

[54] **X-RAY IMAGE INTENSIFIER TUBES
HAVING THE PHOTO-CATHODE
FORMED DIRECTLY ON THE PICK-UP
SCREEN**

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[51] Int. Cl. **H01j 31/50**

[58] Field of Search..... **313/94, 101, 102, 92, 94, 95,
313/68; 252/301.4, 501; 250/213**

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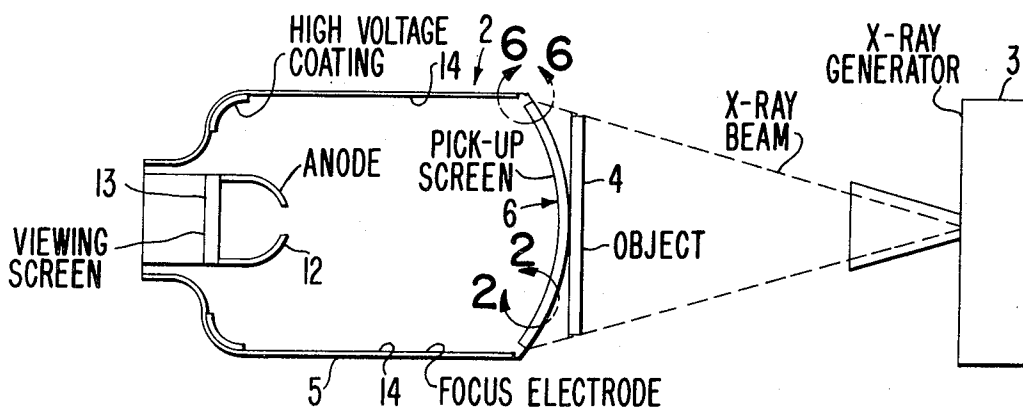
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[57] **ABSTRACT**

The present invention relates in general to x-ray image intensifier tubes and, more particularly, to an improved intensifier tube wherein the photo-cathode is formed directly on the x-ray sensitive phosphor pick-up screen without provision of an intermediate buffer, whereby the sensitivity of the x-ray intensifier tube is increased. Such improved x-ray image intensifier tubes are especially useful for, but not limited in use to, x-ray systems and for intensifying gamma ray images obtained in applications of nuclear medicine.

4 Claims, 6 Drawing Figures



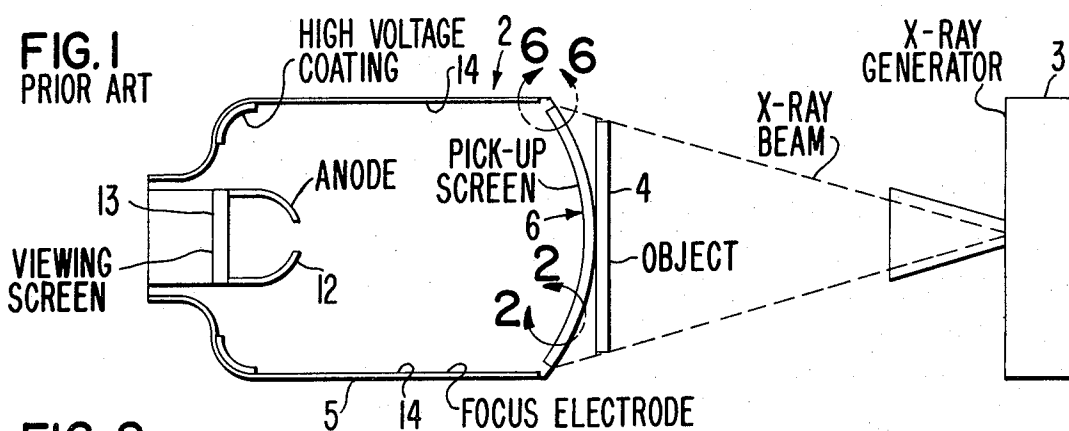


FIG. 2
PRIOR ART

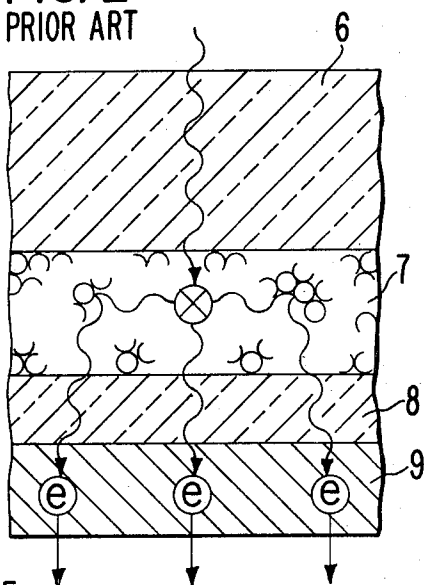


FIG. 3

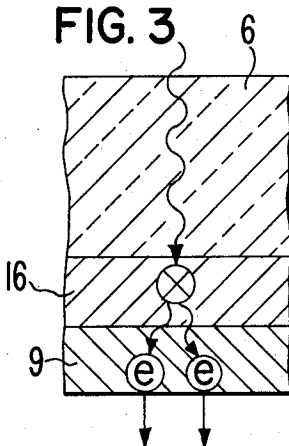


FIG. 6

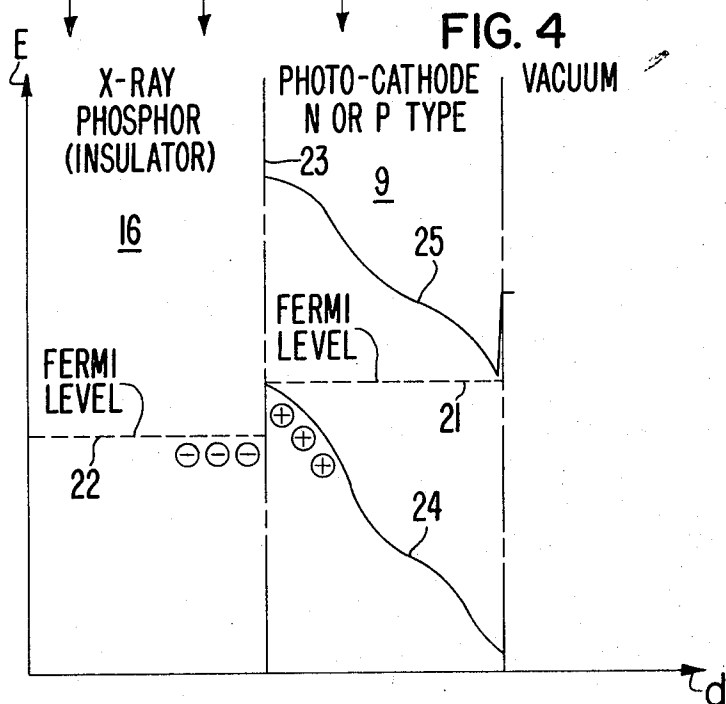
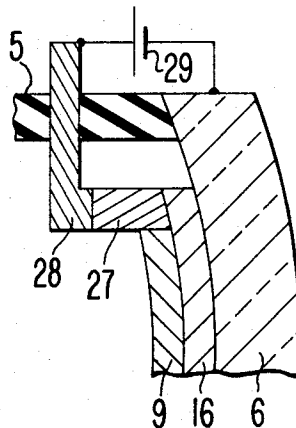
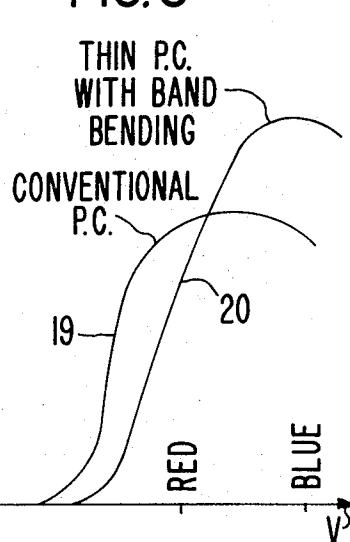


FIG. 5



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X-RAY IMAGE INTENSIFIER TUBES HAVING THE PHOTO-CATHODE FORMED DIRECTLY ON THE PICK-UP SCREEN

Heretofore, x-ray image intensifier tubes have been built wherein the photo-cathode was separated from the x-ray sensitive phosphor, of the pick-up screen, by a chemically inert optically transparent buffer layer. While the buffer layer serves to prevent unwanted chemical reactions between the ZnS x-ray sensitive phosphor of the prior art pick-up screen and one or more of the constituents of the photo-cathode; this buffer tends to detract from the sensitivity of the x-ray intensifier tube. In addition, formation of the buffer requires additional steps during the manufacturing process which it is desired to eliminate.

In the present invention, the x-ray sensitive phosphor of the pick-up screen is selected from the class consisting of alkali metal halides, preferably CsI, NaI or KI. The photo-cathode, preferably selected from the class of C_3Sb , K_3Sb and Rb_3Sb , is formed directly onto the alkali metal halide phosphor of the pick-up screen. In a preferred embodiment, the activator concentration for the pick-up screen material or other p-type dopant is increased at the interface between the pick-up screen and the photo-cathode in order to achieve a favorable band bending of the energy levels at the junction of the two members and, thus, substantially enhance the quantum efficiency of the photo-cathode, thereby improving the sensitivity of the intensifier tube. In another embodiment of the present invention, the photo-cathode is made thinner than that employed heretofore to still further improve the sensitivity of the x-ray intensifier tube.

The principal object of the present invention is the provision of an improved x-ray intensifier tube.

One feature of the present invention is the provision of an x-ray image intensifier tube wherein the photo-cathode is formed directly onto the x-ray sensitive phosphor of the pick-up screen, whereby the sensitivity of the intensifier tube is increased.

Another feature of the present invention is the same as the preceding feature wherein the x-ray sensitive phosphor is selected from the class consisting of an activated alkali metal halide.

Another feature of the present invention is the same as any one or more of the preceding features wherein the photo-cathode is selected from the class consisting of Cs_3Sb , Rb_3Sb , K_3Sb , $Sb-K-Na-Cs$, $Sb-K-Na$, or $Cs-Te$.

Another feature of the present invention is the same as any one or more of the preceding features wherein the photo-cathode layer has a thickness less than 300 Å, whereby the quantum efficiency of the photo-cathode is increased in a spectral region in which the phosphor screen emits.

Another feature of the present invention is the same as any one or more of the preceding wherein the alkali halide fluorescent material of the pick-up screen is doped with an increased concentration of p-type material at its interface with the photo-cathode material to produce a favorable band bending of the energy levels of the photo-cathode material to enhance the quantum efficiency of the photo-cathode.

Another feature of the present invention is the same as any one or more of the preceding features including the provision of means for applying a potential across

the x-ray pick-up screen for causing x-ray liberated electron current in the pick-up screen to drift across into the photo-cathode layer and there to add to the photoemission current for increasing the sensitivity of the image intensifier tube.

Other features and advantages of the present invention will become apparent upon the perusal of the following specification taken in connection with the accompanying drawings wherein:

FIG. 1 is a schematic line diagram of an x-ray system employing an x-ray image intensifier tube of the prior art,

FIG. 2 is an enlarged cross sectional view of a portion of the structure of FIG. 1 delineated by line 2—2,

FIG. 3 is a view similar to that of FIG. 2 depicting an alternate pick-up screen and photo-cathode construction of the present invention,

FIG. 4 is an energy level diagram for the x-ray sensitive phosphor interface and the photo-cathode showing the band bending effects,

FIG. 5 is a plot of photo-cathode current I versus frequency ν of applied optical radiation for the prior art photo-cathodes, and

FIG. 6 is an enlarged sectional view of an alternative embodiment of a portion of the structure of FIG. 1 delineated by line 6—6.

Referring now to FIG. 1, there is shown a prior art x-ray system employing an x-ray image intensifier tube 2. Such a system is described in an article entitled, "X-Ray Image Intensification With A Large Diameter Image Intensifier Tube," appearing in the American Journal of Roentgenology Radium Therapy and Nuclear Medicine, volume 85, pages 323-341 of February 1961. Briefly, an x-ray generator 3 serves to produce and direct a beam of x-rays onto an object 4 to be x-rayed. The image intensifier tube 2 is disposed to receive the x-ray image of the object 4.

The image intensifier tube 2 includes a dielectric vacuum envelope 5, as of glass, approximately 17 inches long and 10 inches in diameter. The pick-up face portion 6 of the tube 2 comprises a spherical x-ray transparent portion of the envelope 5, as of aluminum or conductive glass, which is operated at cathode potential. An image pick-up screen 7 made of x-ray sensitive particulated phosphor such as ZnS is coated onto the inside spherical surface of the envelope portion 6 to a thickness as of 0.020 inch. A chemically inert optically transparent buffer layer 8 is coated over the phosphor layer 7. A photo-cathode layer 9 is formed over the buffer layer 8.

In operation, the x-rays penetrate the object 4 to be observed. The local x-ray attenuation depends on both the thickness and atomic number of the elements forming the object under observation. Thus, the intensity pattern in the x-ray beam after penetration of the object 4 contains information concerning the structure of the object. The x-ray image passes through the envelope section 6 and falls upon the x-ray sensitive phosphor layer 7 wherein the x-ray photons are absorbed and re-emitted as optical photons, typically in the blue frequency range. The optical photons pass through the transparent buffer 8 to the photo-cathode 9 wherein they produce electrons. The electrons are emitted from the photo-cathode in a pattern or image corresponding to the original x-ray image. The elec-

trons are accelerated to a high velocity, as of 30KV, within the tube 2 and are focused through an anode structure 12 onto a fluorescent screen 13 for viewing by the eye or other suitable optical pick-up device. Electron focusing electrodes 14 are deposited on the interior surfaces of the tube 2 to focus the electrons through the anode 12.

In the intensifier tube 2, one 50 Kev photon of x-ray energy absorbed by the x-ray sensitive pick-up screen produces about 2,000 photons of blue light. These 2,000 photons of blue light produce about 400 electrons when absorbed in the photo-cathode layer 9. The 400 electrons emitted from the photo-cathode produce about 400,000 photons of light in the visible band when absorbed by the fluorescent viewing screen 13. Thus, the x-ray image is converted to the visible range and greatly intensified for viewing.

One of the problems with the prior art intensifier tube 2 is that the particulated pick-up screen has less than optimum resolution due to the fact that the particulated material has about one half the density of the material in bulk form. Thus, to provide a certain probability of stopping or absorbing an x-ray photon, the particulated layer 7 must have about twice the thickness of such a layer if it had bulk density. The thicker the layer 7 the poorer its x-ray resolution. Moreover, the particulated material serves to scatter the emitted optical photons, thereby still further reducing resolution.

In addition, it is desirable to utilize a pick-up screen material having a greater intrinsic stopping or absorbing power for x-rays. Such improved materials include the alkali metal halides such as, for example, CsI, KI, NaI, RbI, CsBr and LiI. These improved materials such as CsI and NaI are obtainable in bulk slab form from Harshaw Chemical Company of Cleveland, Ohio. However, when the flat slabs are distorted from the flat slab form into the spherical slab form, to conform to the spherical pick-up face 6 of the image intensifier tube 2, it is found that the conversion efficiency and resolution of the converted x-ray image is deleteriously affected.

Referring now to FIG. 3 there is shown a section of the x-ray pick-up screen formed in accordance with the present invention. More particularly, the alkali metal halide pick-up screen layer 16 is formed on the spherical x-ray transparent substrate member 6 by evaporation in vacuum and the photo-cathode is formed directly on the screen 16.

In one method for forming the screen, the substrate member 6 is cleaned and disposed in a vacuum chamber of a vacuum evaporator. A crucible containing the activated alkali metal halide phosphor in bulk form is heated to a temperature sufficient to evaporate the phosphor material, as by an electrical heating element. The evaporated activated alkali halide is condensed (deposited) on the substrate 6 to the desired thickness as of 0.010 inch for an x-ray image intensifier and to 0.060 inch for a gamma ray intensifier. As used herein, "x-ray" is defined to include x-rays and other high energy radiation including gamma ray radiation.

The bulk activated alkali metal halide may include any one of a number of different activators to render the pick-up screen 16 fluorescent upon absorption of x-rays at room temperature. For example, CsI may include ThI or NaI, Na or LiI as activators. After the screen layer 16 has been deposited, it is preferably an-

nealed to remove any residual minute plastic deformations thereof because such deformations have an adverse effect upon quantum conversion efficiency. A suitable annealing process is to heat the screen 16 in vacuum to within 10° C of the melting point of the screen material for 0.5 to 2.0 hours and then cool the screen 16 through to 400° C in 10 hours and then cool to room temperature in another 10 hours.

The deposited layer of phosphor 16 has a density approximately equal to the bulk density of the alkali halide material. Therefore, the x-ray stopping or absorption power of the layer 16 is substantially improved for a given thickness as compared to the prior particulated phosphor screens. Thus, the thickness of the layer 16 can be reduced compared to the prior screens, thereby providing improved resolution. Moreover, the spherical shape of the layer 16 does not interfere with resolution and conversion efficiency as would be expected to be encountered if a slab of the alkali halide material were shaped to conform to the spherical substrate 6. X-ray image intensifier tubes 2 employing an evaporated x-ray sensitive screen are described and claimed in copending U.S. application Ser. No. 606,514 filed Dec. 27, 1966, now abandoned and assigned to the same assignee as the present invention.

An alternative method for forming the x-ray sensitive phosphor pick-up screen is to slice up a thin flat slab of alkali metal halide phosphor material into sections approximately a centimeter on a side and to fit these sections together to provide a spherical shaped mosaic. The mosaic is bonded to the spherically shaped x-ray transparent envelope portion 6 by a suitable x-ray transparent high vacuum adhesive. Such an x-ray sensitive screen is described and claimed in copending U.S. application Ser. No. 604,764, filed Dec. 27, 1966, now abandoned and assigned to the same assignee as the present invention.

Once the x-ray sensitive pick-up screen 16 has been formed, the photo-cathode layer 9, according to the present invention, is formed directly over the screen layer 16 without the provision of an intermediate buffer layer 8.

The photo-cathode layer 9 is deposited over the x-ray screen layer 16 by evaporating in vacuum a layer of Sb from a bead of metallic antimony. The thickness of the Sb layer is preferably made less than a few hundred Å. The thickness is conveniently measured by monitoring the decrease in light transmission when employing an optically transparent conductive glass envelope portion 6 or by measuring the decrease in reflected light when employing an optically opaque envelope section 6, as of aluminum. The evaporation is stopped when the light transmission or reflection has dropped to about 85 percent of its initial value, this value corresponds to approximately 45 Å of Sb.

While the deposited Sb layer is held at a temperature within the range of 50° to 180° C, preferably 130° C, the Sb film is exposed to Cs vapor. With the reaction of Cs with Sb the resultant material changes from a metallic appearance to a reddish color in transmitted light and is accompanied by an increase in thickness to about 300 Å or less. The electrical resistance of the Sb layer increases indicating a transition from a metal to a semiconductor and a photoemissive current becomes measurable with white light illumination. With increas-

ing Cs content of the film, this current increases to a peak value and then decreases rapidly. When the peak is passed, the exposure to Cs vapor is discontinued and a baking process is continued until the photocurrent again reaches a maximum. During the subsequent cooling of the composite screen and photo-cathode to room temperature, the sensitivity usually rises appreciably. Finally, a very carefully controlled exposure of the photo-cathode surface to a slight amount of oxygen is used to increase the sensitivity of the photo-cathode still further.

While the above description of the photo-cathode material was limited to Cs_3Sb other photo-cathode materials may be employed. More particularly, many photo-cathode materials share common characteristics in that they are semiconducting intermetallic compounds of an alkali metal with metals of groups V and VI of the Periodic Table. While combinations of antimony and cesium have relatively high quantum efficiencies in the visible range, other materials are also useful. Such other materials include Na_3Sb , K_3Sb , Rb_3Sb , $(\text{NaK})_3\text{Sb}$, $(\text{Rb})(\text{NaK})_3\text{Sb}$, $(\text{Cs})(\text{NaK})_3\text{Sb}$ and Cs-Te . Of these materials K_3Sb and Rb_3Sb offer the advantage of reduced dark current.

Also during the activation process of the photo-cathode layer, i.e., during the reaction of the Cs or other vapor with the metallic deposit, the activation process is preferably monitored and optimized using a monitoring light source having an optical wavelength corresponding to the principal wavelength of the fluorescence of the X-ray sensitive phosphor screen layer 16. For example, CsI screen material, activated by ThI , fluoresces primarily in the blue wavelengths. Therefore, a blue light is preferably used for monitoring and optimizing the activation process for the photo-cathode layer 9.

In another embodiment of the present invention, the interface of the x-ray sensitive screen layer 16 with the photo-cathode layer is preferably doped in such a way as to produce a favorable band bending of the energy levels in the photo-cathode layer to enhance the photoemission efficiency. More particularly, the interface of the x-ray sensitive phosphor layer 16 is doped with an increased concentration of p-type dopant such as ThI or I which is added at the interface, as by evaporation, and diffused into the x-ray sensitive layer to a few 1,000 Å to produce a gradient of the p-type dopant at the interface.

Without such excess p-type dopant, the photo-cathode will exhibit certain quantum efficiencies for blue and red light photons, as depicted by curve 19 in the plot of FIG. 5, where photoemission current I is plotted as a function of frequency ν of the incident light photons. Typical peak quantum efficiencies for a conventional (Cs_3Sb) photo-cathode is typically 6 percent for red light and 12 to 20 percent for blue light. The concentration of the p-type dopant at the interface between the x-ray phosphor and the photo-cathode is very difficult to measure. However, the p-type dopant concentration is increased and the cathode thickness decreased to a value which raises the monitored peak blue quantum efficiency to a typical range of 20 to 35 percent. Such increase in the blue quantum efficiency is quite likely accompanied by a decrease in the peak red quantum efficiency to 3 percent or less. Curve 20

of FIG. 5 shows the improved response in the blue frequency range. This peaking of the quantum efficiency in the blue range substantially improves the efficiency of the photo-cathode and improves the sensitivity of the image intensifier tube 2.

It is believed that the mechanism for this improved quantum efficiency is one involving a favorable band bending of the energy levels within the photo-cathode layer 9. More specifically, FIG. 4 shows an energy level diagram for the doped interface of the phosphor 16 and the photo-cathode 9 when formed onto the phosphor 16.

The Fermi level 21 of the photo-cathode has an electropotential above the electropotential of the Fermi level 22 of the doped phosphor 16. When the two layers are formed in contact with each other, the Fermi level potentials in the two materials equalize to the same potential level. This results in electrons flowing across the junction 23 from the photo-cathode to the acceptor sites in the p-doped phosphor 16. The result is that the energy levels for the top of the valance band 24 and the bottom of the conduction band 25 in the photo-cathode 9 are bent upwards at the junction 23. This produces a favorable band bending in the photo-cathode layer 9 which facilitates photoemission because it provides an electrical field inside the photo-cathode at the junction 33 which will accelerate photoexcited electrons toward the surface.

As seen from the energy level diagram of FIG. 4, electrons generated in the photo-cathode see an electric field at the junction 23 in the photo-cathode which tends to cause these electrons to drift toward the surface of the photo-cathode which is exposed to the vacuum. This effect is enhanced in another embodiment of the present invention (see FIG. 6) by the provision of an electrical contact 27 formed on the edge of the photo-cathode layer 9. An electrical lead 28 is connected to the contact 27 and the lead 28 passes through the dielectric envelope 5. A source of potential 29 as of less than 1,000 volts is connected between the x-ray transparent conductive envelope portion 6 and the lead 28 for applying an electrical potential across the x-ray sensitive phosphor 16. This potential serves to cause electron current produced by the absorbed x-ray image in the phosphor 16 to drift across the junction 23 into the photo-cathode 9 and there add to the photoemission current of the photo-cathode 9.

Since many changes could be made in the above construction and many apparently widely different embodiments of this invention could be made without departing from the scope thereof, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

What is claimed is:

1. An x-ray image intensifier tube apparatus including an evacuated envelope structure having an x-ray transparent receiving face portion for passing x-ray images therethrough, an x-ray sensitive fluorescent layer forming a pick-up screen inside of said envelope for receiving the x-ray images and converting same to optical images, a photo-cathode for converting the optical images to electron image patterns, an electrode structure for accelerating the electron image patterns and focusing the electron patterns onto a fluorescent

screen to produce an intensified optical image for viewing which corresponds to the x-ray image, wherein the improvement comprises, said x-ray sensitive fluorescent layer being made of a material selected from the class consisting of activated alkali metal halides, and said photo-cathode being formed as a layer directly on said x-ray sensitive fluorescent layer, whereby the sensitivity of the image intensifier tube is enhanced and wherein said layer of x-ray sensitive pick-up screen material is doped at its interface with said photo-cathode with an increased concentration of p-type dopant to produce a favorable band bending of the energy levels of said photo-cathode material, whereby the quantum efficiency of said photo-cathode is increased.

2. An x-ray image intensifier tube apparatus including an evacuated envelope structure having an x-ray transparent receiving face portion for passing x-ray images therethrough, an x-ray sensitive fluorescent layer forming a pick-up screen inside of said envelope for receiving the x-ray images and converting same to optical images, a photo-cathode for converting the optical images to electron image patterns, an electrode structure for accelerating the electron image patterns and focusing the electron patterns onto a fluorescent screen to produce an intensified optical image for viewing which corresponds to the x-ray image, wherein the improvement comprises, said x-ray sensitive fluorescent layer being made of a material selected from the class consisting of activated alkali metal halides, and said photo-cathode being formed as a layer directly on said x-ray sensitive fluorescent layer, whereby the sensitivity of the image intensifier tube is enhanced and wherein said layer of x-ray sensitive pick-up screen material is doped at its interface with said photo-cathode layer with an increased concentration of p-type dopant in sufficient quantities to produce

an increased blue quantum efficiency typically falling within the range of 20 to 35 percent.

3. The apparatus of claim 2 wherein said pick-up screen layer is activated with an activator material and concentration of such activator material to cause the optical fluorescence of said pick-up screen to occur principally in the blue spectral range of optical wavelengths at room temperature.

4. An x-ray image intensifier tube apparatus including an evacuated envelope structure having an x-ray transparent receiving face portion for passing x-ray images therethrough, an x-ray sensitive fluorescent layer forming a pick-up screen inside of said envelope for receiving the x-ray images and converting same to optical images, a photo-cathode for converting the optical images to electron image patterns, an electrode structure for accelerating the electron image patterns and focusing the electron patterns onto a fluorescent screen to produce an intensified optical image for viewing which corresponds to the x-ray image, wherein the improvement comprises, said x-ray sensitive fluorescent layer being made of a material selected from the class consisting of activated alkali metal halides, and said photo-cathode being formed as a layer directly on said x-ray sensitive fluorescent layer, whereby the sensitivity of the image intensifier tube is enhanced and including means for applying an electrical potential across said x-ray pick-up screen layer for causing current in said pick-up screen generated by absorbed x-rays to flow into said photo-cathode layer and there add to the photoemission current, said potential applying means including a first electrode formed by an electrically conductive x-ray transparent receiving face portion of said vacuum envelope contacting one face of said pick-up screen and a second electrode formed by an electrical contact made to said photo-cathode layer for contacting the other face of said pick-up screen.

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