

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
29 June 2006 (29.06.2006)

PCT

(10) International Publication Number
WO 2006/069009 A2

(51) International Patent Classification:
H01J 35/08 (2006.01)

(21) International Application Number:
PCT/US2005/045971

(22) International Filing Date:
16 December 2005 (16.12.2005)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/637,890 21 December 2004 (21.12.2004) US
60/657,067 28 February 2005 (28.02.2005) US
60/700,242 19 July 2005 (19.07.2005) US
60/725,228 12 October 2005 (12.10.2005) US

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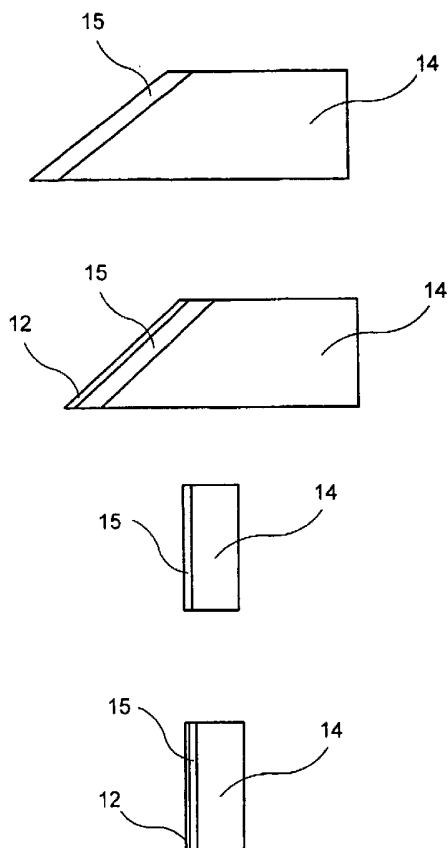
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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, LY, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

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(54) Title: METHOD OF PRODUCING TARGET FOIL MATERIAL FOR X-RAY TUBES



(57) Abstract: X-ray targets made of a single foil alloy, eutectic alloy, compound or intermetallic compound of at least two elements to produce separate line emissions from at least two different elements in the foil, to reduce the reactivity in air or moisture compared to at least one of the said elements producing useful x-rays, or to increase the producing useful x-rays are provided. X-ray targets made by simultaneous deposition of more than one material altering the coefficient of heat transfer compared to layering of said materials are provided. Transmission x-ray tubes configured for use in fluoroscopy by focusing the electron beam onto a small spot on the target or by using a thick target foil to reduce background x-ray noise in measuring an element of interest wherein a second optional thin foil is layered onto the thick target foil to produce excitation energy for the measured element are provided. Transmission x-ray tubes coupled to a single capillary or a bundle of capillaries are also provided.



(84) **Designated States** (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— without international search report and to be republished upon receipt of that report

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

METHOD OF PRODUCING TARGET FOIL MATERIAL FOR X-RAY TUBES

The invention relates to an improved way to make metallic foil targets for x-ray tubes and various applications to use transmission x-ray tubes to detect elements of interest by x-ray fluoroscopy and for x-ray imaging. It further relates to the use of a single capillary or a bundle of capillaries coupled to a transmission x-ray tube and applications thereof.

When transmission tubes with thin x-ray targets are used and the applied tube voltage to the electron beam in kVp is at least two times the K-alpha radiation of the target material in keV, very high percentages of k-alpha emissions are available for attractive use in fluoroscopy, diffraction and x-ray imaging applications. To match the energy of the characteristic x-rays to the task to be accomplished, use of the lanthanum series of metals as well as other metals with a low melting point is desirable. Many of the lanthanum series elements suffer from low melting points, low heat conductivity and high reactivity in air and moisture. As such they are difficult to use as target materials when used in elemental form. In addition low melting point materials used at a temperature just below their melting point results in a high vaporization rate from the surface of the target material and reduced life of the x-ray tube.

Specifically transmission x-ray tubes are further limited because the melting point of the substrate onto which the target is deposited is very low and the thickness of the target materials is limited to tens of microns thickness. Hence all of the electrical heat generated by the electron beam impinging on the target must be removed through the end-window. Beryllium, copper and aluminum are the most commonly used end-window materials and have melting points of 1287°C, 1084°C, and 660°C respectively.

Reflective tube as well would benefit from a wider use of potential target materials with the same disadvantages those materials pose for transmission tubes. Reflection tubes are used almost universally in fluoroscopy applications where the spot size of the focused electron beam impinging the target is less than about 200 microns. X-radiation from such tubes does not have a very high concentration of k-alpha radiation needed for high speed and accurate fluoroscopic measurement of various elements. By way of example such an application is the European Union's "Directive on the restriction of the use of certain hazardous substances" in electrical and electronic

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equipment (RoHS Directive). This directive places restrictions on the use of six substances: cadmium, lead, mercury, hexavalent chromium, polybrominated biphenyls (PBB), and polybrominated diphenyl ethers (PBDE). Particularly, the measurement of cadmium by x-ray fluoroscopy is inefficient, expensive and time consuming. Many different schemes are currently being employed to make such measurements but with limited success. They employ reflection type x-ray tubes with various target materials, filtering schemes and applied tube voltages.

When low energy x-rays are needed for fluoroscopic measurements, transmission tubes suffer in that low energy x-rays are absorbed when passing through the end-window. Because the end-window seals the vacuum to outside air and must also remove heat generated in the x-ray target, thin beryllium windows are not possible.

Recently the use of a single capillary or a bundle of capillaries to guide and focus x-rays has received market acceptance. Such systems current employ reflection x-ray tubes with focused spot sizes. However, the distance from where the x-rays are produced to where the x-rays enter such capillaries is long, causing a loss of x-ray intensity.

What is needed is a way to make x-ray targets of a wide variety of materials whose melting points are at least higher than beryllium, which can produce a high concentration of k-alpha radiation, whose reactivity in air and moisture is not high, whose heat conductivity is adjusted to match the end-window material to provide maximum x-ray tube current, and whose rate of vaporization is low to provide long x-ray tube life. What is also needed is a way to improve fluoroscopic measurements made with reflection tubes. Special efforts are needed to solve the problem of rapid and accurate fluoroscopic detection of cadmium. Additionally a way to produce low energy x-rays for fluoroscopic measurements from transmission tubes is needed. An x-ray tube for use with capillaries is needed whereby the capillary or bundle of capillaries can be placed very close to the point on the target where x-rays are generated.

DESCRIPTION OF THE DRAWINGS

Figure 1 is a representation of a typical transmission type x-ray tube.

Figure 2 is a representation of a typical reflection type x-ray tube.

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Figure 3 depicts two different possible x-ray target configurations for a reflective x-ray tube and two for a transmission tube

Figure 4 is a graphical representation the output spectrum from a transmission tube with a target of 95% cerium 5% aluminum.

Figure 5 is a graphical representation of the output spectrum from a transmission tube with a target made by layering molybdenum onto a zinc telluride target foil previously sputtered onto a beryllium end-window.

Figure 6 is a conceptual drawing depicting a transmission x-ray tube coupled to a single capillary.

Figure 7 represents two configurations for using a bundle of glass capillaries to guide and focus the output from a point source of x-rays.

Figure 8 is a graphical representation of the output spectrum from a transmission tube with a target of molybdenum 25 microns thick.

Figure 9 is a graphical representation of the number of counts of x-ray photons from a transmission tube with a Rhodium target.

Figure 10 is a graphical representation of the flux generated by comparable reflection and transmission x-ray tubes.

Figure 11 is a schematic drawing of an in-line application for a transmission x-ray tube of this invention.

Open transmission tubes are typically used for imaging of electronic circuits as well as other high-resolution applications and may alternatively be used as the x-ray source. Closed tubes are sealed with a vacuum whereas open or "pumped down" tubes have a vacuum pump continuously attached drawing a vacuum as the tube is used usually to allow for frequent replacement of tube parts which tend to fail in operation. For purposes of this invention transmission tubes include both open and closed transmission type tubes except as otherwise stated.

The transmission tube of Figure 1 is comprised of an evacuated housing 6, and end-window anode 1, disposed at the end of the housing exposed to atmosphere.

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An x-ray target foil 2, is deposited on the end-window anode. An electrically heated cathode emits electrons, which are accelerated along the electron beam path 4, and strike the anode target producing x-rays. A power supply is connected between the cathode and anode to the accelerating force for the electron beam. X-rays produced exit the x-ray tube through the end-window. An optional focusing cup 5, typically negatively biased or neutral, focuses the electron beam onto a spot on the target. The largest dimension of the spot is referred to as the focal spot size or spot size. The output x-rays contain both bremsstrahlung (or braking radiation) and characteristic line radiation unique to the target material. If the thickness of the target is about between about 1 and 70 microns and the applied tube voltage in kVp is more than two times the characteristic K-alpha line of the target material, output x-rays from a transmission tube have a very high concentration of K-alpha x-rays compared to reflection tubes. Preferred target thickness for thin target foils from such a tube are 1-10 microns and for a thick target 20-50 microns, depending on application.

For a closed type or "pumped down" system a vacuum pump is typically attached to the evacuated chamber and the vacuum pump continuously pumps a vacuum. Chamber 16 of Figure 1 may be baked at a temperature between 3500 and 5000 C for about 9 to 12 hours to de-gas the parts making the x-ray tube, and then is sealed.

Figure 2 is provided for reference and schematically represents a reflection tube comprised of an evacuated housing in which the cathode (9) and anode (7) are located. The anode 7 is comprised of an x-ray target deposited onto a substrate which substrate removes heat generated when x-rays impinge the anode. Electrons are emitted from the cathode 9 when the cathode is heated. A power supply is connected between the cathode and the anode to provide an electric field which accelerates the electrons from the cathode along an electron beam path 10 and strikes the anode in a spot generating a beam of x-rays 8 which then exit the tube through a side window 11. The reflection tube harvests produced x-rays from the same side of the target that the electron beam impinges.

Figure 3 represents x-ray target configurations for transmission x-ray as well as for reflective tubes. Figures 3A and 3B are for reflection tubes and Figures 3C and 3D for transmission tubes. Figure 3A depicts an x-ray anode target for a reflective tube comprised of a single layer foil of x-ray generating material 15 fixed to an anode

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substrate 14 which is used to remove heat generated when electrons impinge on the target. Figure 3B depicts the same x-ray target with a second foil of target material 12 deposited on top of the single target foil 15 in Figure 3A. Figure 3C depicts an x-ray anode target for a transmission x-ray tube comprised of a single layer of x-ray material 15 deposited onto an anode substrate 14 typically made of a low atomic number metal which is virtually transparent to x-rays. Figure 3D depicts the same x-ray target with a second foil of material deposited on top of the single target foil 15.

It is well known in the field of x-ray targets for reflection x-ray tubes to use tungsten-rhenium and other alloys to improve the melting point and other characteristics of an x-ray target, transmission tub. The end window of transmission x-ray tubes must be made of a low atomic number material such as beryllium, copper, aluminum and alloys thereof to reduce any absorption by the end-window of the x-rays produced. However beryllium has a melting point of 1287°C, copper of 1084°C and aluminum of 660°C. In one preferred embodiment of the current invention two different elements are mixed as alloys, eutectic alloys, intermetallic compounds, or simple compounds when one of the elements needed to produce useful x-rays has a low melting point. Examples of x-ray generating elements whose melting point is below that of beryllium include but are not limited to manganese, copper, tellurium, zinc, silver, tin, barium, lanthanum, cerium, antimony, holmium, dysprosium, bismuth, praseodymium, neodymium, samarium, europium, antimony, barium, bismuth, ytterbium, gold and uranium. Other potential target materials have melting points higher than beryllium but not considerably higher and with lower heat conductivity than beryllium, causing the target foil to reach temperatures greater than 300 degrees higher than the end-window substrate. Those include but are not limited to yttrium, palladium, gadolinium, terbium, erbium, and thulium.

EXAMPLE 1

Aluminum/Antimony

When 20% aluminum with a melting point of 660°C is mixed with 80% antimony with a melting point of 630.5°C the resultant mixture forms a metallic mixture with a melting point of 1040°C, considerably higher than either of the elements making the mixture. Such a mixture is useful in producing an antimony target with k-alpha radiation of 26.357keV without interference from k-alpha radiation of aluminum, which

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is very low energy easily absorbed. Although the resultant melting temperature is still lower than the melting point of beryllium, the materials can still be used in applications where high tube currents are not essential.

EXAMPLE 2

Nickel/Tin

Similarly to produce a target foil emitting k-alpha radiation of tin of 25.270keV, 70% tin with a melting point of 322°C can be mixed with 30% nickel to provide a metal mixture with a melting point of 1230°C. Nickel has a k-alpha of 7.477keV useful to fluoresce elements such as cobalt, iron, manganese, and chromium. Alternatively the k-alpha radiation of nickel might not be needed and the nickel used simply to increase the melting temperature of the alloy whose main function is to produce tin characteristic line x-radiation.

EXAMPLE 3

Sodium/Bismuth

When 30% sodium (melting point of 96°C) is mixed with 70% bismuth (melting point of 268°C), the resultant metal mixture has a melting point of 730°C, considerably higher than either of the components. The characteristic K-lines of sodium are very low energy and not an important factor, but the K-lines or L-lines of bismuth may be used for either fluorescent measurements or for x-ray imaging.

EXAMPLE 4

Lanthanum/Tin

Lanthanum has a k-alpha of 33.440 keV and Iodine a K-absorption of 33.164 keV making Lanthanum an ideal material to produce images with iodine being used to increase the contrast in a number of applications including angiography and mammography among others. In contrast, Sn has a k-alpha of 25.270 keV, well below the k-absorption edge of iodine. Lanthanum, however, melts at 918°C and tin at 232°C. An intermetallic compound comprising 60% Lanthanum and 40% Tin melts at 1575°C thus reducing the likelihood of target melting compared to either metal alone. Taking one image with a high percentage of Lanthanum K-alpha and a second with a high percentage of tin k-alpha then subtracting the images will result in a clear image of

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the iodine only. Higher tube voltages produce more lanthanum k-alpha radiation and lower voltages more tin. Aside from melting point considerations lanthanum is a highly reactive element oxidizing rapidly when exposed to air which reactivity is mediated by the Tin.

In another preferred embodiment of the current invention elements highly reactivity in air or moisture mediated by mixing these elements with another metal or non-metal including but not limited to aluminum, iron, sulfur or nickel and then depositing the resultant alloy, eutectic alloy, compound or intermetallic compound onto an anode substrate. Various deposition techniques may be used, but typically the mixture would be formed into a sputtering disc for sputtering onto the substrate.

Examples of reactive x-ray generating metals for potential use in transmission x-ray tubes include but are not limited to lithium, sodium, potassium, cesium, francium, lanthanum, cerium, praseodymium, neodymium, europium, gadolinium, terbium, holmium, erbium, thulium, barium, strontium, rubidium, cesium, scandium, yttrium, zirconium, and niobium.

EXAMPLE 5

Cerium/Aluminum

Figure 4 shows an x-ray spectrum taken from a transmission tube with a ~5 micron thick target made of a mixture of 5% aluminum and 95% cerium at an applied tube voltage of 80kVp and tube current of 5 μ A. The vertical axis is number of counts and the horizontal axis is the photon energy of the x-rays produced. The K-alpha characteristic line is shown as Item 21 and the K-beta by Item 22. The energy of K-alpha line of aluminum 1.487keV and readily absorbed by air the beryllium end window and air. Pure cerium is too reactive to be used in a production environment and causes corruption of sputtering and vacuum instrumentation. The percent of aluminum is not limited to 5%.

EXAMPLE 6

Cerium/Sulfur

Cerium melts at 795°C. However, combining 18.6% sulfur by weight with cerium results in a target material with 81.4% cerium but with a melting point of

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2450°C. The k-alpha of Cerium is 34.717 and is particularly well positioned to excite fluorescence in iodine, tellurium, antimony, tin, indium and cadmium for both x-ray imaging and x-ray fluoroscopy applications among others. Sulfur has a k-alpha of 2.308 keV and does not interfere with measurements of higher Z elements.¹ Mixing sulfur with cerium mediates its high reactivity and makes it useful as an x-ray target material.

EXAMPLE 7

Neodymium/Tellurium

Neodymium quickly tarnishes in air, forming an oxide that spalls off and exposes the metal to further oxidation. It requires costly care to use it in a manufacturing environment. Yet when mixed with tellurium with 46.9% tellurium and 53.1% neodymium by weight, the resultant metallic mixture NdTe is considerably more stable. In addition the melting points of neodymium and tellurium are 1024°C and 450°C respectively while the chemical compound NdTe has a melting point of 2025°C. Neodymium is particularly well positioned to measure barium in fluoroscopic applications and tellurium to measure cadmium.

In some applications it is desirable to increase the heat conductivity of the x-ray target allowing heat to pass more readily to the anode substrate decreasing the temperature in the x-ray generating layer and increasing the temperature of the substrate. In other applications it is desirable to decrease the heat conductivity resulting in higher temperatures in the x-ray generating layer. In another embodiment simultaneous sputtering or otherwise depositing an additional material to mix with the x-ray generating metal (Figure 5 – Reference numeral 15) increasing the capability of the tube to dissipate heat and improving the service life of the x-ray tube. The material used to adjust the coefficient of heat conductivity may also generate useful x-rays, but that is not an essential element of this embodiment.

EXAMPLE 8

Molybdenum Telluride/Nickel

An alternative to using zinc telluride of Example 9 below would be to use molybdenum telluride (Mo_3Te_4) which has a melting point of $1300 \pm 70^\circ\text{C}$ considerably higher than the melting point of tellurium, 449.57°C. An alternative to layering nickel onto the Molybdenum telluride, which is a poor conductor of heat, is to simultaneously

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sputter the two materials. The resultant mixture of materials has a heat conductivity considerably higher than the mass equivalent of the two materials layered separately. Alternative materials to nickel include but are not limited to copper and iron. Either of those metals of a concentration by weight of between about 5 and 25% will increase the thermal conductivity of molybdenum telluride.

EXAMPLE 9

Zinc Telluride/Molybdenum

Figure 5 is a graphical representation of the spectrum of a transmission tube made with a 5 micron thick zinc telluride target foil deposited on a beryllium end-window 1 mm thick followed by depositing 1 micron of molybdenum thereon. The spectrum was taken with an applied tube voltage of 80kVp and tube current of 5 microampere and clearly shows K-alpha peaks of zinc 31, molybdenum 32 and tellurium 32. These three K-alpha peaks are particularly well positioned to measure cadmium, bromine, lead, mercury and chromium of the European RoHS directive on banned substances. Zinc telluride has very poor heat conductivity and severely limits the power dissipated in the anode. Simultaneous sputtering of zinc telluride and molybdenum in about equal weights to the layered target significantly improves heat dissipation and hence useful tube power.

EXAMPLE 10

Rhodium/Titanium

Rhodium with a melting point of 1964°C is often the target material of choice for x-ray fluoroscopy using reflection x-ray tubes. For use in transmission x-ray tubes, its coefficient of heat transfer is 150 /Wm-1K-1 compared to 170 for the beryllium used as the anode substrate. Heat is rapidly transferred to the beryllium raising the temperature of the beryllium until it melts while the temperature of the rhodium target is still well below its melting point. Simultaneous sputtering of 5 to 20% by weight of a material such as titanium with a coefficient of heat transfer of only 22 /Wm-1K-1 slows the transfer of heat to the substrate, increasing the temperature in the rhodium layer and subsequently the useful tube power.

In one embodiment of the current invention a focused transmission tube is used to produce x-rays with a focal spot size of about 0.1 microns to 3 mm for use in

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fluoroscopic measurement of the presence and concentration of elements in an object to be measured. Preferred spot sizes are usually between 3 microns and 200 microns. The output of an x-ray tube is collimated into a small beam of x-rays impinging the object to be analyzed, utilizing only a small portion of the beam and constraining x-ray fluorescence to the radiated portion of the object. If the location of radiating x-ray beam is known and varied, a map showing presence and concentration of one or more elements of interest can be produced well known by those skilled in the art. Using a transmission tube has many advantages over the use of reflection tubes. Significantly higher percentages K-alpha x-radiation of the precise energy required to excite a specific element of interest in the object can be produced at higher tube voltages than can be produced by reflection tubes. The collimator can be located very close to the x-ray spot, typically within 1 or 2 millimeters compared to about 20 to 30 millimeters for reflection tubes, significantly reducing the $1/r^2$ losses of x-ray beam intensity of the reflection tube.

EXAMPLE 11

Rhodium

Figure 9 is a representation of the output spectrum of such a transmission tube useful in x-ray fluoroscopy with a rhodium target foil 6 microns thick deposited on a 250 micron thick beryllium end-window and focused to a spot size of 40 microns with a tube voltage of 90kVp. Optimal target thickness may vary from 1 micron to as much as 70 with a preferred thickness of 2 to 30 microns and tube voltage may be varied from about 20 kVp to 300 kVp with a preferred voltage of about 40 to 150 kVp to fit specific application needs. The vertical axis 41 represents the number of spectrometer counts and the horizontal axis 42 the energy of the resultant x-rays. Reference numeral 43 is the K-alpha characteristic line of 20.214 keV for Rhodium. Although rhodium is the target material of choice for fluoroscopy, any number of target materials may be used to replace rhodium.

In Example 11 above the L-line radiation of Rhodium from the transmission tube has been absorbed by the thick 250 micron beryllium window and is not available for fluoroscopic measurements of elements with a low atomic number such as sulfur, phosphorous, silicon, aluminum, magnesium, sodium and others. Use of a thinner beryllium end-window adds cost and increased risk of air leaking into the evacuated housing aside from reducing the heat that can be dissipated from the target.

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In yet another embodiment of the current invention a thin foil of x-ray producing material, in this case rhodium, of about 0.1 microns to about 10 microns is deposited on the opposite side of the end-window where the electron beam impinges. The preferred thickness is 0.5 to 3 microns. Bremsstrahlung radiation or characteristic line x-radiation generated by the x-ray target passes through the end-window, is absorbed by the thin foil on the outside of the tube, and low energy characteristic x-rays produced. In some applications the thin foil on the outside of the end-window may produce K-line radiation from materials including but not limited to scandium, titanium, aluminum, silicon. Another advantage of using a thin layer of target material on the outside of the end-window is that varying the thickness of the outside layer will determine the ratio of K-line radiation intensity to L-line radiation intensity, something that is not possible with current state of the art fluoroscopic x-ray tubes. Although a similar layer may be used on the outside of the window of a reflection type tube, a transmission tube is preferred. Placing the foil within 0.25 to 1 mm, the thickness of the end-window, of the x-ray generating spot is considerably more efficient. Additionally filter blur is reduced.

In another preferred embodiment of the current invention, a single target materials made from an alloy, eutectic alloy, compound or intermetallic compound of two or more elements, generally available from commercial producers, is provided. It is well known that layering target materials or using multiple targets and selectively moving the electron beam from one to the other, can produce x-rays containing useful characteristic lines of more than a single element but at added cost. However mixing two or more elements into a single target avoids such cost. Examples 8 and 9 above disclose the use of zinc telluride and molybdenum telluride in a target material wherein the characteristic lines of tellurium and zinc or molybdenum and tellurium are useful in speeding measurement of multiple elements in the RoHS fluoroscopic application.

EXAMPLE 12

LANTHANUM/TIN

Iodine is often used as an imaging agent in angiography and mammography among others. After injecting a patient with an Iodine based imaging agent, taking one x-ray image with a high percentage of Lanthanum K-alpha (33.440 keV) and a second with a high percentage of tin k-alpha (25.270 keV) then subtracting the images will result in a clear image of the iodine with a K-absorption of 33.164 keV. Similarly dual imaging of the tin content in solder can be accomplished with the same

two elements, Lanthanum and Tin to provide a quality control tool for soldering operations. An intermetallic compound comprising 60% Lanthanum and 40% Tin provides one of any number of possible target materials with sufficient amounts of each material to produce high intensity K-line x-rays for both Tin and Lanthanum. Amount of K-alpha radiation from each element is adjusted by varying the x-ray tube voltage.

The rate of evaporation of tantalum as published in 1939 by The American Physical Society can be expressed by $\log_{10} M = 7.86 - 39,310 / T$, where M is the rate of evaporation in grams per cm^2 per sec. and T is the temperature on the Kelvin scale. The calculated amount of vaporization of a tantalum target 2 microns thick after 50,000 hours at 1600°K is still less than 0.01 microns. If the temperature is raised to 20000 K the vaporization increases to 0.1 microns. If the target material reaches 2000°C , an anode substrate of an x-ray tube made predominantly from beryllium, copper or aluminum would melt.

Many of the target materials useful for x-ray fluoroscopy, imaging and diffraction held at temperatures near their melting point have a very high rate of vaporization and early target failure. Another preferred embodiment of the current invention provides the deposition of a thin layer of sacrificial material on the order of 0.02 to 0.10 microns thick (Figures 3B and 3D Reference numeral 12) of low vaporization chosen from one including but not limited to tungsten, tantalum, chromium, molybdenum, and rhodium onto a target which would otherwise suffer loss of target material and failure. Using a preferred thickness of 40 to 500 nanometers of sacrificial material will not appreciably change tube output.

In one preferred embodiment of the current invention a transmission tube described above is coupled to a single capillary or a bundle of capillaries, typically made of specialty glass well known to those skilled in the art or any suitable material as well, which guide and focus a portion of the x-rays produced by a transmission type x-ray tube.

Figure 6 represents a single capillary coupled to the output of a transmission type tube 34 representing a focused electron beam of a transmission tube striking the target 36 in a focal spot. The target deposited on an anode substrate 35 generates a beam of x-rays Item 38 a portion of which exit the end-window and enter a single capillary 37 to exit the opposite end of the capillary. Typically such a single

capillary is used to focus the x-rays from a focal spot of about 20 to 150 microns diameter to a very narrow beam of x-rays on the order of 1- 10 microns.

Figure 7 represents a bundle of capillaries used to focus the spot size of an x-ray tube to produce even higher resolution of the x-ray beam useful for diffraction, fluorescence and imaging or to provide a close to parallel beam of x-rays to reduce scattering inside the object. X-rays generated at the focal spot of a transmission target 47. Reference numeral 44 illustrates how a bundle of capillaries can receive x-rays from a point source and guide them into a nearly parallel beam of x-rays. Reference numerals 45 and 48 are graphical representations of how an individual x-ray beam travels inside a single capillary within the capillary bundle. Reference numeral 46 illustrates use of a bundle of capillaries to receive x-rays and refocus them at a second point in space. However, this invention is not limited to those two uses.

Although the transmission losses inside the capillary or capillaries are increased because the spot where x-rays are generated is place close to the entrance of the capillary in a transmission tube, these losses are not as great as the savings in x-ray intensity due to normal $1/r^2$ losses not realized inside the capillary. Using a transmission tube allows placement of the capillaries as close as about 0.075 to 2mm, the thickness of the end-window, increasing significantly the intensity of x-radiation exiting the capillary compared to that from reflection tubes where placement is limited to a minimum of about 20 to 30 mm. Other advantages of transmission tubes include a high percentage of characteristic line emission compared to reflection tubes described above.

In x-ray medical and non-destructive test imaging a bundle of capillaries has the added advantage well know to those skilled in the art of filtering out unwanted high energy x-rays, from transmission x-ray tubes operating at high tube voltages.

Although the performance of transmission tubes configured to provide K or L-line radiation can be significantly improved with a capillary or bundle of capillaries improvements to tubes used to produce predominantly bremsstrahlung radiation have similar benefits. Hence this invention is not limited to any particular kind of transmission x-ray tube.

Improving the speed and accuracy of fluoroscopic measurements can be accomplished by using a thick target foil of a transmission x-ray tube. In another

preferred embodiment a thick target foil about 10 to 70 microns thick deposited onto the anode substrate (Reference numeral 14 of Figure 3C or 3D) will absorb a high percentage of bremsstrahlung x-rays generated inside the foil within an energy band about 10-20 keV above the foil's K-absorption energy. Making a fluoroscopic measurement of an element with a characteristic line emission within that energy band greatly reduces background bremsstrahlung improving speed and or accuracy of measuring presence or concentration of the element. Any of a number of filtering schemes can be used if necessary to reduce the K-alpha output of the thick foil should its intensity be too high for delicate x-ray fluoroscopes.

EXAMPLE 13

Thick Molybdenum Target Transmission Tube

Figure 8 demonstrates the output spectrum from a 25 micron thick molybdenum target of a transmission x-ray tube with an electron beam energy of 60kVp. The region 39, of the output energy spectrum just greater (about 20.1 to 30keV) than K-absorption energy of molybdenum, 20.002 keV, is a region where very few x-ray photons are generated by the thick molybdenum target because the energy in that region is absorbed by the target and fluoresced as K-line radiation. By way of example, cadmium, the most difficult of the RoHS directive banned substances, has a K-alpha value of 23.172 higher than and close to the k-absorption energy of molybdenum. Using the transmission tube described, background bremsstrahlung radiation is significantly reduced improving the signal to noise ratio for measuring cadmium.

Although the molybdenum target provides enough bremsstrahlung radiation above the k-absorption edge of cadmium to cause the cadmium to fluoresce, in another embodiment of the invention an additional thin target material (Figure 3D Reference numeral 12) is deposited onto the molybdenum thick target to increase the amount of x-rays absorbed by cadmium and increase speed and or accuracy of the measurement. The thin target can be about 0.5 microns to 10 microns thick and be of any target material which provides output x-rays excite cadmium but does not generating further interference from Compton Scattering. Examples of such target materials include but are not limited to Lanthanum, Cerium, Neodymium, Gadolinium, Thulium, Tantalum and Tungsten. Although molybdenum and cadmium were used by way of example, the underlying principle can be applied to any of a number of target materials and measured elements.

It will be obvious to those skilled in the art that all of the above target configurations can be used to cover all or only a portion of the substrate onto which they are deposited. It is possible to construct an x-ray target with multiple target sections any one of which can be made according to the disclosures of this invention. The electron beam 13 or beams can be made to impinge each target section selectively and can be controlled to move from impinging one of the target sections to impinging another in any of a number of different ways including scanning of the target.

Although disclosure of ways to produce a single foil target are disclosed, use of such targets may also be made by adding additional foils of other x-ray producing materials to form a compound target either for transmission or reflective x-ray tubes.

In one preferred embodiment of the current invention a transmission type tube is used to provide x-rays for automated in-line inspection of objects. Objects are fed into the inspection station, inspected and then removed automatically by a material handling apparatus. Figure 11 represents one such an application. A conveyor belt 44 feeds products 48 which can be stopped during the inspection or move continuously through the station. However, any material handling apparatus well known to those skilled in the art can also be employed. In Figure 11 a line sensor 49 well known by those versed in the art is used to sense the image and an image processor 50 collects a series of line images and transforms them into an image of the entire object. A power supply 46 provides electrical power to the x-ray tube assembly 45 conventionally containing the x-ray tube immersed in a cooling and electrically isolating fluid. The x-ray tube produces x-rays 47 used to produce x-ray images of the product. Although this particular representation shows a line image sensor, various sensors, well known by anyone skilled in the art, can be used either for imaging or fluoroscopy or a combination thereof.

As shown in Figures 1 and 2 the cone angle of x-rays produced 8 is considerably wider for a transmission x-ray tube than for a reflection tube. Reflection the x-ray tubes are typically placed 35 cm from the conveyor can provide the same field of inspection at distances as close as 20 cm depending on the size of product being examined, decreasing the amount of x-ray flux needed and significantly reducing the heat load on the x-ray target. Figure 10 describes the amount and angular distribution of total x-ray flux produced by reflection type tubes currently in the market compared to the output flux of a closed transmission tube of the current invention. Tube voltage was

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60 kVp and tube current 50 microAmps for both measurements. Focal spot sizes for both tube were ~100 microns. Aside from the considerable improvement in out put angle, even at the center of the x-ray cone, the transmission tube provides considerable more output flux. Although the preferred embodiment uses a closed transmission x-ray tube, open tubes may also be employed at more expense.

Using a transmission tube with the target thickness, target material and subsequent tube voltage optimally chosen for sensor used in the in-line application can provide a three to five-fold improvement in total x-ray flux at the critical x-ray imaging energy compared to reflection tubes. When a high content bremsstrahlung output will suffice, the target materials typically include but are not limited to tungsten, tantalum, platinum and other high Z elements producing a resultant three to four times more bremsstrahlung x-rays than a reflection tubes currently used. When k-alpha radiation is more efficient for a specific sensor/product application, the tube voltage, target thickness and target material may be chosen to provide a very high percentage of k-alpha radiation. Such optimization of target design provides from 3 to 5 fold improvements in x-ray output at critical energies compared to reflection tubes. For example in an application where the difference in absorption of the foreign matter to be identified in the product is close to the absorption of the product being inspected, a high percentage of monochromatic x-radiation provides even further improvements in accuracy of the inspection station as well as its speed.

Because of the speed required of in-line inspection stations, spot sizes of less than 1 mm have not been widely used. The considerable performance improvements offered by a transmission tube of this invention allow for spot sizes of less than 200 microns with resultant higher system resolution without seriously slowing line speed.

What we claimed is:

1. An x-ray target material made from an alloy, eutectic alloy, compound or intermetallic compound of two or more elements that produces useful characteristic x-ray line emissions from more than one element.

2. An x-ray target material for transmission x-ray tubes made by an alloy, eutectic alloy, compound or intermetallic compound wherein the melting point of the resultant mixture is higher than that of at least one of the element(s) producing useful x-rays;

wherein the anode substrate onto which the target is deposited is made of a material chosen from one of beryllium, aluminum, and copper or alloys thereof, and

wherein said element is chosen from one of manganese, copper, tellurium, zinc, silver, tin, barium, lanthanum, cerium, antimony, holmium, dysprosium, bismuth, praseodymium, neodymium, samarium, europium, antimony, barium, bismuth, ytterbium, gold, uranium, yttrium, palladium, gadolinium, terbium, erbium, and thulium.

3. An x-ray target material made by an alloy, eutectic alloy, compound or intermetallic compound wherein the reactivity in air or moisture of the mixture is lower than that of at least one of the elements(s) producing useful x-rays.

4. An x-ray target made by simultaneous deposition of two or more materials wherein the heat conductivity of the resultant deposited target is different than the heat conductivity of the mass equivalent materials layered separately one on the other.

5. An x-ray target made by depositing a target foil with a high vaporization rate onto an anode substrate;

wherein a thin layer of high melting point sacrificial material is deposited onto said target foil.

6. A transmission x-ray tube comprising:
an evacuated housing either sealed after evacuation or continuously evacuated;

an end window anode disposed in said housing comprised of a target of at least one thin foil attached to a substrate comprising an end-window substantially transparent to x-rays;

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a cathode disposed in said housing which emits an electron beam, which proceeds along a beam path in said housing to strike said anode in a spot, generating a beam of x-rays exiting the housing through the end window;

a power supply connected to said cathode and anode providing a selected electron beam energy to produce said beam of x-rays;

wherein a second thin foil is deposited on the side of the outside of the end-window where said electron beam does not impinge; and

wherein said second thin foil produces useful x-rays with energies significantly absorbed if passed through the end-window.

7. A transmission x-ray tube comprising:

an evacuated housing either sealed after evacuation or continuously evacuated;

an end window anode disposed in said housing comprised of a target of at least one thin foil attached to a substrate comprising an end-window substantially transparent to x-rays;

a cathode disposed in said housing which emits an electron beam, which proceeds along a beam path in said housing to strike said anode in a spot, generating a beam of x-rays exiting the housing through the end window;

a power supply connected to said cathode and anode providing a selected electron beam energy to produce said beam of x-rays;

wherein the e-beam is focused above, below or onto the target by a focusing lens; and

wherein a capillary or bundle of capillaries is placed in close proximity to the end-window to collect at least part of said x-ray beam and to guide x-rays to exit the other end of the capillary or bundle of capillaries.

8. A transmission x-ray tube for use in x-ray fluoroscopy comprising:

an evacuated housing either sealed after evacuation or continuously evacuated;

an end window anode disposed in said housing comprised of a target of at least one thin foil attached to a substrate comprising an end-window substantially transparent to x-rays;

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a cathode disposed in said housing which emits an electron beam, which proceeds along a beam path in said housing to strike said anode in a spot, generating a beam of x-rays exiting the housing through the end window;

a power supply connected to said cathode and anode providing a selected electron beam energy to produce said beam of x-rays;

wherein the e-beam is focused above, below or onto the target by a focusing lens; and

wherein collimation is used to guide the output x-rays to a location on the object being measured.

9. A closed transmission x-ray tube for use in x-ray fluoroscopy comprising:

an evacuated housing either sealed after evacuation or continuously evacuated;

an end window anode disposed in said housing comprised of a target of at least one foil attached to a substrate comprising an end-window substantially transparent to x-rays;

a cathode disposed in said housing which emits an electron beam, which proceeds along a beam path in said housing to strike said anode in a spot, generating a beam of x-rays exiting the housing through the end window;

a power supply connected to said cathode and anode providing a selected electron beam energy to produce said beam of x-rays;

wherein foil is between 10 and 70 microns thick and absorbs a high portion of the bremsstrahlung radiation of the x-ray tube adjacent to and higher than the energy of the k-absorption energy of said foil; and

wherein at least one element being measured by the x-ray fluoroscope produces at least one characteristic x-ray line emission of energy adjacent to and higher than said k-absorption energy.

10. A transmission x-ray tube of claim 9, wherein a second foil of x-ray generating material is deposited onto said foil wherein the second foil generates x-rays of appropriate energy to cause said element being measured to produce said characteristic line x-radiation.

11. An apparatus for examining objects in-line comprising:

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a transmission x-ray tube with a focused electron beam providing a focal spot on the target disposed inside such tube producing a beam of x-rays which exits the tube through the end-window of the tube forming a cone of x-rays;

a power supply connected to such tube providing a variable supply of electron beam energy and electron beam current and for said tube;

positioning of said tube and objects to be examined such that objects to be examined are placed inside the x-ray cone for irradiation by such x-rays;

an automated material handling apparatus to introduce the objects into said x-ray cone for examination and to remove them after examination is complete; and

at least one sensor placed in an appropriate location to sense x-rays which exit said object irradiated by x-rays from said transmission tube.

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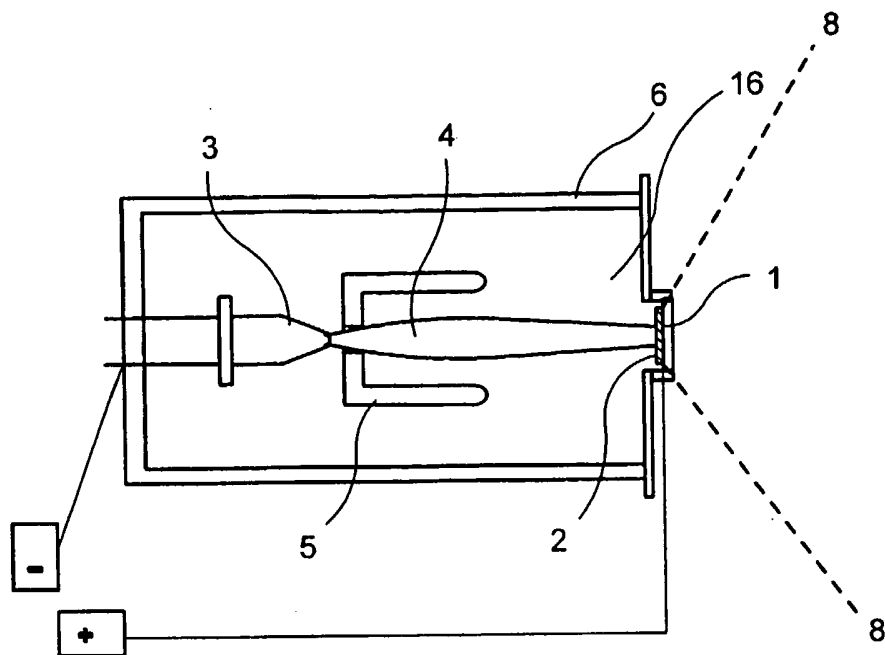


FIG. 1

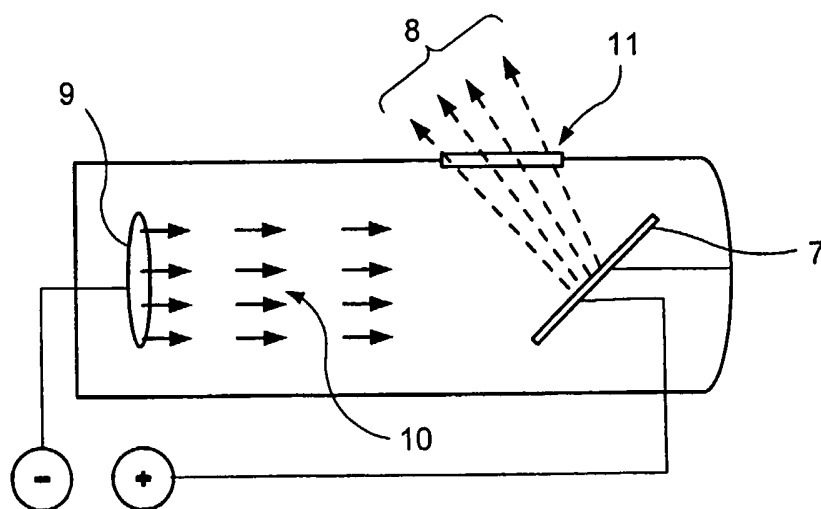
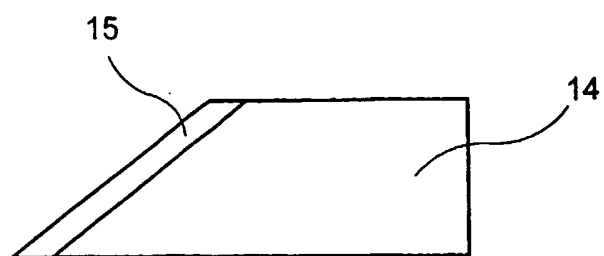
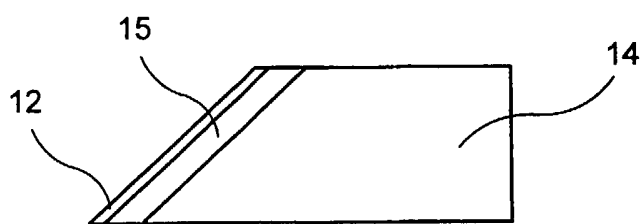


FIG. 2

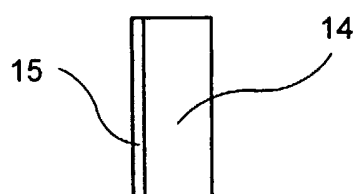
2 / 6



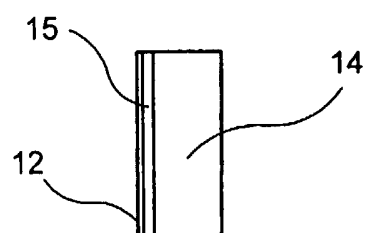
3A



3B



3C



3D

FIG. 3

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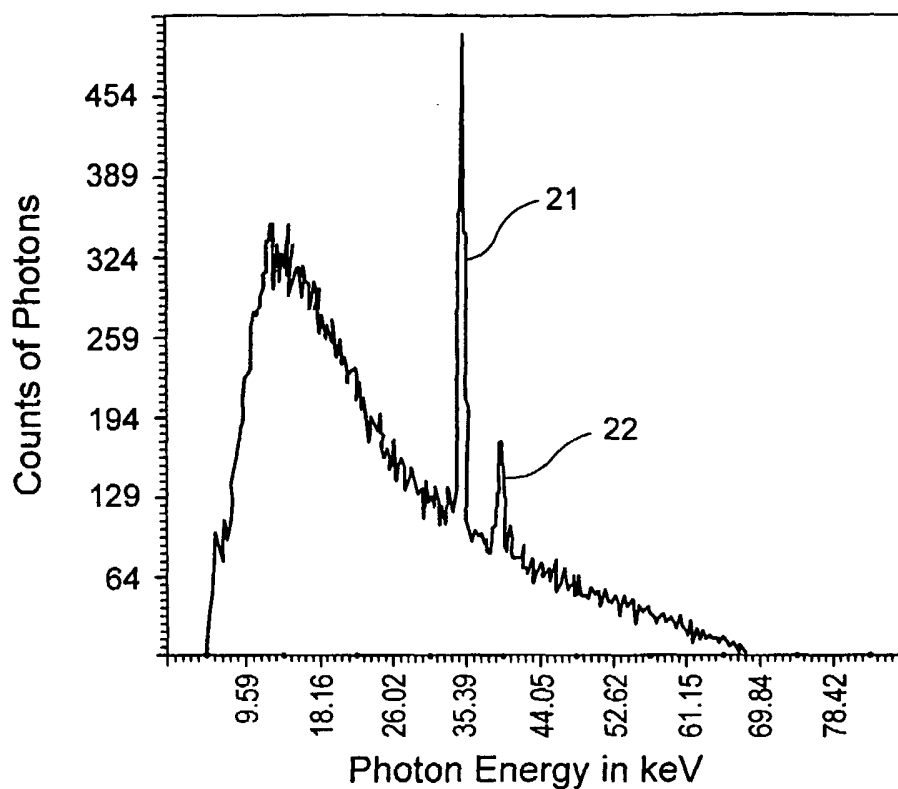


FIG. 4

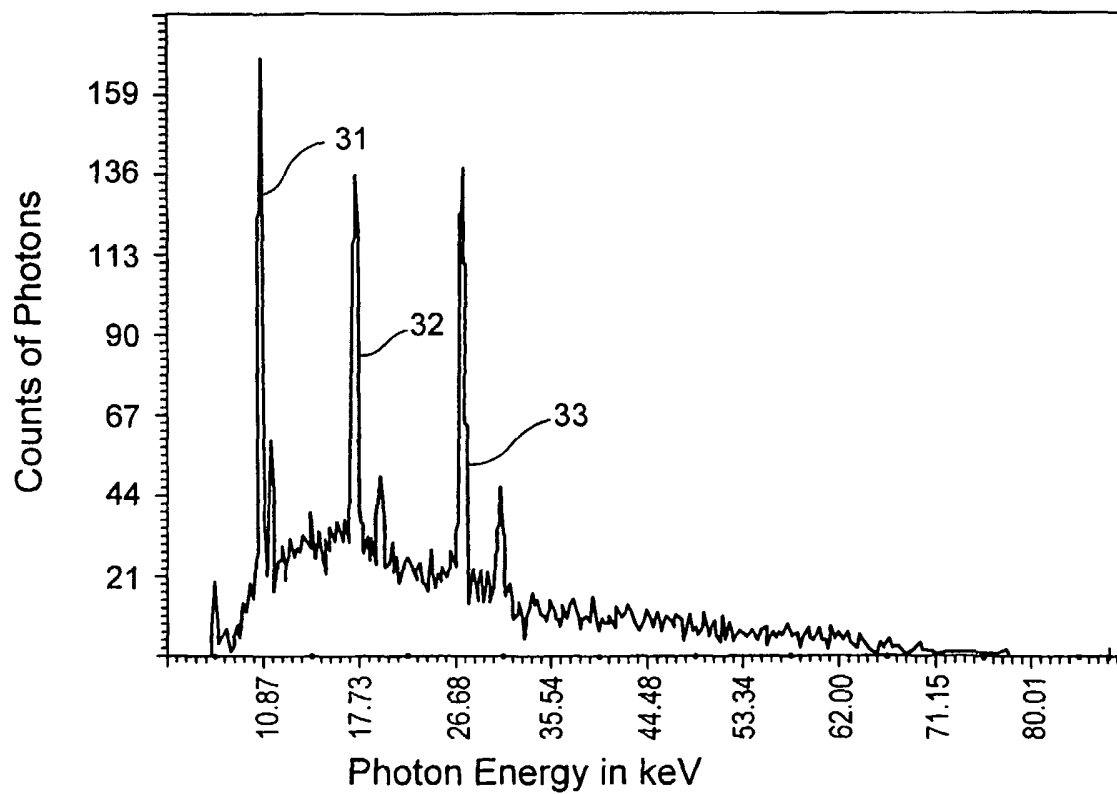


FIG. 5

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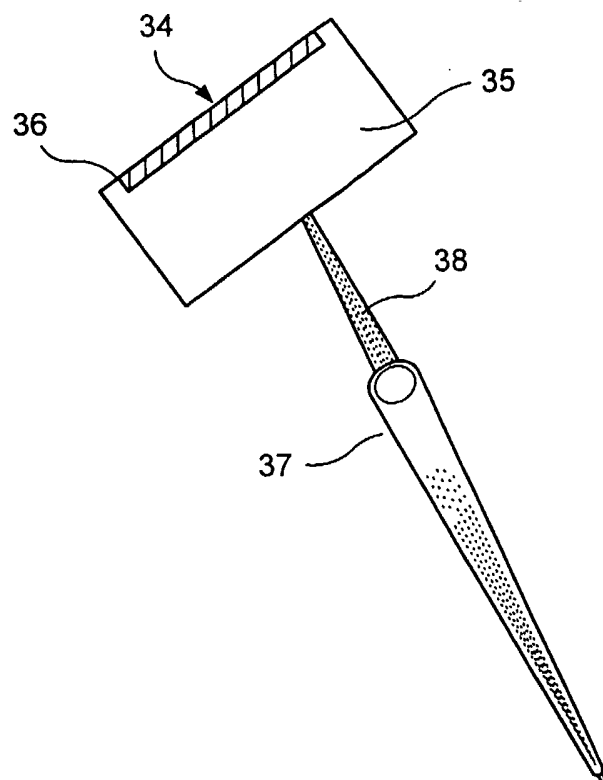


FIG. 6

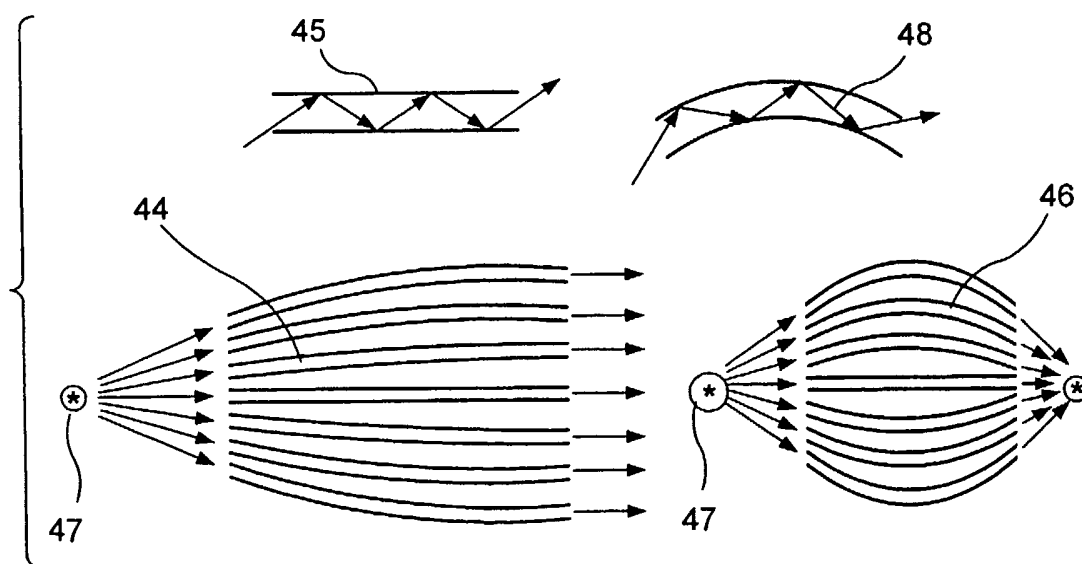


FIG. 7

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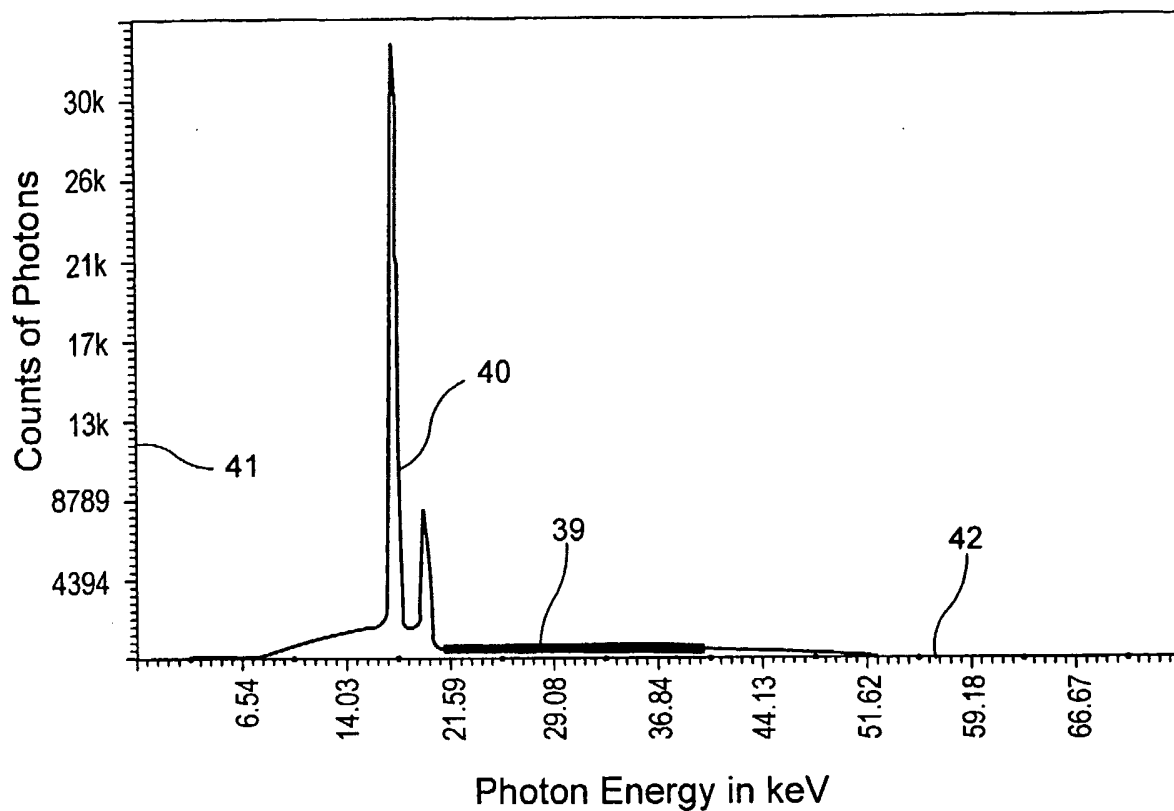


FIG. 8

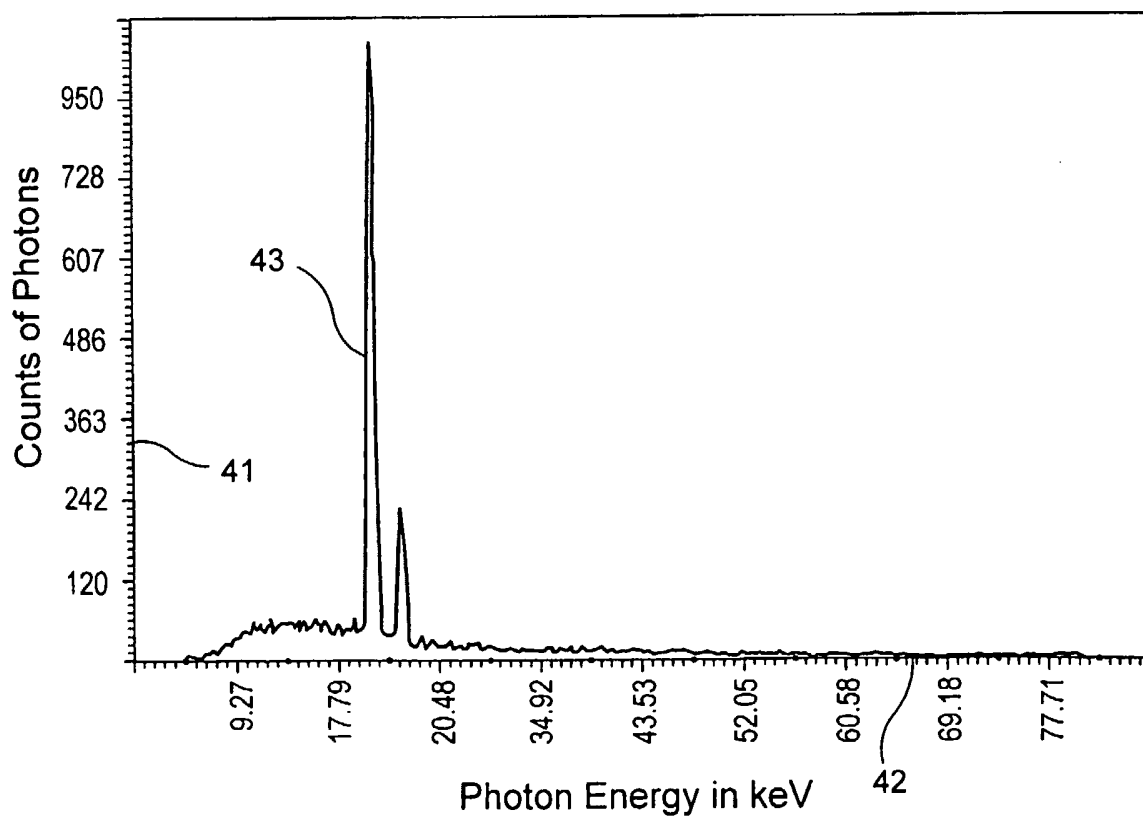


FIG. 9

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Comparison of Flux at Various Angles
Reflection Tube and Transmission Tube at 50 microA
and 60 kV Tube Voltage

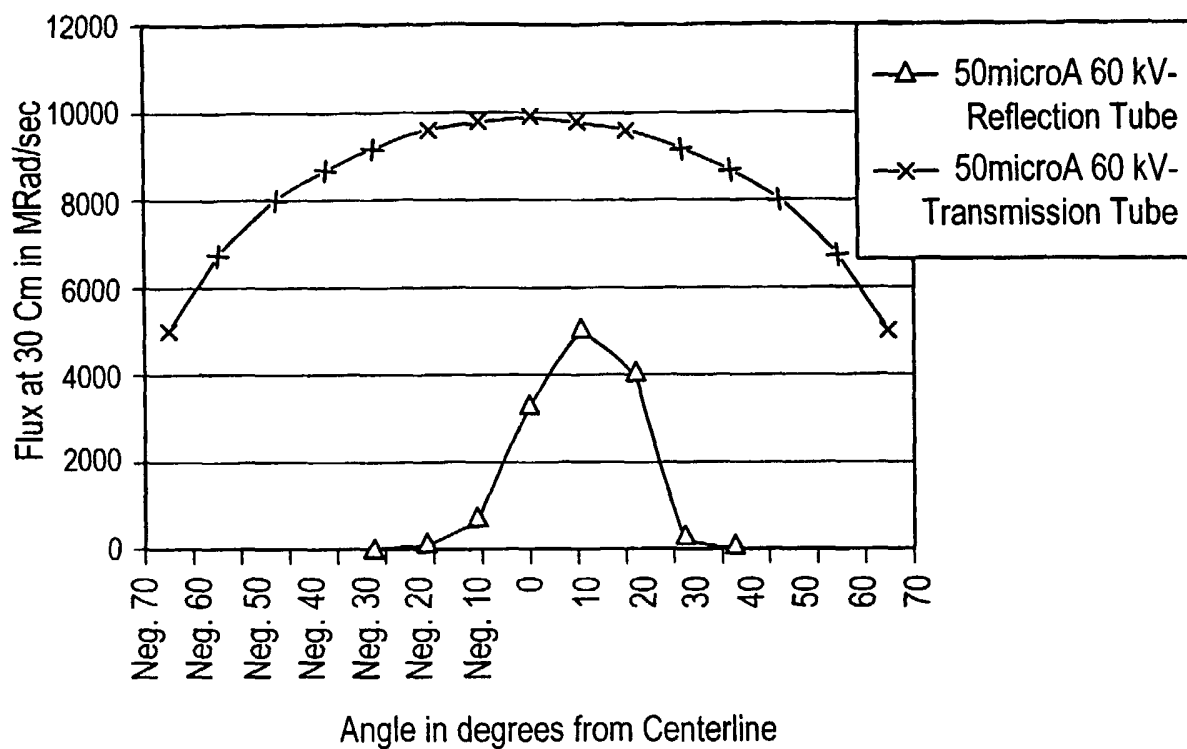


FIG. 10

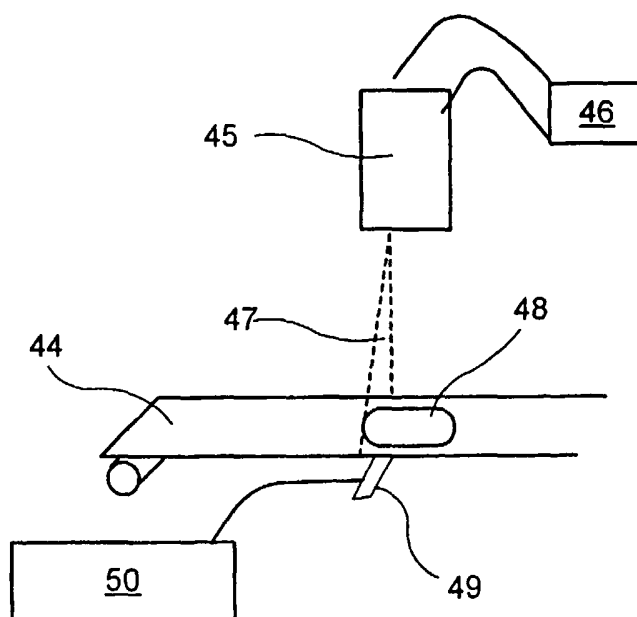


FIG. 11