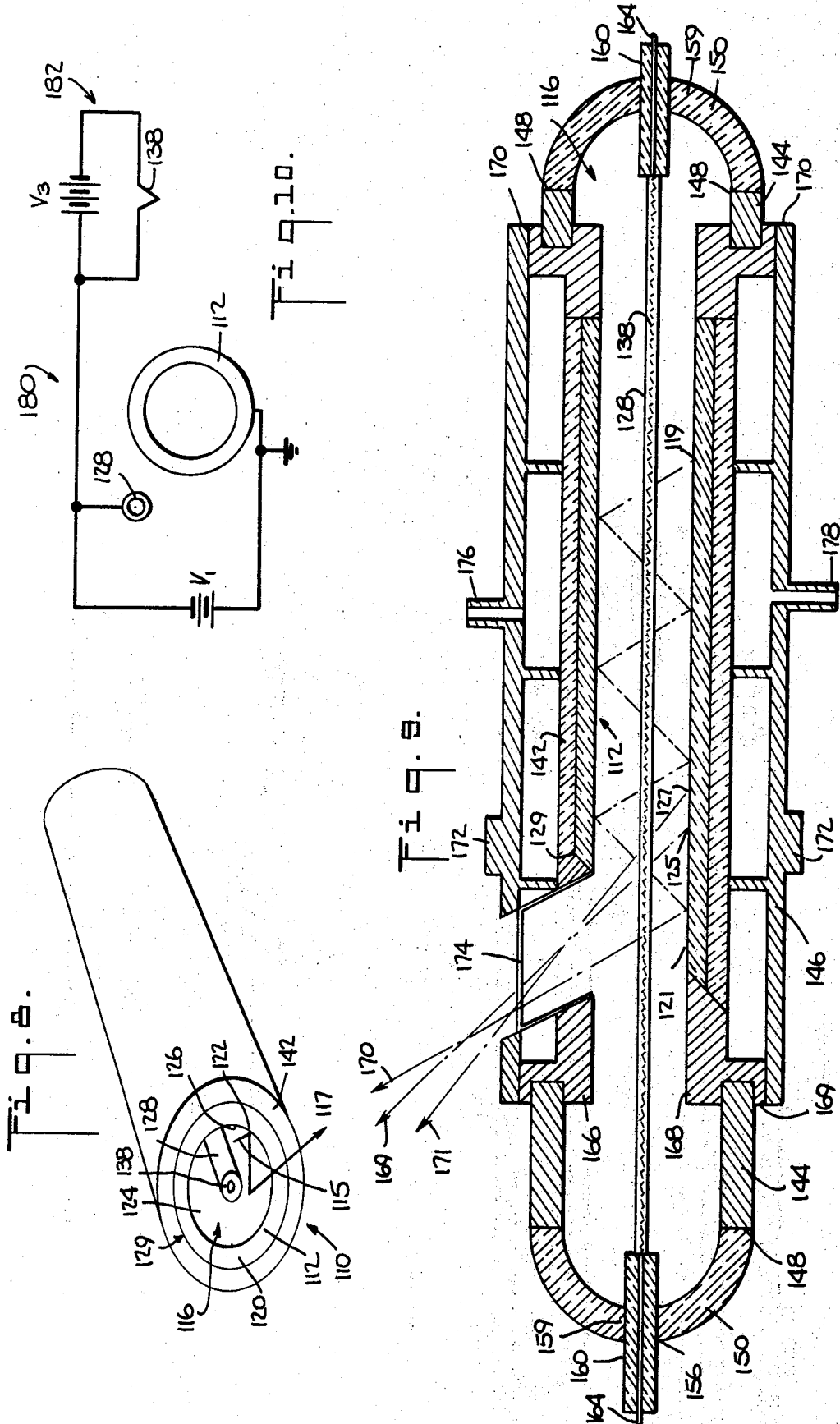
An x-ray source is disclosed for providing a brilliant, extremely low divergence, monochromatic x-ray beam. X-rays are generated by electron bombardment on the surfaces of a single crystal. The x-rays are subsequently repeatedly diffracted by an adjacent crystal surface. The x-ray beams emitted from the ends of the crystal in Bragg directions are monochromatic and with a divergence controlled by the diffraction process. The divergence of the emitted x-ray beams is independent of the final focal spot geometry. This permits heat transfer from a large x-ray emission area, a relatively large focal area but maintains a low divergence, high intensity and improved monochromaticity in the x-ray beam.

29 Claims, 16 Drawing Figures









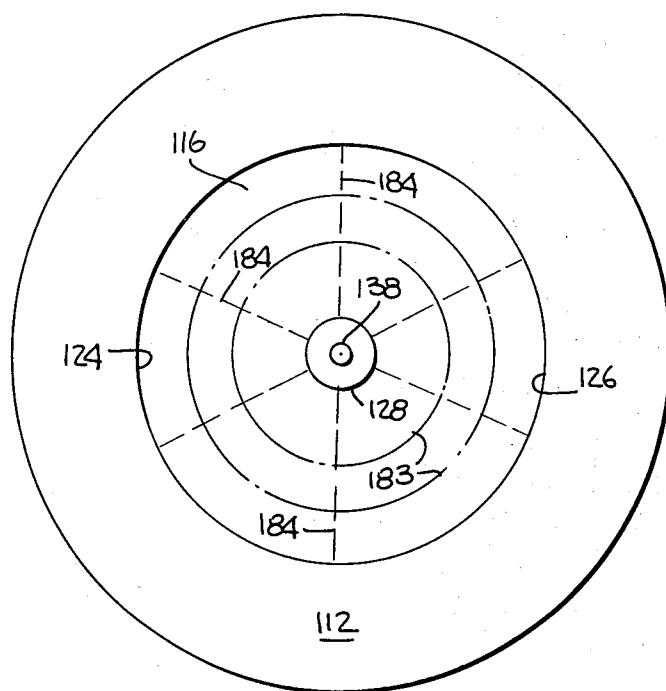


Fig. 11.

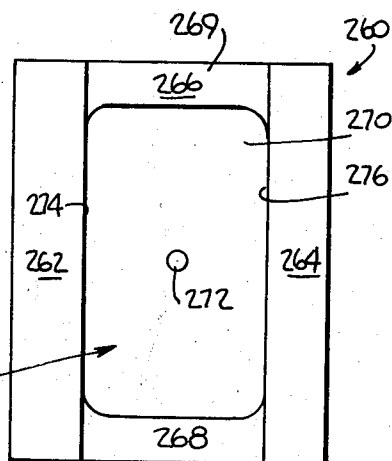


Fig. 14.

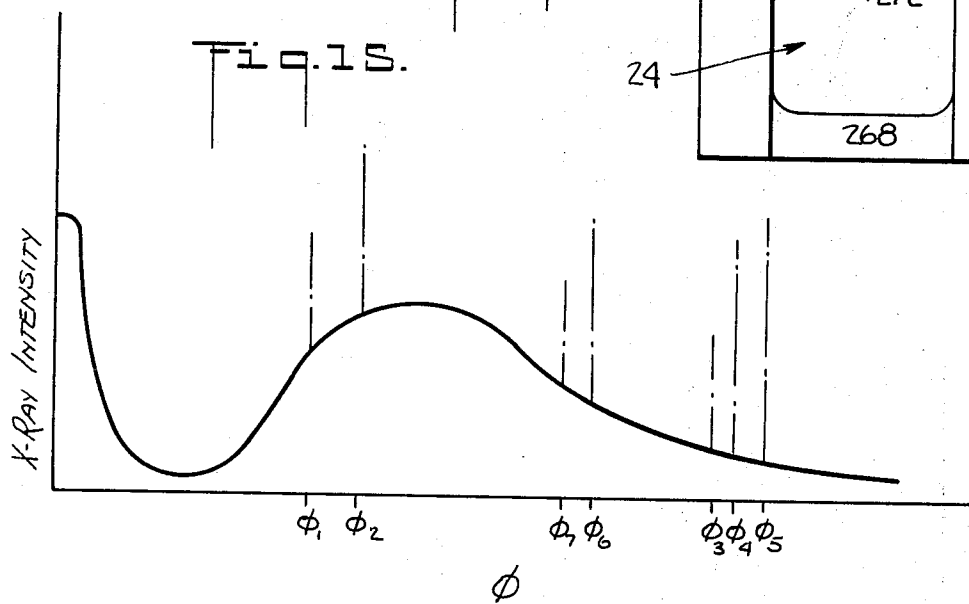


Fig. 15.

Fig. 12.

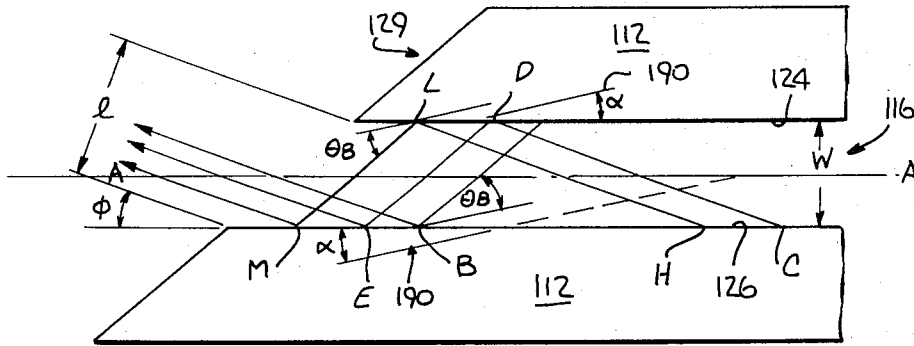


Fig. 13.

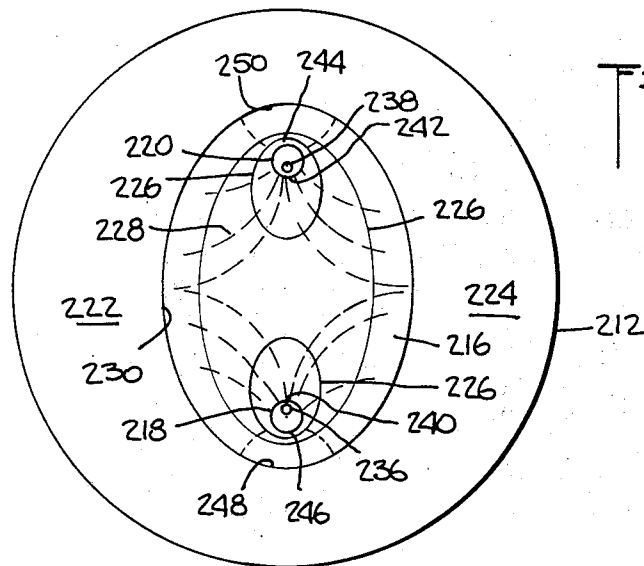
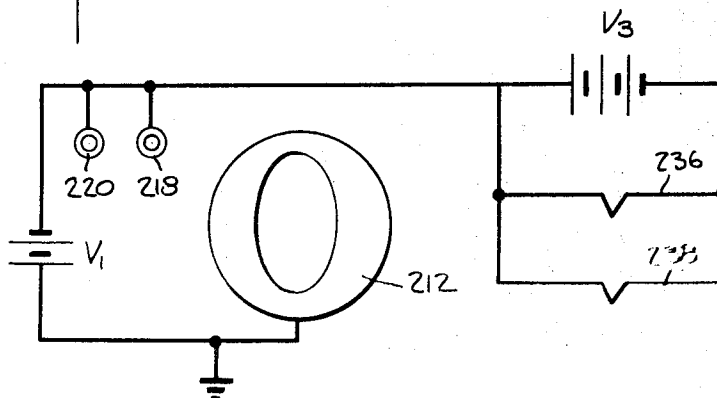


Fig. 14.



X-RAY SOURCE

This application is a continuation-in-part of application Ser. No. 146,741 filed May 25, 1971 now abandoned.

BACKGROUND OF THE INVENTION

In conventional x-ray equipment x-rays are generated by directing a fast stream of electrons to a focal spot which frequently is a flat, metallic surface. The production of x-rays through electron deceleration and/or electron ionization affects the spectral character of the x-ray generated. X-ray production from electron impact is extremely inefficient and consequently conventional x-ray sources have inherent limitations affecting quantity of the x-rays generated. Because of the extremely low efficiency of x-ray generation by electron bombardment, intense electron power must impinge on the focal spot to produce a brilliant x-ray source. The intensity of the electron power per unit area and consequently the brilliance of the x-rays are limited by the character of the material forming the focal spot. The intense electron power causes local heating, distortion and ultimately deterioration of the target in conventional x-ray sources. Metals like tungsten, platinum, molybdenum and copper, are often used as focal targets in x-ray tubes because of their high atomic number, high x-ray production efficiency, high melting points and/or high thermal conductivity. Still the efficiency of these tubes in converting the electron energy into x-ray photon energy is only one percent or so. The majority of the electron energy supplied to the focal area is carried off as heat to prevent the focal spot from melting.

The brilliance of the x-ray source, i.e., the x-ray emissivity per unit area, can be increased by decreasing the size of the focal spot and letting the surrounding metal more effectively cool the focal area. This is achieved by increasing the electron energy loading per unit area in the focal spot but it also decreases the total electron power input and the total x-ray power output. In commercial x-ray tubes a useable balance is achieved between the total x-ray intensity and the brilliance of the source. This balance will depend on the application of the particular x-ray tube.

Attempts to focus x-ray sources using lenses have been frustrated since all materials have an index of refraction at x-ray frequencies that differs from one only in the fifth figure. Thus, x-ray lens design is nearly impossible. Single crystal x-ray monochrometers can focus an x-ray beam and change the spectral distribution. The focusing of an x-ray beam using a monochrometer is accomplished by a bent single crystal diffracting the x-ray beam and focusing it into a localized area. This increases the intensity of some particular wavelength relative to other wavelengths but decreases the total brilliance of the x-ray source. Thus the demand for an intense, low divergence, x-ray source has been unsatisfied mainly because x-ray production by electron bombardment is a highly inefficient process.

X-ray applications in diagnostic radiography, therapeutic radiography, metallurgical diffraction and metallurgical radiography not only require a high intensity x-ray beam but also a monochromatic, low divergence x-ray beam. For example, diagnostic radiography can be achieved without penumbra effects reducing the image resolution in the radiograph, if a low divergence

x-ray source is available. Diagnostic radiography is presently attempted with polychromatic x-ray beams appropriately filtered to produce a partly monochromatic beam. The filter significantly reduces the intensity of short wavelength radiation but the long wavelength radiation is not adequately reduced in intensity. The long wavelengths are preferentially absorbed in the radiographed area on the skin and surface layers and produce undesired radiological effects. A high intensity x-ray source reduces the time that a patient is exposed to the x-ray beam so no blurring due to motion occurs in the radiograph.

In therapeutic radiography the accumulated radiological dosage is important. The demand is for a low divergence x-ray beam that will be absorbed by the diseased organ. A divergenceless x-ray beam can be directed at the organ without the beam spreading. A monochromatic x-ray source permits nearly uniform absorption to the organ by appropriate selection of the wavelength. The x-ray beam when rotated relative to the subject gives a high accumulated radiation dosage to the diseased organ.

Metallurgical diffraction requires a low divergence, monochromatic, intense x-ray beam. Such an x-ray beam permits improved angular resolution of the diffraction pattern, improved signal to noise in the diffraction pattern, and gives an intense diffracted x-ray beam for rapid recording of the diffraction pattern at significant statistical levels.

Metallurgical radiography may be improved by using a low divergence, monochromatic x-ray source. The low divergence reduces penumbra effects and improves the resolution in the radiograph. The contrast in the radiograph can be enhanced by selecting the wavelength of the x-ray so that it is only partly absorbed in the radiographed object.

SUMMARY OF THE INVENTION

The present invention provides an x-ray source for emitting an intense monochromatic, extremely low divergence x-ray beam.

According to the present invention x-rays are initially generated from electron ionization of a solid and/or deceleration of electrons emitted from an electron source. The x-rays generated are collected by repeatedly diffracting the x-rays within the area where the x-rays are generated. The x-ray source emits mostly diffracted x-rays. The diffraction process is highly efficient, thus the final area is an intensely emissive surface resulting in an extremely high brilliance x-ray source. X-rays emitted are spectrally monochromatic in a given direction and in addition the divergence is that of the rocking curve width, typically 10^{-4} radians in the plane that contains the normal to the (hkl) type diffraction planes and the central line axis of the electron emissive surface. In a plane perpendicular to this emission plane, the geometry of the source determines the divergence of the exiting beam.

In accordance with the present invention the apparatus for generating an intense, monochromatic, low divergence x-ray beam comprises an evacuated tube having a slotted single crystal anode defining x-ray emissive surfaces which may or may not be coated with a thin film of an efficient x-ray generating material, and an electron source preferably a filament. The x-ray apparatus may also include a cooling arrangement, a bias cup, and a cathode cap. In a preferred embodiment of

the x-ray apparatus, the filament is arranged in spaced relation to the slot in the single crystal and electrons emitted from the filament generate x-rays on the surfaces of the slot. A small percentage of x-rays generated are diffracted by the surface of the slot diagonally across from the point of origin of the x-ray. Each x-ray diffracted in this manner diffracts repeatedly as it progresses through the slot until it is finally emitted from the opening of the slot in the single crystal.

In a modified form of the present invention, the apparatus for generating an intense, monochromatic, low divergence x-ray beam comprises an evacuated tube having a hollow single crystal anode defining x-ray emissive surfaces, abraded or chemically polished, which may or may not be coated with a thin film of an efficient x-ray generating material and an electron source. The modified x-ray apparatus may also include a cooling arrangement. In a preferred embodiment of the modified x-ray apparatus, the cathode which utilizes thermionic and high field emission is arranged in spaced relation to the hole in the single crystal and electrons emitted from the cathode generate x-rays on the surfaces of the hole. A small percentage of x-rays generated are diffracted by the crystal surface inside of the hole diagonally across from the point of origin of the x-ray. Each x-ray diffracted in this manner diffracts repeatedly as it progresses through the hole until it is finally emitted from the opening of the hole in the end of the single crystal.

In the modified embodiment of the invention the x-ray source includes a hollowed generally cylindrical single crystal with a hole extending longitudinally of the center axis of the crystal. The hole is of a geometry that maximizes the electron flux on parts of the crystal's inside walls, reduces the stress on the interior crystal surface, optimizes the heat transfer through the crystal's side walls, and maximizes the accumulative, longitudinal x-ray intensity. The filament is preferably of a cold cathode design and placed in spaced relation to the inside surface of the hole. The filament ideally does not geometrically interfere with passage of the x-ray beam along the hole.

In a further modification of the invention, the hollowed single crystal may be of a split-crystal with two longitudinal sections so as to conserve crystal. The separate sides of the split-crystal may be adjusted so a single (h, k, l) plane is selected to diffract while the other $(h' k' l')$ planes are not in the proper geometry to multiply diffract. At very short wavelengths and small Bragg angles (h, k, l) planes can contribute to the final beam thus a split-crystal will maintain the highly desired monochromaticity of the x-ray beam at short wavelengths.

In a further modification to the invention the hollowed single crystal hole extends along the center axis and has an elliptical cross section. A pair of spaced filaments extend along the hole in spaced relation to the interior surface of the hole.

The single crystal is of such quality over the length of the slot or hole defining the x-ray emissive surface to permit an x-ray beam of the emitted characteristic radiation or continuous radiation to be diffracted repeatedly in conformity with Bragg's Law along the slot or hole in the crystal. The quality of the single crystal is such that the (h, k, l) type planes chosen as the diffracting planes at one end of the crystal are aligned nearly parallel to the (h, k, l) planes at the other end of the

crystal. Multiple diffraction occurs from (h, k, l) type planes over the entire length of the slotted vertical surfaces and over the entire length of the interior surface of the hollow crystal to provide an intense, monochromatic, brilliant, low divergence x-ray beam.

DESCRIPTION OF THE DRAWINGS

A preferred embodiment has been chosen for purposes of illustrating the present invention and is shown in the accompanying drawings wherein:

FIG. 1 is an exploded perspective view showing the components of the x-ray source according to the present invention.

FIG. 2 is a plan view of an evacuated tube encapsulating the x-ray source.

FIG. 3 is a wiring diagram for the filament, cathode and single crystal anode.

FIG. 4 is an elevation view in section of the x-ray source illustrating the electron emission pattern within the x-ray source.

FIG. 5 is a plan view of the x-ray source of FIG. 1 showing schemetically a ray diagram of the x-ray source of FIG. 1.

FIG. 6 is a plan view of the x-ray source showing schematically a ray diagram of a modified x-ray source.

FIG. 7 is a graph illustrating x-ray intensity at various angles taken with respect to the x-ray source.

FIG. 8 is a perspective view of a modification of the present invention in the form of a generally cylindrical single crystal x-ray source.

FIG. 9 is an enlarged section view of an evacuated tube encapsulating an x-ray source utilizing a single crystal of the form illustrated in FIG. 8.

FIG. 10 is a wiring diagram for the x-ray source of FIG. 9.

FIG. 11 is an enlarged elevation view in section of the single crystal x-ray source of FIG. 8 illustrating the electron emission pattern within the x-ray source.

FIG. 12 is a plan view in section of the x-ray source of FIG. 8 showing schematically a ray diagram of the x-ray source of FIG. 8.

FIG. 13 is an elevation view in section of another modified x-ray source showing schematically an electron emission pattern.

FIG. 14 is an elevation view in section of another modified x-ray source showing schematically separate single crystals in each side wall.

FIG. 15 is a graph illustrating x-ray intensity at various angles taken with respect to the x-ray source.

FIG. 16 is a wiring diagram for the x-ray source of FIG. 13.

DETAILED DESCRIPTION

Referring now to FIG. 1 the x-ray source 10 comprises a single crystal anode 12 preferably in the form of a rectangular block 14 with a longitudinal recess or slot 16 defining a base 18 and upstanding side walls 20, 22. The inner surfaces 24, 26 of the side walls are x-ray emissive surfaces for the generation and diffraction of x-rays as described below in detail.

The quality of the single crystal is important for the x-ray source. The crystal must have sufficient perfection over the length of the slot so as to permit an x-ray beam of the emitted characteristic radiation and the continuous radiation to be repeatedly diffracted along the slot in the crystal in conformity with Bragg's Law.

This criterion restricts the misorientation in the single crystal of the (h, k, l) type planes that have been chosen as the diffracting planes at one end of the crystal, to be aligned nearly parallel to the (h, k, l) type planes at the other end of the crystal. If the (h, k, l) type planes at each end of the crystal, and the material in between are oriented within the width of the x-ray rocking curve then multiple diffraction will occur from (h, k, l) type planes over the entire length of the slot surfaces 24 and 26. To permit the beam to repeatedly diffract from the crystal on each side of the slot, the crystal on one side of the slot must be oriented, to within the width of the x-ray rocking curve, to the part of the crystal on the other half of the slot. It is known in the art of single crystal growing that misorientations in undeformed high quality single crystals are caused by dislocations in the form of subgrain boundaries. Dislocation free crystal is thus preferred for a multiple diffraction x-ray source but a single crystal that is not dislocation free may also be used.

A bias cup 28 is provided in the x-ray source for uniformly illuminating the vertical side walls of the single crystal with electrons. The bias cup is selected to conform with the geometry of the single crystal and preferably comprises an elongated sheet 30 of a suitable metal such as stainless steel being suitably bent to define a central depression or cup 32 which registers with and nests within the single crystal slot 16. A pair of longitudinally extending slots 34, 36 are located in the side walls of the bias cup in confronting relationship to the respective side walls 24, 26 of the single crystal slot. The bias cup fits into the single crystal slot but does not touch the single crystal. As more fully described below an excitation potential is applied to the bias cup to provide for acceleration of electrons through the bias cup slots toward the x-ray emitting surfaces 24, 26. The bias cup also serves as a shield for absorbing stray x-rays.

An electron source preferably an elongated filament 38 nests within the bias cup and together with a cathode cap 40 provides a uniform source of electrons to the slots 34, 36 in the bias cup. The electrons pass through the slots to the x-ray emissive surfaces of the single crystal. The cathode cap provides a shield for absorbing stray x-rays.

A suitable cooling arrangement is provided for the x-ray source. An anode plate 42 may be used to encase and cool the single crystal by any well-known method.

The cooling of the crystal may be accomplished by passing a cooling fluid directly through the single crystal or thermally adhering the single crystal to an anode plate 42 and then cooling the anode plate. Adequate cooling is required to preserve the perfection of the x-ray emissive surfaces from thermal distortion, damage, and deterioration and to remove rapidly the power dissipated in the large focal area.

The single crystal, filament, bias cup, cathode cap and anode plate are assembled for operation within an evacuated tube 44 which is shown in FIG. 2.

Referring now to FIG. 2, the x-ray source is encased in the evacuated tube 44 which includes an evacuated housing 46 preferably metal, with a glass to metal seal 48 supporting a glass high voltage insulation member 50. The insulation member 50 has a large central recession 52 having electrical feedthroughs 54, 56, and 58 in end wall 59 for receiving the high voltage lead 60, the bias lead 62, and the filament supply 64. The x-ray

anode plate 42 and the single crystal 14 are supported and connected to and integral with the tube housing at support members 64 and 66. The forward support 66 is to accurately align and position the entire x-ray tube and hence the x-ray beams 68 and 70 with respect to an external part of the x-ray machine. A pair of beryllium windows 23 and 29 are located at the end of the tube to provide for exit of x-ray photons from the tube.

The x-ray tube is cooled by passing a fluid through the cooling entrance tube 72. The cooling fluid leaves the x-ray tube through the exit tube 74 after having cooled the anode plate 42.

As shown schematically in FIG. 3, the x-ray source includes an electric circuit 80 for supplying electrons and for accelerating the electrons to the x-ray emissive surfaces of the single crystal anode. The x-ray source has a constant potential or rectified voltages supplied so that the x-ray anode 12 is maintained at a large positive voltage, the excitation voltage V_1 , with respect to the cathode cap 40 and the bias cup 30, the bias cup and the cathode cap are maintained at the same voltage and the filament is maintained at a small negative voltage V_2 with respect to the bias cup and the cathode cap. The heater circuit for the filament supplies the voltage V_3 across the filament 38 to supply electrons which are accelerated between the bias cup 30 and the x-ray anode 12. The bias voltage V_2 permits full utilization of the electron generating surface of the filament and better electron illumination of the vertical side walls of the single crystal.

The potential V_1 applied between the bias cup and the single crystal accelerates the electrons generated by the filament. The bias cup, cathode cap, and filament in combination are used to distribute the electrons over the slotted holes in the bias cup. The electrons are accelerated and generate the x-rays over the x-ray emissive surfaces 24, 26 of the slot 16 in the single crystal in FIG. 1. The bias cup and filament arrangement also provides stability and control over the electron beam current by isolating the filament from the direct effect of the accelerating potential. The equipotential lines 82 and the trajectory of electron lines 84 inside the single crystal slot are illustrated in FIG. 4. Electrons emitted from the filament 38 in FIG. 4 pass through the slotted holes 34, 36 in the bias cup 30 and impinge on the surfaces 24 and 26 on the single crystal 14. In the surface of the single crystal the electron ionizes an atom and/or decelerates thereby to generate an x-ray. The bottom of the bias cup 31 does not interfere with the multiple diffraction of the x-rays within the slotted cavity. The electrons in FIG. 4 strike the single crystal 14 just below the bottom 31 of the bias cup 30 and permit free passage of the x-rays from surface 24 to surface 26 without striking the bottom of the bias cup 31.

The cathode cap 40 accelerates electrons emitted from the top of the filament 38 towards the slotted holes in the bias cup. It provides full utilization of the entire filament and controlled illumination of the slots in the bias cup with electrons. The cap and bias cup provide shielding by absorbing stray x-rays.

Referring now to FIG. 1, in operation, an electron generated at the hot filament moves toward a slot in the bias cup and is rapidly accelerated by the excitation potential between the bias cup and the single crystal. Upon striking an x-ray emissive surface 24 or 26 the electron excites an atom or decelerates to produce an

x-ray shown as the ray being emitted at 15 and being diffracted by the single crystal on the (h, k, l) plane which is parallel to the 26 surface. This ray will also be diffracted by the plane $(\bar{h}, \bar{k}, \bar{l})$ on the surface 24. It is finally emitted as the x-ray 17.

As shown in FIG. 2, an x-ray emitted at 19 is repeatedly diffracted by the single crystal along the vertical side walls of the slot 16. This x-ray photon 68 is finally emitted by the focal area 21 and passes through the evacuated housing at the beryllium window 23. Two x-ray photons within the continuous spectrum are emitted on the vertical walls of the single crystal at 25 and 27. These x-ray photons 69 and 70 are not diffracted and pass directly through the beryllium window 29. The x-ray beam 68 has been multiply diffracted twenty times before being emitted by the focal area 21. This x-ray photon has traveled nearly the entire length of the slot in the single crystal and therefore the x-ray beam 68 is collected from twenty times more area than a conventional x-ray source with a focal area the size of focal area 21. At comparable electron loading per unit area of the vertical side walls and comparable divergences, this x-ray source is considerably more intense.

FIGS. 5 and 6 illustrate the geometry of various single crystal slots and more particularly the geometry of x-rays repeatedly diffracted in conformity with Bragg's Law. FIG. 5 illustrates a single crystal 14 with slot 16 having side walls 24 and 26 and a center axis A—A. In the single crystal illustrated the (h, k, l) type planes 90 are oriented so that the trace of each (h, k, l) type plane forms a line extending vertically of its side wall (represented by point B in FIG. 5) and lying perpendicular to the center axis A—A. Each (h, k, l) plane defines an angle with respect to the center axis and the side walls of the slot. In this geometry, the plane with the most x-ray intensity in the emitted beam passes through the center of the slot, is parallel to the center axis of the slot, and bisects sidewalls 24 and 26 in FIG. 1. This is the plane of emission which is shown in FIG. 5. The trace of the focal area in the plane of emission is determined from the geometry of the slot, the crystallography of the slot, and the geometry of the diffraction. The x-ray beam emitted from the source emerges as an x-ray sector determined by the geometry of the target and the x-ray window 23. The widths of the emitted x-ray beams are given as: $l = w \cos \phi$, where l is the width of the emitted x-ray beam, w is the slot width, and ϕ is the angle formed by the emitted beam with respect to the center axis A—A. The angle ϕ from the geometry of FIG. 5 is $\phi = \theta_B \pm \alpha$, where θ_B is the angle of incidence (and diffraction) of an x-ray diffracted in accordance with Bragg's Law.

In FIG. 5 consider an x-ray wavelength λ emitted at C, it travels to point D where it satisfies Bragg's Law for the (h, k, l) plane, $\theta_B = \sin^{-1}(\lambda/2d_{hkl})$, where d is the distance between (h, k, l) planes. This x-ray is diffracted to the point E. At E the x-ray must also satisfy Bragg's Law since E is a part of the same single crystal that was at D, thus at E there is an $(\bar{h}, \bar{k}, \bar{l})$ plane parallel to the (h, k, l) plane at D. The included angle θ_B between parallel planes are equal, thus the x-ray enters the back side of the (h, k, l) plane at E at just the Bragg angle and it is therefore diffracted. The x-rays may be emitted from the end of the slot as two beams. This is shown in FIG. 5 for a square ended slot. In FIG. 5 x-rays originating at C and F emerge from the x-ray slot

in different directions and with the widths $w \cos(\theta_B \pm \alpha)$.

The slot geometry in FIG. 6 gives a single x-ray beam and under many applications this is more appropriate. In the geometry of FIG. 6 the ends of the slot are not the same distance down the slot and x-rays generated at G and H diffract respectively at J, K and L, M, and are emitted from the x-ray source in parallel directions. The width l of the x-ray beam for the offset slot is given by $w \sin 2\theta_B / \sin(\theta_B \pm \alpha)$.

The intensity of the emission beam is plotted in FIG. 7 versus the angle ϕ . The majority of the intensity of the x-ray beam when ϕ is near zero and α is near zero is from x-rays that have not been diffracted. These beams are polychromatic and have a divergence determined by the geometry of the x-ray source as in conventional x-ray sources. Thus at low angles the multiple x-ray source can be a conventional x-ray source. At higher angles of ϕ , the intensity of the x-ray beam from repeatedly diffracted x-rays increases. There is a large contribution of non-divergent, monochromatic radiation at a fixed value of ϕ . The radiation at the angles ϕ_1 and ϕ_2 in FIG. 7 is due to the characteristic radiation emitted from the material on the surface of the slot, the $K\beta$ and $K\alpha$ x-ray lines respectively. An x-ray window at ϕ_2 is a good choice for a monochromatic, non-divergent, x-ray window. The characteristic L lines are shown at higher numbered angles of ϕ .

The surfaces of the slot 24 and 26 in FIG. 1 need not be restricted to the same material as the single crystal. These surfaces may be coated with a very thin layer of a second material having a high x-ray production efficiency, such as tungsten, platinum, molybdenum or copper coated on a silicon single crystal. This layer must be thin enough to be transparent to the x-rays but thick enough to absorb a large portion of the electrons striking the sides of the slot. The x-rays generated in the surface layer are characterized by the material in the surface layer but these x-rays would be diffracted by the single crystal under the thin surface film. The quality of the surfaces 24 and 26 in FIG. 1 is important in that a slightly abraded surface on a perfect single crystal will reflect x-rays at a larger divergence than the perfect crystal does thus producing a more intense x-ray beam. The surface of the single crystal may be coated, abraded or perfect depending on the use of the x-ray source.

A multiple diffraction x-ray source has the following useful preferred embodiments, but is not restricted to only these examples. For application in diagnostic radiography, the x-ray tube requires a penetrating radiation that is about 70 percent absorbed in passing through the radiographed subject. Consider Mo $K\alpha$ radiation as the appropriate wavelength for a radiograph of a specific subject. The single crystal in the x-ray tube is constructed from a Czochralski grown single crystal of Silicon that is oriented with the $\langle 110 \rangle$ direction parallel to the longitudinal axis of the silicon crystal. Choose the vertical standing side walls of the longitudinal slot in the single crystal as the (111) and $(\bar{1}\bar{1}\bar{1})$ planes in the single crystal. The surface of the vertical walls in the slot may be coated with a very thin layer of molybdenum about 1,000Å thick. The x-ray tube with an excitation potential V_1 of say 100 KV and a tube current of 1,000 ma will need a large area to dissipate the heat generated. Such a large power can be dissipated by the large area in the side walls of the slotted single crystal

when the crystal is a meter long. The slot may be 3mm wide the x-ray emissive height approximately 5mm. The electron power dissipated per unit area in the vertical side wall is half an order of magnitude below the power dissipated per unit area in a conventional x-ray diffraction tube, although the total power is comparable to the power supplied to a rotating anode, radiographic unit. The Mo K_{α} x-ray for the (333) and (333) planes in the vertical standing side walls of the slot is repeatedly diffracted about 100 times if it travels the entire length of the slot. About 50 percent of the repeatedly diffracted x-ray beams will be absorbed by the molybdenum coated surface layer and the silicon single crystal. The useable intensity from a rotating anode and this multiple diffraction source are comparable although the rotating anode tube is slightly more intense but at a much larger divergence in the plane of emission with a polychromatic beam. Thus by slightly increasing the exposure time, the long wavelength radiological damage to the surface layers of the subject is eliminated, in addition the resolution in the radiograph is significantly improved.

A multiple diffraction x-ray source may also be used for metallurgical diffraction to identify the atomic or microstructural character of materials. Consider the diffraction tube and diffractometer used in the powder pattern recorded on a scanning 2θ x-ray diffractometer. The x-ray diffractometer is designed to improve the resolution of the diffracted x-rays. This is achieved by reducing the horizontal divergence from the x-ray source and the horizontal divergence of the diffracted beam thereby improving the instrument resolution. The reduction in horizontal divergence severely limits the intensity of the diffracted x-ray beam. If the impinging x-ray beam on the powder sample were inherently more parallel, monochromatic and intense then the diffracted beam would have a higher intensity, and less background noise for the same resolution. The following multiple diffraction x-ray source will generate a monochromatic, low divergence brilliant x-ray source.

The central crystal is made from a low dislocation density Germanium single crystal, Czochralski grown with the $\langle 111 \rangle$ direction in the crystal parallel to the longitudinal axis of the slot. The vertical side walls of the slot are chosen to coincide with the (110) and (110) planes. With this geometry a slot 50 cm long, 5 mm high and 5 mm wide supplies an intense x-ray beam. The (220) and the (220) planes have a Bragg angle of 18 degrees with a Ge K_{α} x-ray. Choose the x-ray port in the encapsulating housing to pass this Ge K_{α} x-ray beam. An excitation potential of 35 Kilovolts and 400 ma produces a power loading of about 280 watts/cm² on the Germanium surfaces. The total power supplied to the tube is two orders of magnitude higher than what is available in conventional diffractometer tubes and the power loading per unit area is about an order of magnitude below conventional diffractometer tubes. The final x-ray focal area is 5 mm wide with vertical height of 5 mm and the Ge K_{α} x-ray beam has two orders of magnitude lower horizontal divergence and half the vertical divergence of a conventional diffraction tube. In addition, the x-ray beam is monochromatic. The diffracted beam, because the impinging x-ray beam is of high brilliance and monochromatic, will be practically devoid of background noise. Also the diffracted beam, will be two orders of magni-

tude more intense than is presently available with conventional diffraction tubes. This permits the x-ray scan of the 2θ angle to proceed 100 times faster maintaining the same counting statistics.

For metallurgical and diagnostic radiography a short wavelength x-ray beam is often required. An x-ray source made from a single crystal of tungsten, Czochralski grown with the $\langle 001 \rangle$ direction along the longitudinal axis of the crystal forms a crystal slot for an x-ray source emitting the tungsten K_{α} x-rays. The side walls of the slot for this geometry are the (320) plane and the (320) plane. The diffraction plane is the (660) plane in the (320) wall and the (660) plane in the (320) wall. With this geometry α , in FIG. 6, is 11.31° . The tungsten K_{α} x-ray beam, diffracted from (660) type planes has a Bragg angle of 16.5° . The K_{α} x-ray beam makes an angle of 27.9° and 5.3° with the longitudinal slot axis. The x-ray beam emitted from an offset slotted crystal as shown in FIG. 6 makes an angle of 27.9° with the crystal axis. A slot 100 cm long, 0.3 cm wide and 0.5 cm high provides a large surface for dissipating the heat generated by the impinging electrons. The final focal area is 1.7 cm by 0.5 cm. The total electronic power to the x-ray source could be as large as 300 ma at 150 KV which is a power loading per unit area an order of magnitude lower than diffraction units but a total power comparable to a rotating anode x-ray tube. This is an intense, low divergence short wavelength, monochromatic x-ray source.

Referring now to FIG. 8 the x-ray source 110 comprises a single crystal anode 112 preferably in the form of a circular cylinder with a longitudinal hole 116 defining a continuous cylinder wall with opposed side walls 120 and 122. The inner surfaces 124, 126 of the cylinder side walls are x-ray emissive surfaces for the generation and diffraction of x-rays as described below in detail.

The quality of the single crystal is as described above in connection with the embodiment of FIGS. 1-7 in order to permit an x-ray beam of the emitted characteristic radiation and the continuous radiation to be repeatedly diffracted along the hollow in the crystal in conformity with Bragg's Law. To permit the beam to repeatedly diffract from the crystal and lose very little intensity, the structure factor of the (h, k, l) plane should be equal to one. Multiple diffraction will occur with little or no losses after repeated diffraction for a unit structure factor.

It will be observed in FIG. 8 as well as in FIGS. 9 and 12 that the exposed face 129 of the crystal appears as an oval lying in a plane inclined from the vertical where the central axis of the hole is horizontal. It is to be understood that the exposed face of the crystal may lie in a plane normal to the central axis of the hole in the crystal.

An electron source in the form of a cathode 128 is provided in the x-ray source for uniformly illuminating the interior walls of the single crystal with electrons. The cathode is selected to conform with the geometry of the single crystal and preferably comprises an elongated, open-end tube of a suitable metal such as tungsten or an oxide coated cathode which registers with and nests within the single crystal hole 116. The cathode fits into the single crystal hole but does not touch the single crystal. As more fully described below an excitation potential is applied to the cathode to provide

for acceleration of electrons toward the x-ray emitting surfaces 124, 126.

A heater preferably an elongated filament 138 nests within the cathode 128 and together with high field emission from the cathode provides a uniform source of electrons to the x-ray emissive surfaces of the single crystal.

A suitable cooling arrangement is provided for the x-ray source. An anode cylinder 142 may be used to encase and cool the single crystal by any well-known method. The cooling of the crystal may be accomplished by passing a cooling fluid directly over the single crystal or thermally adhering the single crystal to an anode cylinder 142 and then cooling the anode cylinder. Adequate cooling is required to preserve the perfection of the x-ray emissive surfaces from thermal distortion, damage, and deterioration and to rapidly remove the power dissipated in the large focal area.

The single crystal 112, filament 138, cathode 128, and anode cylinder 142 are assembled for operation within an evacuated tube 144 which is shown in FIG. 9.

Referring now to FIG. 9, the x-ray source is encased in the evacuated tube 144 which includes a housing 146 preferably metal, with a glass to metal seal 148 supporting a glass high voltage insulation member 150 at each end of the tube. The insulation member 150 has electrical feedthrough 156 in each end wall 159 for receiving the high voltage lead 160 and the filament supply 164. The x-ray end plates 166 and 168 support the single crystal 112 and are connected to and integral with the tube housing at 169 and 170. The forward encasement ring 172 is to accurately align and position the entire x-ray tube and hence the x-ray beam with respect to an external part of the x-ray machine. A beryllium window 174 is located on one side of the tube to provide for exit of x-ray photons from the tube.

The x-ray tube is cooled by passing a fluid through the cooling entrance tube 176. The cooling fluid leaves the x-ray tube through the exit tube 178 after having cooled the crystal 112.

As shown schematically in FIG. 10, the x-ray source includes an electric circuit 180 for supplying electrons and for accelerating the electrons to the x-ray emissive surfaces of the single crystal anode 112. The x-ray source has a constant potential or rectified voltages supplied so that the x-ray anode 112 is maintained at a large positive voltage, the excitation voltage V_1 , with respect to the cathode 128. The heater circuit 182 for the filament supplies the voltage V_3 across the filament 138 to heat the cathode which helps supply electrons that are accelerated between cathode 128 and the x-ray anode 112.

The cathode 128 and filament 138 in combination are used to generate the electrons which are distributed uniformly over the crystal walls. The filament by slightly heating the cathode provides stability and control over the electron beam current. The electrons emitted at the cathode accelerate to the anode by means of the potential V_1 applied between the cathode and the single crystal anode. The accelerated electrons impinge on and generate x-rays over the x-ray emissive surfaces of the hole in the single crystal in FIG. 8. In the surface of the single crystal, an electron ionizes an atom and/or decelerates thereby to generate an x-ray.

The equipotential lines 183 and the trajectory of electron lines 184 inside the single crystal hole 116 are illustrated in FIG. 11, and as shown, the electrons strike the single crystal on all inside surfaces.

Referring now to FIG. 8, in operation, an electron generated at the cathode moves toward the single crystal and is rapidly accelerated by the excitation potential between the cathode and the single crystal. Upon striking an x-ray emissive surface 124 or 126 the electron excites an atom or decelerates to produce an x-ray shown as the ray emitted at 115 and being diffracted by the single crystal on the (hkl) plane which is parallel to the 126 surface. This ray will also be diffracted by the plane $(\bar{h}\bar{k}\bar{l})$ on the surface 124. It is finally emitted as the x-ray 117.

As shown in FIG. 9, an x-ray emitted at 119 is repeatedly diffracted by the single crystal along the side walls of the hole 116. This x-ray photon 170 is finally emitted by the focal area 121 and passes through the evacuated housing at the beryllium window 174. Two x-ray photons within the continuous spectrum are emitted on the vertical walls of the single crystal at 125 and 127. These x-ray photons 169 and 171 are not diffracted and pass directly through the beryllium window 174. The x-ray beam 170 has been multiply diffracted six times before being emitted by the focal area 121. This x-ray photon has traveled nearly the entire length of the cavity in the single crystal and therefore the x-ray beam 170 is collected from at least six times more area than a conventional x-ray source with a focal area the size of focal area 121. At comparable electron loading per unit area of the inside walls and comparable divergences, this x-ray source is considerably more intense.

FIG. 12 illustrates the geometry of x-rays repeatedly diffracted in conformity with Bragg's Law and the geometry of various single crystal holes. FIG. 12 illustrates a single crystal 112 with hole 116 having side surfaces 124 and 126 and a center axis A—A. In the single crystal illustrated the (hkl) type planes 190 are oriented so that the trace of each (hkl) type plane forms a curved line which is vertical, perpendicular to the plane of the drawing at the point B in FIG. 12 and perpendicular to the center axis A—A. Each (hkl) plane defines an angle with respect to the center axis and the center of the side walls of the hole. In this geometry, the plane with the most x-ray intensity in the emitted beam passes through the center of the hole, is parallel to the center axis of the hole, and bisects sidewalls 124 and 126 in FIG. 8. This is the plane of emission which is shown in FIG. 12. The trace of the focal area in the plane of emission is determined from the geometry of the hole, the crystallography of the hole, and the geometry of the diffraction. The x-ray beam emitted from the source emerges as an x-ray sector determined by the geometry of the target and x-ray window. The widths of the emitted x-ray beams are given as: $l = w \sin 2\phi_B / \sin(\phi)$ where l is the width of the emitted x-ray beam, w is the hole width, θ_B is the angle of incidence (and diffraction) of an x-ray diffracted in accordance with Bragg's Law and ϕ is the angle formed by the emitted beam with respect to the center axis A—A. The angle ϕ from the geometry of FIG. 12 is $\phi = \theta_B - \alpha$.

In FIG. 12 consider an x-ray of wavelength λ emitted at C, it travels to point D where it satisfies Bragg's Law for the (hkl) plane, $\theta_B = \sin^{-1}(\lambda/2d_{hkl})$, where d is the distance between (hkl) planes. This x-ray is diffracted to the point E. At E the x-ray must also satisfy Bragg's

Law since E is a part of the same single crystal that was at D, thus at E there is an $(\bar{h} \bar{k} \bar{l})$ plane parallel to the $(h k l)$ plane at D. The included angles θ_B between parallel planes are equal; thus the x-ray enters the back side of the $(h k l)$ plane at E at just the Bragg angle and it is therefore diffracted. The end geometry of the crystal in FIG. 5 gives a single x-ray beam. In the geometry of FIG. 12 the ends of the crystal are not the same distance down the hole and x-rays generated at C and H diffract respectively at D, E and L, M, and are emitted from the x-ray source in parallel directions.

FIG. 13 shows a further modification of the present invention in which a single crystal 212 has an elliptical hole 216 with two cathodes 218 and 220 which cooperate to emit electrons which are accelerated to the side walls 222 and 224. The geometrical arrangement of the cathodes and the elliptical hole permits free passage of x-rays between the inside surfaces 232 and 230. The equipotential lines 226 and the trajectory of the electron lines 228 are shown inside the single crystal hole. Electrons emitted from the cathodes 218 and 220 are accelerated to produce high energy electrons which cause x-ray emission from the x-ray emissive surfaces 230 and 232 of side walls 222 and 224. The cathodes are heated by filaments shown as 236 and 238. In FIG. 13 the surfaces 240 and 242 of each cathode emit more electrons than opposite surfaces 244 and 246. This may be achieved by preferentially heating or shaping or coating the cathode surfaces 242 and 244. Thus, electron illumination is not uniform over the crystal surface but is more intense on the surfaces 230 and 232 than on 248 and 250. As shown in FIG. 16, the cathodes 218 and 220 are electrically connected in parallel and the filaments 236 and 238 are electrically connected in parallel.

FIG. 14 illustrates a still further modification of the present invention in which an x-ray source 260 comprises side walls 262, 264 and top and bottom walls 266, 268 which form a hollow tube 269 and define an x-ray cavity 270. The side walls are made from single crystals with the $(h k l)$ planes in one crystal parallel to the $(h k l)$ planes in the other crystal. The upper and lower walls 266, 268 of the tube are constructed from polycrystalline material. The cathode 272 conforms to the geometry of the hole 270. In the arrangement of FIG. 14 the quantity of single crystal needed to build an x-ray tube is significantly reduced. The x-rays will repeatedly diffract across the hole 270 provided the crystallographic orientation of wall 262 is the same as the crystallographic orientation of wall 264. Then all the reflecting planes in the opposed side walls will be parallel and usable as multiple reflecting planes. In certain x-ray tubes where short wavelengths are used it is desirable to have only a single (h, k, l) plane in crystal wall 262 parallel to a single (h, k, l) plane in crystal wall 264. For this application crystal wall 264 may be rotated about the normal to the (h, k, l) plane. The simplest case is when the crystal surfaces 274, 276 are parallel to the (h, k, l) planes then a rotation of crystal wall 262 about the normal to the surface 274 will maintain only the (h, k, l) planes in a parallel arrangement. Thus x-rays will only be repeatedly diffracted along the hole 270 from only the (h, k, l) plane.

The intensity of the emission beam is plotted in FIG. 15 versus the angle ϕ , shown in FIG. 12. The majority of the intensity of the x-ray beam when ϕ is near zero, and when α is near zero, is from x-rays that have not

been diffracted. These beams are polychromatic and have a divergence determined by the geometry of the x-ray source as in conventional x-ray sources. Thus at low angles the multiple x-ray source can be a conventional x-ray source. At higher angles of ϕ , the intensity of the x-ray beam from repeatedly diffracted x-rays increases. There is a large contribution of non-divergent, monochromatic radiation at a fixed value of ϕ . The radiation at the angles ϕ_1 and ϕ_2 in FIG. 15 is due to the characteristic radiation emitted from the material on the surface of the hole, the $K\beta$ and $K\alpha$ x-ray lines respectively. An x-ray window at ϕ_2 is a good choice for a monochromatic, non-divergent, x-ray beam. The characteristic L lines are shown at ϕ_3, ϕ_4 , and ϕ_5 . A second (h', k', l') plane is giving $K\alpha$ and $K\beta$ radiation at ϕ_6 and ϕ_7 .

As described above in connection with the embodiment of FIGS. 1-7, the surfaces of the hole in each modified embodiment need not be restricted to the same material as the single crystal but may be coated with materials having high x-ray production efficiency, including in addition, uranium. Moreover, the surface may be coated, abraded, or perfect as described above.

A multiple diffraction x-ray source has the following useful preferred embodiments, but is not restricted to only these examples. For application in diagnostic radiography, the x-ray tube requires a penetrating radiation that is about 70 percent absorbed in passing through the radiographed subject. Consider $MoK\alpha$ radiation as the appropriate wavelength for a radiograph of a specific subject. The single crystal in the x-ray tube is constructed from an Electron Beam grown single crystal of molybdenum that is oriented with the $\langle 100 \rangle$ direction parallel to the longitudinal axis of the molybdenum crystal. The side walls of the longitudinal hole in the single crystal will contain the (010) and the $(\bar{0}\bar{1}0)$ planes. The x-ray tube with an excitation potential V_1 of say 100 KV and a tube current of 500 ma will need a large area to dissipate the heat generated. Such a large power can be dissipated by the inside surface of the side walls of the hollow single crystal (FIG. 8) when the crystal is 20.0 cm long. The hole may be 1.0 cm. in diameter. The electron power dissipated per unit area in the inside walls of the crystal is half an order of magnitude below the power dissipated per unit area in a conventional x-ray diffraction tube, although the total power is comparable to the peak power supplied to a rotating anode, radiographic unit. The $MoK\alpha$ x-ray for the (020) and $(\bar{0}\bar{2}0)$ planes which have unity structure factor in the diameter of the hole is repeatedly diffracted about 5 times if it travels the entire length of the hole. The usable intensity from a rotating anode and this multiple diffraction source are comparable although the rotating anode tube is a pulsed tube with a much larger divergence in the plane of emission with a polychromatic beam. Thus, by slightly increasing the exposure time, the long wavelength radiological damage to the surface layers of the subject is eliminated, in addition the resolution and the contrast in the radiograph is significantly improved.

The following multiple diffraction x-ray source will generate a monochromatic, low divergence brilliant x-ray source and may be used for metallurgical diffraction to identify the atomic or microstructural character of materials. The central crystal is made from a low dislocation density copper single crystal, grown from the

melt by Bridgemen technique with the $\langle 110 \rangle$ direction in the crystal parallel to the longitudinal axis of the hole. Part of the side walls of the hole coincides with the (111) and (111) planes. The wall segments and the longitudinal axis of the hole define the plane of emission. A hole in the crystal 50 cm long, and 0.5 cm in diameter can supply an intense x-ray beam. The (111) and the (111) planes have a Bragg angle of 21.6° with a $\text{CuK}\alpha$ x-ray. Choose the x-ray port in the encapsulating housing to pass this $\text{CuK}\alpha$ x-ray beam. An excitation potential of 35 Kilovolts and 400 ma produces a power loading of about 190 watts/cm² on the interior copper surface. The total power supplied to the tube is two orders of magnitude higher than what is available in conventional diffractometer tubes. The final extended x-ray focal area is 0.93 cm wide with vertical height of 0.5 cm and the $\text{CuK}\alpha$ x-ray beam has two orders of magnitude lower horizontal divergence and half the vertical divergence of a conventional diffraction tube. In addition, the x-ray beam is monochromatic. The diffracted beam, because the impinging x-ray beam is of high brilliance and monochromatic, will be practically devoid of background noise. Also the diffracted beam, will be two orders of magnitude more intense than is presently available with conventional diffraction tubes. This permits the x-ray scan of the 2θ angle to proceed 100 times faster maintaining the same counting statistics.

For metallurgical and diagnostic radiography a short wavelength x-ray beam is often required. An x-ray source made from a single crystal of tungsten, Electron Beam grown with the $\langle 111 \rangle$ direction along the longitudinal axis of the crystal with a longitudinal circular hole in the crystal is the basis for an x-ray source emitting the tungsten $\text{K}\alpha$ x-rays. The side walls of the hole, in the plane of emission, for this geometry are the (110) plane and the (110) plane. The diffraction planes are the (220) plane and the (220) plane although the (202), (202) or the (022), (022) could also be used. With this geometry α in FIG. 12 is 0° . The tungsten $\text{K}\alpha$ x-ray beam, diffracted from (220) type planes has a Bragg angle of 5.4° . The $\text{K}\alpha$ x-ray beam makes an angle of 5.4° with the longitudinal hole axis. The x-ray beam emitted from an offset hollowed crystal as shown in FIG. 12 makes an angle of 5.4° with the crystal axis. A hole 100 cm long, and 0.5 cm in diameter provides a large surface for dissipating the heat generated by the impinging electrons. The final focal area is 5.4 cm by 0.5 cm. The total electronic power to the x-ray source could be as large as 300 ma at 150 KV which is a power loading per unit area an order of magnitude lower than diffraction units but a total power comparable to a rotating anode x-ray tube. This is an intense, low divergence short wavelength x-ray source.

A monochromatic tungsten $\text{K}\alpha$ x-ray source can be made from a split-crystal design. The x-ray source is made from a single crystal of tungsten, Electron Beam grown with the $\langle 110 \rangle$ direction along the longitudinal axis of the crystal with a square hole as shown in FIG. 14. The side walls of the hole, in the plane of emission for this geometry are the (001) and (001) planes. The right hand wall is rotated about $\langle 001 \rangle$ axis by $+3^\circ$ so only the (002), (004), (006) etc. planes can diffract multiply. The tungsten $\text{K}\alpha$ x-ray beam makes a Bragg angle of 3.7° , 7.6° and 11.5° from the crystal walls for (002), (004) and (006) planes respectively diffracting.

The atomic scattering factor decreases for increasing angle but a high intensity x-ray beam can be achieved at 11.5° using the (006) plane when the crystal is 50 cm long, 0.5 cm high and 0.3 cm wide and the specific power ratings already cited for tungsten are used. This x-ray beam is highly monochromatic.

What is claimed is:

1. An x-ray source comprising an electron source and a single crystal anode defining spaced surfaces for generating x-rays and for repeatedly diffracting generated x-rays to provide an intense, monochromatic, low divergence x-ray beam.

2. An x-ray source comprising an elongated single crystal anode having a longitudinal slot defining spaced x-ray emissive surfaces, an elongated electron source located in spaced relation to said x-ray emissive surfaces, means for accelerating the electrons to bombard said surfaces for generating x-rays which are repeatedly diffracted to produce an intense, monochromatic, low divergence x-ray beam.

3. The x-ray source defined in claim 2 in which the single crystal has (h, k, l) type planes which are parallel to each other along said crystal so that the x-rays repeatedly diffract in conformity with Bragg's Law.

4. The x-ray source defined in claim 2 in which said single crystal anode is open at the ends of the slot for emission of an x-ray beam from the x-ray source.

5. An x-ray source comprising an elongated single crystal anode having a longitudinal slot defining confronting x-ray emissive surfaces, said single crystal anode having (h, k, l) type planes at one end of the crystal aligned nearly parallel to the (h, k, l) type planes at the other end of the slot to provide for repeated diffraction of x-rays over the entire length of said slot, said slot being open-ended to provide for x-ray emission from said crystal, an electron source arranged longitudinally of said slot in confronting relation with said x-ray emissive surfaces, means for exciting said electron source to emit electrons, means for accelerating said electrons toward said slot surfaces to generate x-rays whereby a portion of said x-rays generated are repeatedly diffracted along said slot to produce an intense, monochromatic, low divergence x-ray beam emitted from said slot.

6. The x-ray source as defined in claim 5 in which said single crystal anode (h, k, l) type planes are oriented within the width of an x-ray rocking curve.

7. The x-ray source as defined in claim 5 in which said single crystal anode is a silicon crystal.

8. The x-ray source as defined in claim 5 in which said single crystal anode is a Germanium crystal.

9. The x-ray source as defined in claim 5 in which said single crystal anode is a tungsten crystal.

10. An x-ray source comprising a single crystal anode having a cooling slot defining spaced, confronting x-ray emissive surfaces, a source of electrons disposed along said slot in spaced relation to said x-ray emissive surfaces, means for exciting said electron source to emit electrons, a bias cup lying along said slot adjacent said electron source for accelerating electrons toward said x-ray emissive surfaces, said bias cup having elongated slots adjacent said electron source defining an access path from the source to the x-ray emissive surfaces, means for applying an acceleration potential to said bias cup, said bias cup being further adapted to absorb stray x-ray emissions, a cathode cap overlying said electron source and cooperating to accelerate electrons

17

toward said x-ray emissive surface and to absorb stray x-ray emissions, means for applying an acceleration potential to said cathode cap, and means for cooling said single crystal anode.

11. The x-ray source defined by claim 10 in which the bias cup and cathode cap cooperate to enclose said electron source and to direct and accelerate emitted electrons through said slots toward said x-ray emissive surface.

12. An x-ray source comprising a single crystal anode having an open ended elongated slot defining spaced, confronting x-ray emissive surfaces, said slot being open at opposed ends thereof, said crystal having (h, k, l) type planes throughout which are aligned parallel to each other, an electron source disposed in said slot, means for accelerating electrons toward said x-ray emissive surfaces which generate and repeatedly diffract x-rays along said slot, said x-ray emissive surfaces adjacent one end thereof defining opposed focal areas for emitting a plurality of intense, low divergence, monochromatic x-ray beams from said source, and means for cooling said anode.

13. The x-ray source defined in claim 12 in which the terminal portion of one of said x-ray emissive surfaces extends beyond the terminal portion of the other surface to define a single focal area for emitting an intense, low divergence, monochromatic x-ray beam.

14. An x-ray source comprising an evacuated tube, a single crystal anode positioned in said tube for generating and directing x-ray beams toward one end of said tube, said tube having at least one window defining an exit path for x-rays from said tube, means for positioning said anode in operative alignment with said windows, said anode comprising a slotted single crystal having (h, k, l) type planes throughout aligned nearly parallel to each other for diffracting x-rays along said slot in conformity with Bragg's Law, means for generating a stream of electrons for bombarding said crystal, and means for cooling said anode.

15. An x-ray source comprising an electron source and a single crystal anode defining spaced surfaces for generating x-rays, said single crystal anode spaced surfaces having a plurality of (h, k, l) planes arranged substantially parallel to each other for repeatedly diffracting generated x-rays for providing an x-ray beam.

16. An x-ray source comprising a single crystal anode having a hole defining spaced x-ray emissive surfaces, an electron source located in spaced relation to said x-ray emissive surfaces, means for accelerating electrons to said surfaces for generating x-rays which repeatedly diffract to produce an x-ray beam emerging from said hole.

17. An x-ray source as defined in claim 16 in which

18

said anode has a generally cylindrical hole defining the spaced x-ray emissive surfaces.

18. An x-ray source as defined in claim 16 in which said anode has a generally elliptical hole defining the x-ray emissive surfaces.

19. An x-ray source as defined in claim 18 which includes a plurality of electron sources lying in spaced relation to said x-ray emissive surfaces.

20. An x-ray source as defined in claim 16 in which said anode has a generally rectangular hole defining the x-ray emissive surfaces.

21. An x-ray source as defined in claim 16 in which said x-ray emissive surfaces lie within spaced planes.

22. An x-ray source as defined in claim 16 in which one spaced x-ray emissive surface contains at least one (h, k, l) type plane cooperating with another (h, k, l) type plane located in the other x-ray emissive surface to repeatedly diffract an x-ray generated within said x-ray source.

23. An x-ray source comprising a single crystal anode having spaced x-ray emissive surfaces, an electron source located in spaced relation to said x-ray emissive surfaces, means for accelerating electrons to bombard said surfaces for generating x-rays which are repeatedly diffracted to produce x-ray beam emerging from said source.

24. An x-ray source as defined in claim 1 in which the anode has (h, k, l) type planes in said x-ray emissive surfaces, which planes cooperate with each other to repeatedly diffract x-rays along the x-ray emissive surfaces to form an intense, low divergence x-ray beam.

25. An x-ray source as defined in claim 24 in which said (h, k, l) type planes are generally parallel to each other.

26. A single crystal anode for an x-ray source comprising an elongated single crystal having a hollow defining confronting x-ray emissive and diffracting surfaces wherein the (h, k, l) type planes are aligned nearly parallel through said crystal.

27. A single crystal anode for an x-ray source comprising an elongated single crystal having a longitudinal slot defining confronting x-ray emissive and diffracting surfaces wherein the (h, k, l) type planes are aligned nearly parallel through said crystal.

28. A single crystal as defined in claim 27 in which said surfaces are coated with a thin film of a highly efficient x-ray generating material.

29. The crystal defined in claim 28 in which said coating comprises a highly efficient x-ray generating material selected from the group consisting of tungsten, platinum, molybdenum, or copper.

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