Modification of X-ray Generator by Energy Reusing

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Abstract: X-ray is an important tool for charactering and analyzing materials. However, current X-ray generation is cost with low efficiency. For X-ray tube, which is mostly used in laboratories, only has an energy usage of 1% with all other energy dissipated into tremendous heats, and it needs continuous cool water flows to cool down the cathode. It generates X-ray by the bremsstrahlung of high energy electrons bombarding on the cathode target, the bremsstrahlung would contain X-ray with sufficiently high energy of the electrons. But most part of the electron energy becomes heats. In order to generate X-ray more cheaply with higher efficiency, methods about reusing the released heats during the working of the X-ray tube are brought up. Mimicking the photovoltaic effect, nonequilibrium carriers could also be injected via thermion emission when heating a metal, such injection is same to that of photonic injection which produces electromotive in a photovoltaic cell. In a photovoltaic cell the electron-hole pair generated by incident photons are nonequilibrium carriers that causes electromotive, while the thermion emission creates such electron-hole pairs via thermal excitation. Connecting metals suitable for thermion emission from the cathode into the p-n junction so that thermions as nonequilibrium carriers can be well injected into the p-n junction when the metals are heated by the cathode, with Thomson effect which enhances such injection, a thermal voltaic cell can be constructed and it can produce electricity only by heating the metals outside. Applying such thermal voltaic cell into current X-ray tube, it would produce electricity while absorbing the tremendous heats emerges when X-ray tube is working. Water flows are still used to control the temperature, but letting them boiling to keep the cathode at a temperature best for thermal voltaic cell, and the vapor may be used to drive a mini thermal power plant. In this way, the energy usage could be modified to a higher proportion. Stepwise up-conversion is possible to generate X-ray more cheaply but there are no suitable materials so far.

Key words: X-ray, Thermion, Semiconductor Device, Thermal Voltaic, p-n Junction, Nonequilibrium Carriers, Thermal Electricity, Conversion

1 Introduction[1]

X-ray was first discovered by Röntgen in 1895 and has a wide range of application. It is revealed as a kind of electromagnetic wave, because it can be diffracted by crystals (its traveling at the speed of light and not being induced by mass should manifest its electromagnetic property). For its high energy packet X-ray has low absorption and good penetration, and its ability to hit the electrons in energy levels close to the nucleus, it could cause phenomena that is inaccessible by usual photons.

For example, when an X-ray photon hit an electron in K shell of an atom, the jumping of electron from higher shells into this hole would emit characteristic X-ray, i.e., monochromic X-ray with each photon,

$$\varepsilon = \frac{2\pi^2 m e^4 (z-\sigma)^2}{h^2} \cdot \left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right) \tag{1}$$

this property can be used to element analysing.

X-ray has been applied to analyse energy levels inside atoms, measuring defects in materials and analysing crystal structure etc. For a crystal surfaces with distance d, using Bragg formula,

$$2d\sin\theta = n\lambda \tag{2}$$

a known λ corresponds to a special d is computable by measuring the interference in terms of θ:

$$2d\sin\theta_n = n\lambda$$
$$2d\sin\theta_m = m\lambda$$
$$d = \frac{\lambda}{2}\frac{m-n}{\sin\theta_m - \sin\theta_n} \quad (3)$$

the more data used, the more precise the result.

As interpreted in the appendix, current X-ray generator uses a tube with high energy electrons bombarding the target to produce bremsstrahlung. Yet, such X-ray generator produces too much heat with too less X-ray. Only 1% of the total energy can be used effectively, the other part of the energy was all converted into useless energy.

For the enormous heat produced by the current X-ray generator, it needs consistent stream of cold water to cool the target down and the tuber is easy to be broken for such tremendous heats. Such amount of heat and low efficiency raises up costs and dangerous when generating X-ray.

To modify this low energy use, a thermal voltaic cell that produce electricity from heats was brought up and was applied into current X-ray tube, combining with a mini thermal power plant to control the temperature. The water used in the mini thermal power plant is that used to cool down the cathode in the original instrument.

Such heat voltaic cell also verifies what Boltzmann interpreted about the entropy, that the second law of thermodynamics is only valid for an isolated system and it should be probabilistic for a non-isolated system. Any macroscopic process has possibilities to go against the natural, entropy-increasing direction.[2]

2 Up Conversion with Photovoltaic Effect Method

Using several kinds of materials, photons can be converted into high frequency with the total energy unchanged. That's a process called up-conversion[3].

In an atom, there are several layers of electrons, i.e., $K, L, M, N \cdots$ shells. Each layer belongs to degenerate eigenstates of a certain energy in the atom, the number of the degenerate states of a same energy represents the maximum number of electrons that may be filled in each layer. When electrons transfer from an energy level onto another energy level, the same amount of energy would simultaneously be released. Usually such process emits or absorbs photons.

When photons going through some kinds of special materials, such as non-linear optical crystals, the metastable energy levels of atoms produced by these materials will help electrons to be excited into higher energy levels with photons that have lower energy in each wave packet than the excitation energy needed onto higher energy levels directly. Just like some stepping stones used to climb onto a high mountain, the electrons on the lower energy eigenstates can stay in these metastable states temporally and absorb more photons at these states. When photons are energetic enough to be absorbed by these metastable states, these electrons would be uplifted again into higher energy states. In this way, a high excitation states can be produced by several photons without the frequency that is needed to make such excitation state at one time. Finally, the characteristic photons would be produced by the reversing of these final excitations.

However, the photons of X-ray have much higher frequency even than that of ultraviolet, say, more than 1,000 times as energetic as ultraviolet photons; therefore, it is much harder to produce such kinds of material that can convert visible or infrared photons into X-ray than up-conversion from the infrared. A more accessible way is to upconvert photons with several steps, i.e., converting infrared light into visible light first, then converting these visible lights into ultraviolet, and converting those ultraviolet into higher frequencies and so on. Probably such kinds of mechanism can be accessed in future, with some new materials, but this surely needs time.

Since up-conversion can convert infrared light into visible light[4], or from visible light into ultraviolet[5], the extra thermal energy can be converted into visible or ultraviolet photons and then produce electricity using photovoltaic effect. In this way, the infrared caused heats can be converted into electromotive of a photovoltaic cell.

Many kinds of materials are able to make up-conversion of infrared to visible light or visible to ultraviolet light[6]. Er^{3+} doped cadmium chloride and zinc chloride glass can convert visible light into ultraviolet[5]; TADF fluorescein derivative can convert red light into blue light[7]; Some kinds of nanoparticles are also competent for such conversions.

3 Thermal Electricity Generator

Thermal power plants burn billions of tons of fossil fuels every day. These electricity generators, called alternator, turn the thermal energy produced by them into electric power via a principle found by Michael Faraday, who could be a greater scientist if he got more professional trainings. The principle is named electro-magnetic induction, it describes the current produced when a close cycle of circuit was being cut by moving magnetic field lines. All the alternator today is made according to this principle, every house needs the electricity produced in this way.

As mentioned before, the target of the X-ray generator produces enormous amount of heat, and the heat is so dangerous that even a little scarce of cooling system would damage the generator. For this reason, these dangerous heats can be used to construct a mini thermal power station like those used today to cool down the system[8].

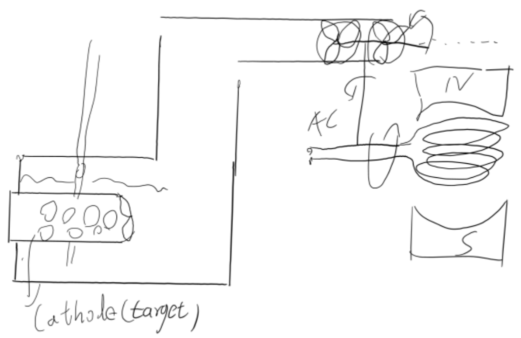

Fig.1 Mini power generator in an X-ray generator

As shown in Fig.1, the cathode was embedded into a container filled with relatively low boiling points and stable chemistry properties such as water. Several turbines are posed on the only outlet of the container[9]. When the X-ray tube starts working, the heat produced when the high energy electrons bombarding on the cathode would be absorbed by the liquid in the container. And the liquid would be spoiled into gas which would rush out to boost the turbine's rotation. Like those wind power station and hydro power station, the rotation of these turbines produces alternating current and the energy lose through heat dissipation in the generation of X-ray can thus be recycled. If the acceleration voltage is substituted with this electric energy partly, the total efficiency will be improved. At least the percent of effective energy would be larger than 1%. Of course, this electricity can be used into other instruments, this modified X-ray tube takes a role as an energy source in this respect.

Even if this does not produce much electricity, it is a better way to control the temperature of the system so that makes the thermal voltaic cells which would be introduced in section 3 work well.

4 Thermal Injection for p-n Junction

Let's have a short review of the structure of solar cell first. As Fig.2 shows, by doping a semiconductor with donor and accepter with some technologies, a p-n junction can be formed in a semiconductor where the p region was doped by donor (more free electrons), such as phosphorous, and the n region was doped by accepter (more free holes), such as boron[10]. In this way, the electrons and holes that excess the 4 covalent bonds of each site in the lattice will combine and leave the sites which contribute them an opposite charge, i.e., the p-n junction would get a space charge layer with a built-in electric field.

In the process of photovoltaic effect in p-n junction, a photon would tear a combined electron-hole pair apart and the electrons and holes would be transferred to the other side of the space charge layer by the built-in electric field, and the energy from the sun was thus converted into the electromotive between p layer and n layer.

The essence of electric generation of such solar cell is that, the energy released by an electron and a hole in p-n junction is larger than the electric potential between them; consequently, they combine with each

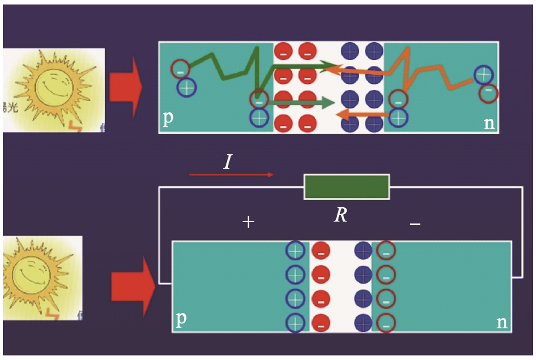

Fig.2 Solar cell

other to reach an equilibrium and release positive energy. However, when a photon that is energetic enough to hit the combined electrons or holes in the p-n junction, the pairs become apart again and go back to the layer under the built-in electric field where they stay originally. In this way, the photons inject nonequilibrium carriers hence reverse the equilibrium by electron-hole combination and hold an electromotive between p layer and n layer [11-12]. For the combination energy of nonequilibrium carriers are larger than the electric energy they needed to mate, their strong trend to mate makes an electromotive between the p layer and n layer, called photoelectromotive [11]. This process also lowers the electric potential of the built-in electric field, as shown in Fig.3. In Fig.3, 1 and 2 are the potential between p layer and n layer, the motion of 3 and 4 is the reverse motion of the combination of electrons and holes from donor and acceptor respectively. The combination energy holds such potential and the incident light reverse their combination.

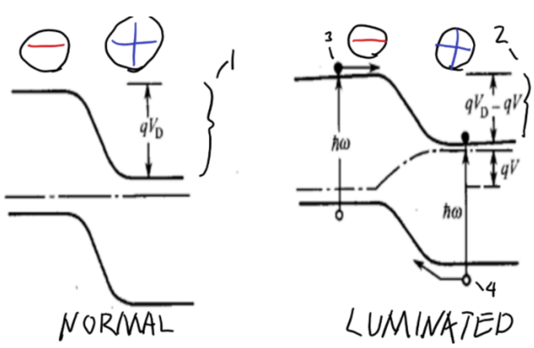

Fig.3 The energy band in p-n junction

In fact, any process that inject nonequilibrium carriers into p-n junction, i.e., processes that generate electron-hole pairs nearby the p-n junction have same effect of electricity generation. They hold the system at nonequilibrium and these nonequilibrium carries lead to electromotive between p and n layer, which possess a higher potential that is needed for the carriers to overcome the built-in electric field they form after their recombination, no matter recombined via the current or the diffusion in p-n junction. For this reason, theoretically, the voltaic effect could also be generated by thermal power, and this is a thermal voltaic effect.

If doping some semiconductor that is able to release thermions with donor and acceptor similarly, electron-hole pairs is still able to be separated by the built-in electric field so that an electromotive can be formed. This heat injection is another kind of nonequilibrium carrier injection. After that, the electromotive can be used to accelerate the electrons to produce more X-ray, or to do anything that is useful. In addition, the hotter the semiconductor is, the higher the density of thermions would be, and higher power of electricity can thus be produced.

However, the temperature for thermion emission is always very high for semiconductor, and this may destroy the devices themselves; hence, it is necessary to find ways to inject nonequilibrium carriers by heat in relatively low temperature, i.e., under several hundred K, and it should also be combined with mini thermal alternator previously, such that the temperature would not be excessively high so that the device can work safely, while these excessive heats also become electricity.

5 Result: Thermal Voltaic Cell and X-ray Tube Modification

As mentioned in section 3, it is possible to inject nonequilibrium carriers by heat, but what we need is to manage this at relatively low temperature. If we manage this, electricity can be generated in small cells only contacting with relatively high temperature source, without other changes. This is rebel to the second law of thermodynamics, but Boltzmann said this is possible because the entropy is probabilistic, the good consistence between Planck's blackbody radiation formula verified this[2]. The second law of thermodynamics should be only valid for closed system. These heats were converted into electricity by our mental works, and this is a probabilistic process.

As shown in ref. [13], under the background of several kinds of gases, the temperature for thermion emission of gold varies and they are only few hundred K, that is ideal for nonequilibrium injection into semiconductor p-n junctions to generate electromotive. More works in relevant areas are possible to find more ideal materials for nonequilibrium injection via absorbing heats, with good conductivity of electricity and heats.

With such thermion emission of metals at relatively low temperature, connecting such metals from the cathode target of the X-ray tube into the p-n junction around its space charge layer, with good thermal contact between the metals and the cathode target, the enormous heat from the bombardment of electrons on the target would generate electromotive between the p layer and n layer of the junction via the thermions emitted by the metals; hence, the heat is able to be converted into electricity which is available again. Utilizing such electricity would cool down the target and recycle those heat into useful energy again, of course they can be used to generate X-ray again. To protect such devices, it should be combined with the mini thermal power station as that in section 1.

In addition, electricity thermal effect also contributes to injecting nonequilibrium carriers for metals [9]. Thomson effect produce electromotive when a conductor has temperature gradient. This is equivalent to a voltaic cell, the electrons tend to diffuse from high temperature region to low temperature region in such processes; thence, the temperature gradient would add an electromotive from low temperature to high temperature. When electrons are propelled by this electromotive, they would absorb the heats to gain energy, and this enhances the nonequilibrium injection into the p-n junction.

As shown in Fig.4, connecting some kinds of metals (4 in the figure) that has good performance on thermion emission as well as electric and thermal conductivity from the cathode target in X-ray tube into a p-n junction around its space charge layer , with good contact to both the target and the inside of p-n junction, combined with a mini thermal power plant of which the water flow cools down the system, added with the contribution from the thermal electricity effect, a p-n junction will generate a remarkable electromotive using the tremendous heats of the cathode target created by the X-Ray tube when generating X-ray.

The metal absorbs heats and emits thermions as nonequilibrium carriers which would be injected into the p-n junction and create electromotive, and such process is enhanced by Thomson effect. The mini thermal power plant uses the water vapor produced by the water flow which is used to control the temperature of the cathode target. When the water is heated by the cathode the vapor would propel the mini thermal power plant.

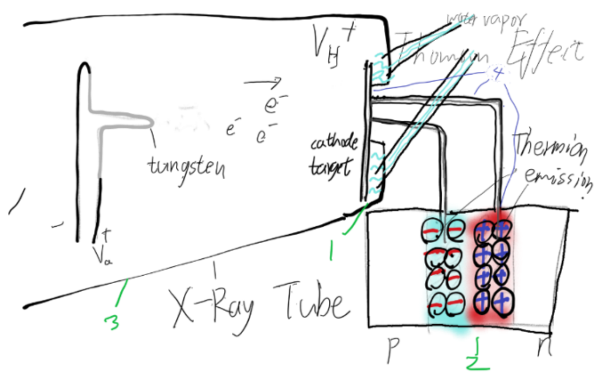

Fig.4 The X-ray tube connect with thermal voltaic cell

X-ray tube is introduced in the appendix, the thermion emission into the p-n junction generates electromotive between p layer and n layer.

This modification would level up the energy efficiency in X-ray generation and the structure from 4 to 2 in Fig.4 constitute a thermal voltaic cell which is able to produce electricity via absorbing heat. The metal denoted by 4 absorbs heat and injects nonequilibrium carriers into the p-n junction with the enhancement from Thomson effect in it, an electromotive larger than the built-in electric field after the recombination of these carriers would be generated between the p and

n layer of the p-n junction. Such thermal voltaic cell can be used in any condition as long as the material denoted by 4 can be heated at a moderately high temperature, usually about several hundred K. The water flows of the mini power plant denoted by 1 control the temperature at several hundreds K so that the thermal voltaic cell can works healthily.

6 Conclusion

Mimicking photovoltaic effect, a p-n junction is able to generate electromotive via any kind of nonequilibrium carrier injection including thermal injection. Utilizing thermion emission of large variety of metals at relatively low temperature, i.e., about several hundred K, thermions can be injected as nonequilibrium carriers into a p-n junction and generate electromotive consequently. Connecting such kinds of metals or any materials that is good at thermion emission as well as good thermal and electric conductivity into a p-n junction, with good thermal and electric contact at both sides, the electricity could be generated by heating these metals or materials. It works as long as the thermions can be emitted when heating these metals or materials and injected into a p-n junction structure. Such mechanism could be called as a thermal voltaic effect, it absorbs heats and convert them into electricity. What’s more, it does not make extra changes, just like that of converting photons into electricity by photovoltaic effects. For metals, the Thomson effect caused by temperature gradient would also enhance the thermion emission as well as their injection into the p-n junction. This device is called as thermal voltaic cell, mimicking photovoltaic cell.

In an X-ray tube, the bombardments of electrons on the cathode target always generate tremendous heats and only 1% of the energy can be used to create X-ray effectively. This instrument always needs continuous cool water flows behind the cathode to control the temperature.

Combining a mini thermal power station as introduced in section 1, this thermal voltaic cell is capable to generate electricity with the tremendous heats emerges as the X-ray tube is working. For the energy is conserved in this process, such electricity generation would cool down the cathode target while converting those heats into electricity. And the mini thermal power station controls the temperature of the cathode while converting the extra heats into electricity as well. It is noticeable that thermal voltaic cell generates DC but the mini thermal power station generates AC. And if the thermal voltaic cell works enough powerful, the mini thermal power station may just cool down the temperature when the remarkable electricity is being generated by the cell.

Up-conversion is another possible way to generate X-ray with lower energy loss. However, there is no suitable materials to convert infrared or ultraviolet into X-ray, a photon of X-ray is 1000 times energetic as an ultraviolet photon, i.e., each X-ray photon needs 1000 ultraviolet photon. It is possible to convert infrared, visible light and ultraviolet into X-ray into higher frequencies stepwise, which makes the frequencies increase exponentially, but this needs more works in relative area and it is not certain whether such mechanism can be found successfully. Up-conversion is able to convert infrared emitted by hot bodies into visible light or to convert visible light into ultraviolet for now, and visible light and ultraviolet are capable of generate electricity via photovoltaic effects.

In a word, using the thermion emission effect enhanced by Thomson effect when heating some kinds of metals, nonequilibrium carriers can be injected into a p-n junction and therefore generate electromotive larger than the built-in electric field after their combination, such that these heats is converted into electricity. Like photovoltaic effect, such mechanism does not cause other changes, it can be called as a thermal voltaic effect which produce electricity by heat, and a device for such mechanism is called a thermal voltaic cell, as mentioned before. The energy usage in an X-ray tube can therefore be improved by the application of such thermal voltaic cell combined with a mini thermal power plant that controls the temperature.

More works are needed to find more ideal materials for thermal thermion emission with good conductivity of electricity and heats, and metals have an advantage of Thomson effect. More studies are needed in photon conversion.

Appendix: Structure of X-ray Tube[14]

As that shown in Fig.5, current X-ray generator generally consists of an electron source, a high voltage accelerating electric field and a target (cathode) onto which high speed electrons will bombard. The principles under such X-ray generator mainly come from electrodynamics: when an electron with energy of few tens of eV suddenly brakes on the cathode, electromagnetic waves with frequencies between X-ray range would be released. This is the so-called bremsstrahlung.

The Tungsten Anode in Fig.4 plays a role as an electron source. Letting a small current pass through the tungsten, it would be heated up so that electrons can absorb those heat and escape from the tungsten. The tungsten with currents circuiting inside emits thermions into the free space.

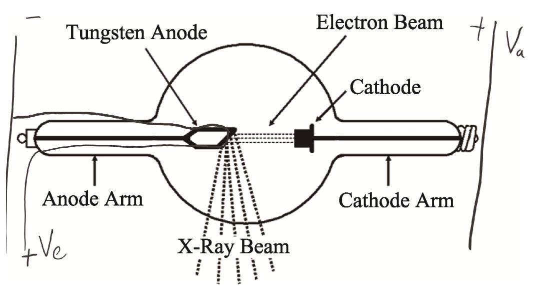

Fig.5 Structure of general X-ray generator. $V_a \gg V_e$

The free space between the anode and the cathode should be vacant, through which the electron can go through without energy loss. And there is also a high electric voltage difference between the anode and the cathode through which electrons can be accelerated into a few tens of keV. When such electrons bombard onto the cathode, the steep deceleration of it would release bremsstrahlung, and this is the source of X-ray in an X-ray tube. With other optical facilitates, different kinds of X-ray can be produced in this tube, such as monochromatic X-ray.

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