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Electrical Characteristics of Flat Cesium Antimonide Photocathode Emitters in Panel Devices

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The Cs_3Sb photocathode was formed by non-vacuum process technology. An in-situ vacuum device was fabricated successively with flat cesium antimonide photocathode emitters fabricated in a process chamber. The electrical properties of the device were characterized. Electron emission from the devices was induced by photoemitted electrons, which were accelerated by an anode electric field that was shielded from the photoemitter surface. The electrical characteristics of the devices were investigated by measuring the anode current as a function of device operation times with respect to applied anode voltages. Planar blue LED light with a 450 nm wavelength was used as an excitation source. The results showed that the cesium antimonide photocathode emitter has the potential of long lifetime with stable electron emission characteristics in panel devices. These features demonstrate that the cesium antimony photocathodes produced by non-vacuum processing technology is suitable for flat cathodes in panel device applications.

Keywords: Photocathode, Flat emitter, Reflective mode, Current density, Charge dose

1. INTRODUCTION

Cesium antimonide (Cs_3Sb) is a well-known mono-alkali compound semiconductor photocathode [1,2]. The main reasons for its successful use in electron emission devices are as follows: good characteristics regarding photon absorption, low work function (sum of the band gap energy and the electron affinity in this case), relatively high quantum efficiency in the visible region, lower dark current, fast response time in the picosecond range, tolerance of vacuum contaminants below 10^{-6} Torr, reasonable lifetime, ease of fabrication (only two chemical species), and intrinsic crystalline structure.

It is intrinsically a p type semiconductor with the band gap energy of 1.6 eV and the electron affinity of 0.45 eV [2,3]. It also has a reflective emission mode with a long electron diffusion length and high quantum efficiency in the visible spectral range (over 10% for blue light) [4]. Unlike negative electron affinity materials which owe their high quantum efficiency essentially to a monolayer of Cs adsorbed at the surface, Cs_3Sb photocathodes are bulk materials in a highly crystalline form and therefore possess a superior lifetime as desired in the accelerator environment. It is easier to manufacture than multi-alkali photocathodes such as Cs_2KSb or Na_2KSb, yet has a good response in the visible spectral range. In addition, it can be easily converted from the p type semiconductor to an n type semiconductor by adjusting the amount of Cs in the thermo-chemical Cs-Sb reactions.

The conventional method of photocathode production is complicated and complex. It requires ultra-high vacuum (UHV) conditions, at least below 10^{-7} torr, in manufacturing processes [5-10]. It also requires specialized and expensive equipment. It can only be performed by highly trained engineers. The photocathode formation area is usually small and is therefore limited to small sized and highly specialized device applications.

In the present paper, we report on Cs_3Sb photocathode production using non-vacuum processing technology and a successive in-situ evacuated panel device fabrication. The processing technology is viable for low-cost manufacturing. For the panel device, Cs_3Sb photocathodes are utilized as flat electron emitters, which are suitable for general applications. By observing the

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electrical properties of the devices, we examined the electrical characteristics of the Cs_3Sb photocathode emitter in the panel device. We find that the Cs_3Sb photocathode produced using a non-vacuum processing technique has stable electron emission characteristics without fluctuation as a function of an elapsed time. It also demonstrates the possibility of an extended long lifetime with a characteristic of re-cesiation under various operating conditions, which makes it a suitable cathode material for panel devices.

2. EXPERIMENTS

A glove-box-type process chamber is the experimental setup for fabrication. The Cs_3Sb photocathode is produced and an evacuated panel device is then fabricated in situ within the process chamber. The panel device is connected to a vacuum furnace on the side as well as a thermal evaporator on the bottom.

The process chamber is bakable and filled with an inert gas such as N_2 (99.999% pure) to prevent a reaction between the photocathode and oxygen and/or water molecules. The chamber also comprises an oven and a molten bath. The role of the molten bath filled with a sodium metal is to absorb O_2 and H_2O molecules in the chamber, keeping the levels of both O_2 and H_2O maintained below 0.01 ppm. Thus, the process chamber can maintain optimal atmospheric conditions throughout all fabrication processes in a strictly controlled manner. In addition, the process chamber has an evacuation tool for the evacuated panel devices.

For photocathode production, we prepare a metal sheet with a thickness of 100 μm as a substrate. Micro-hole arrays are fabricated on the metal substrate by photolithography and wet etching (Fig. 1). The diameter of the hole on the top region is around 90 μm, while that on the bottom region is about 180 μm. The difference in diameter is due to the anisotropic etching profile of the metal. The first part in the production procedure of the photocathode is the deposition of antimony on the bottom region of the metal substrate by the thermal evaporator. The film thickness is about 300 Å, controlled by a quartz crystal thickness monitor. Production of Cs_3Sb photocathode is prepared by heating the oven to 150 ~ 170℃, and evaporating Cs to the antimony surface in the oven. The vapor of the Cs thermo-chemically reacts with the antimony layer to yield a stable Cs_3Sb compound. The vapor does not react with the metal substrate due to the antimony layer which is deposited on the metal substrate. This microstructure, with the photocathode formed on the bottom side, was attached to the cathode plate for device fabrication, followed by in-situ device fabrication in the process chamber

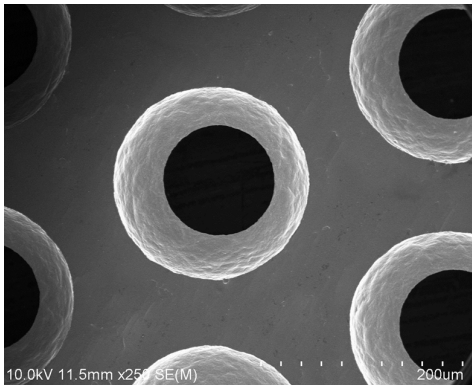

Fig. 1. Schematic diagram of a microstructure with patterned micro-holes showing images of bottom side.

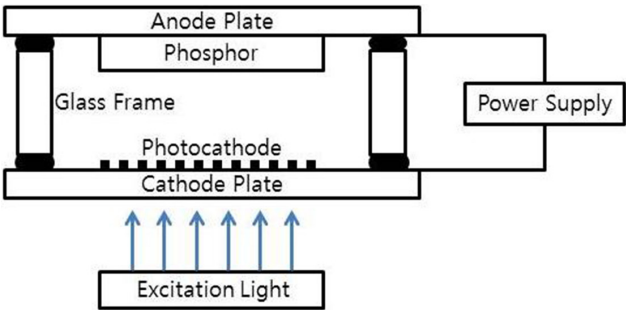

Fig. 2. Schematic diagram of a measurement set-up of the photocathode vacuum device.

For panel device fabrication, we prepare the following components: an anode plate (600 mm × 600 mm × 5 mm) with P-22 green phosphor (ZnS:Cu, Al), a glass frame (500 mm × 500 mm × 5 mm), and a cathode plate (700 mm × 700 mm × 5 mm) . The material used for the substrate plates and the frame is soda-lime glass. Thermal treatment for all materials is carried out in the vacuum furnace prior to fabrication in order to minimize outgassing during device operation. The bottom region of the metal substrate is attached to the cathode plate. The process steps for making the panel device are similar to those for the field emission device. The anode plate and the cathode plate are aligned and sealed with the glass frame between them. The gap distance between the anode plate and the cathode plate is 500 mm due to the glass frame. The device is evacuated after sealing by using an evacuation tool equipped within the process chamber of the glove box. When the pressure reaches 1.0×10^{-6} Torr, it is capped and finally an evacuated panel device is ready for operation. The vacuum level of the panel based on this evacuation method is usually higher than the values on capping by at least one order of magnitude. More details regarding the fabrication of the evacuated panel device can be found elsewhere [10,11].

Figure 2 shows a schematic diagram of a test set-up of the photocathode vacuum device. For electrical measurements, the evacuated panel device is placed on a lamp in such a way that the cathode plate faces the LED planar lamp. Blue light with a wavelength of 450 nm was used as a photocathode excitation light source. The luminance of the excitation light source LED lamp was 1,000 cd/m^2. A variable DC power supply was used to provide the anode with voltages from 0 to 30 kV. The value of the corresponding emission current was monitored from a 4-digit indicator with the power supply.

The brightness of the device was measured together with the relevant photometric data using a BM-7 luminance colorimeter by Topcon.

3. RESULTS AND DISCUSSION

In the photocathodes, optical power decays exponentially according to the Lambert-Beer law $P(z) = P(0) \exp(-\alpha z)$, where α is the absorption of the coefficient specific of the photocathode material and the wavelength of light, and z is the penetration depth of the material [13]. The distribution of absorbed photons in the photocathode layer is the loss of optical power -dP(z). It has the same shape as P(z), so the distribution of the created electron-hole pairs also follows the same exponential shape. In order to be emitted from the photocathode, the photo-induced electrons in the conduction band of the photocathode must reach the photocathode surface by diffusion.

In the transmissive mode, photons enter the photocathode

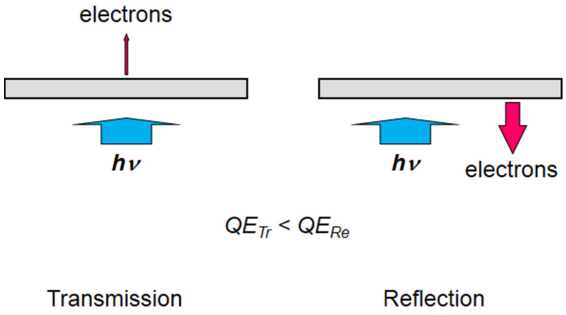

Fig. 3. Schematic diagram of photocathode emission. Photocathodes can be classified according to the photoelectron emission process into a transmissive mode and a reflective mode.

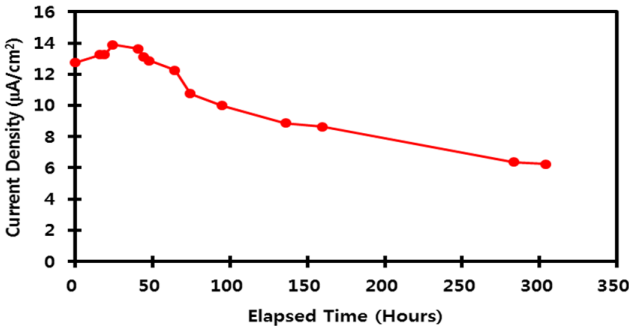

Fig. 4. Emission current density versus elapsed time plot of a Cs_3Sb emitter based panel device with Cu anode plate.

layer from one side, while the photoelectrons emerge into a vacuum on the opposite side of the layer. The photoelectrons must be emitted at a surface that is far from the photon entry surface. The electrons have a relatively low chance to diffuse from the region close to the photon entry surface to the surface on the opposite side. Therefore, the transmissive photocathode has very low quantum efficiency (QE).

In the reflective mode, however, the situation significantly differs. The photoelectrons are emitted through the same surface by which the photons have entered. The majority of electron-hole pairs are created very close to the photon entry surface due to the Lambert-Beer exponential law and therefore have a high chance of reaching the same surface and escaping through it into the vacuum. As a consequence, the reflective photocathode offers QE nearly twice that of the transmissive photocathode [13].

Figure 3 illustrates a schematic diagram of the photocathode emission modes. The reflective photocathode has many important advantages over the transmissive photocathode. Apart from a higher QE and a wide spectral range in sensitivity, it has the very important advantage of a simple manufacturing process. This leads to a very significant cost reduction. In addition, since photons do not need to pass through the photocathode, its thickness to be deposited is not critical.

Figure 4 shows a change of emission characteristics of the Cs_3Sb emitter in the panel device as a function of the elapsed time. The Cu deposited anode plate without phosphors was used in this device. The electron emission in the panel device is a photoemission based field assisted process. The emitter was continuously operated for over 300 hours under a bias field of 2 V/μm. As shown in Fig. 3, the emission current density did not fluctuate in response to the excitation light and decreased with time. The initial current density was as high as 13 μA/cm^2 and decreased to the value of 6.3 μA/cm^2, 50% of the initial value which can be

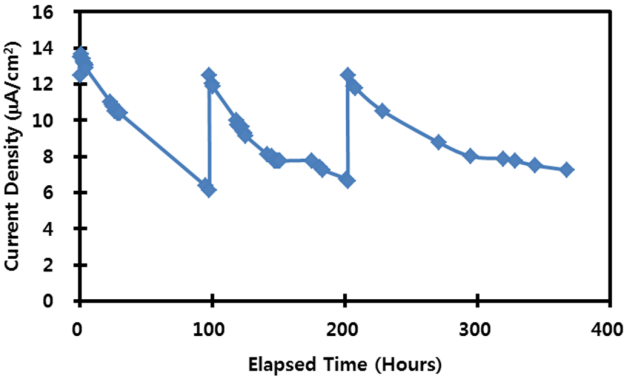

Fig. 5. Emission current density versus elapsed time plot of a Cs_3Sb emitter based panel device with a P-22 green phosphor coated anode plate.

considered as the lifetime in this experiment, after 300 hours of operation. This indicates that the QE of the emitter gradually degraded during the device operation. It seems that the occurrence of degradation behavior at standard running conditions partly related to a gradual change of the crystalline Cs_3Sb microstructure by evaporating Cs under continuous optical and electrical stresses.

Figure 5 presents the current density evolution with time for the panel device continuously running for more than 350 hours. The initial current density level was 13 μA/cm^2. It gradually decreased with stable emission characteristics to 6.5 μA/cm^2, a level at about half the initial current density, after 100 hours. At this point, we raised the input light until the current density again read 13 μA/cm^2 in order to investigate the emission characteristics of the photocathode emitter in the device. Interestingly, it was observed that the initial current density gradually decreased to 6.5 μA/cm^2 after 110 hours. This indicates that the second successive emission profile is similar to the previous emission profile, with an extended lifetime of the 50% decay in the initial current density. We adjusted the input light again to reach the initial current density level of 13 μA/cm^2. The third successive emission profile was also similar to the previous emission profile, with the current density starting at 13 μA/cm^2 and reducing to 7.3 μA/cm^2 after 170 hours, resulting in a more extended 50% decay of lifetime. One possible explanation for the mechanism observed is that the Cs vapors, evaporated from the original Cs_3Sb surface under optical and electrical stresses for the device operation and present as residual Cs vapors in the device [14], react with the partially degraded Cs_3Sb to form a fresh Cs_3Sb surface under operating conditions. Another important factor that affects the operation of a phosphor coated panel device is outgassing from the phosphors. The rate of outgassing is usually high in the first part of the device operation, and then decreases with an extended operation time. For the extended lifetime of the 50% decay, it can be explained that the reactive Cs vapors also react with the outgassing species, which results in better vacuum conditions and induces less degradation of the photocathode due to vacuum contaminants. These results indicate that the Cs_3Sb emitter based evacuated panel device can have the potential of long lifetime as long as the vacuum pressure levels are maintained to some extent. The degradation could be correlated with the total amount of charge per unit area falling on the anode plate. The electron charge dose accumulated on the anode plate is determined from the time of operation and the average current.

Figure 6 shows the cumulative charges deposited on a unit

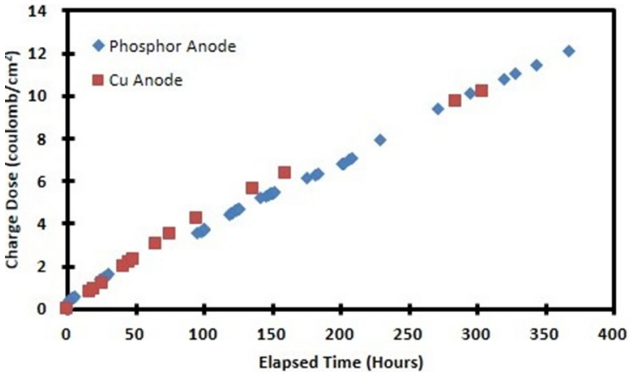

Fig. 6. Cumulative charge doses as a function of elapsed time in the operation of the device with the design shown in Fig. 2.

area in coulomb/cm^2 as a function of time. The cumulative charge dose increases with time in contrast to the current density. As shown in the figure, the charge doses deposited on the Cu plate are almost the same as those deposited on the phosphor plate as a function of time. In other words, the charge dose with respect to the elapsed time is nearly the same regardless of anode conditions when the same excitation light is used for the panel devices. This indicates that the emitter degradation depends on the cumulative charge dose at constant anode voltage and it appears rapid at first followed by a more gradual decline. In addition, the photo-responsivity of a photocathode can be identical to the same excitation light source.

4. CONCLUSIONS

We successfully demonstrated the production of a Cs_3Sb photocathode using a simple non-vacuum experimental setup and fabrication of a successive panel device in-situ. The Cs_3Sb photocathode produced was stable in the operation of the panel device, comparable to that of commercially available photonic devices produced under ultra-high vacuum environments. The measured parameters such as current density, charge doses, and a 50% decay lifetime exhibited stable characteristics without fluctuation. The Cs_3Sb emitter exhibited the capability of high current density and an extended lifetime, making it a suitable cathode material for planar panel device applications.

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