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A Study on Operating Lifetime of Cs_3Sb Emitters in Panel Device Applications

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Non-vacuum processing technology was used to produce Cs_3Sb photocathodes on substrates and fabricate in-situ panel devices. Electrical properties of these panel devices were characterized by measuring anode current and charge dose as functions of devices operation time. An excitation light source with a 475 nm wavelength was used for photocathodes. Results showed that emission properties of these photocathode emitters depended heavily on the vacuum level of these devices and that Cs_3Sb flat emitters had the potential of operating for a long lifetime with stable electron emission characteristics via re-cesiation process in the panel device. These features make Cs_3Sb photocathodes suitable as flat emitters in panel device applications.

Keywords: Photocathode, Quantum efficiency, Current density, Excitation source, Spectral range

1. INTRODUCTION

The Cs_3Sb photocathode is intrinsically a p type semiconductor with band gap energy of 1.6 eV and electron affinity of 0.45 eV [1]. It also has a reflective emission mode with a long electron diffusion length and high quantum efficiency in visible spectral range (over 10% for blue light). Unlike negative electron affinity materials with high quantum efficiency essentially due to a monolayer of Cs adsorbed at the surface, Cs_3Sb photocathodes are bulk materials in highly crystalline form. Therefore, they possess superior lifetime which is desired in an accelerator environment. It is simpler to manufacture Cs_3Sb photocathodes than making multi-alkali photocathode such Cs_2KSb or Na_2KSb. In addition, it can be easily converted from a p type semiconductor to an n type semiconductor by adjusting the amount of Cs in thermo-chemical Cs-Sb reactions.

Conventional method of photocathode production is complicated. It requires ultra-high vacuum (UHV) conditions (at least below 10^{-7} torr) in the manufacturing process [2-6]. It requires specialized and expensive equipment. Photocathode formation area is usually small. Thus, applications of photocathodes have been restricted. They are used in evacuated glass tubes such as photodiodes, photomultipliers, and imaging tubes [7-9]. One reason is that photocathodes are chemically very reactive when operated in the very best vacuum environments.

In the present paper, we report the production of Cs_3Sb photocathode by using a 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. They are suitable for general applications. By measuring the emission current and charge dose, we examined electrical properties of Cs_3Sb photocathode emitter in the panel device. We found that the Cs_3Sb photocathode produced by the non-vacuum processing technique had stable electron emission characteristics without fluctuation as a function of an operation time. It also demonstrated a possibility of having extended and long lifetime with characteristic of re-cesiation under operating conditions, making it a suitable cathode material for panel devices.

2. EXPERIMENTS

A glove-box-type process chamber was used as the experimental setup for fabrication. The Cs_3Sb photocathode was produced and sequentially an evacuated panel device was fabricated in situ within the process chamber. It was connected to a vacuum furnace on the

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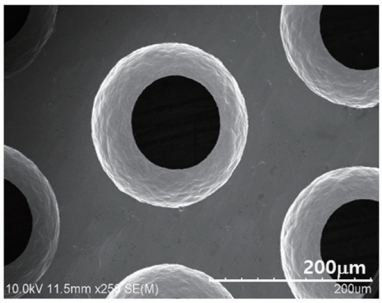

Fig. 1. Schematic diagram of a microstructure with patterned micro-holes at the bottom.

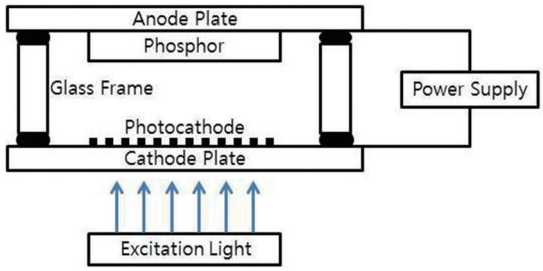

Fig. 2. Schematic diagram of a measurement set-up for the panel device based on Cs_3Sb photocathode emitters.

side as well as a thermal evaporator on the bottom.

The process chamber was filled with an inert gas such as N_2 (5N purity) to prevent reaction between the photocathode and oxygen and/or water molecules. An oven and a molten bath were placed in the chamber. The molten bath was filled with a sodium metal. The role of molten sodium was to absorb O_2 and H_2O molecules in the chamber, keeping levels of both O_2 and H_2O below 0.01 ppm. Thus, the process chamber could maintain optimal atmospheric conditions throughout all fabrication processes in a strictly controlled manner.

For photocathode production, we prepared a metal sheet at thickness of 100 μm as substrate. Micro-hole arrays were fabricated on the metal substrate by photolithography and wet etching (Fig. 1). The diameter of the hole on the top region was around 90 μm while that on the bottom region was about 180 μm. The difference in diameter was caused by anisotropic etching profile of the metal. The first part in the production procedure of the photocathode was the deposition of antimony on the bottom region of the metal substrate by a thermal evaporator. The film thickness was about 300 Å. It was controlled by a quartz crystal thickness monitor. Cs_3Sb photocathode was prepared by heating the oven to 150 ~ 170℃ and evaporating Cs to the antimony surface in the oven. The Cs vapor reacted with the antimony layer thermo-chemically to yield a stable Cs_3Sb compound. This microstructure with photocathode formed on the bottom side was attached onto the cathode plate for device fabrication. In-situ device fabrication was then followed in the process chamber.

For panel device fabrication, we prepared the following components: two kinds of anode plates (600 mm × 600 mm × 5 mm, one with Cu thin film, the other with P-22 green phosphor), a glass frame (500 mm × 500 mm × 5 mm), and a cathode plate (700 mm × 700 mm × 5 mm). These components were all soda-lime glasses. Thermal treatment for all materials was carried out in the vacuum furnace prior to fabrication in order to minimize outgassing during device operation. The bottom region of the metal substrate was attached to the cathode plate. The process steps for making the panel device were similar to those for making field emission device. The anode plate and the cathode plate were aligned and sealed with the glass frame between them. The device was evacuated after sealing by using an evacuation tool equipped within the process chamber of the glove box. When the pressure reached 1.0×10^{-6} Torr, it was capped. Finally, an evacuated panel device was ready for operation. More details regarding fabrication of the evacuated panel device can be found elsewhere [10].

Figure 2 illustrates a schematic diagram of the panel device with measurement setup. For electrical measurements, the device was placed on the planar excitation light source in a manner such that the cathode plate faced the light. Blue light with a wavelength of 475 nm was used as a photocathode excitation light source. A variable DC power supply was used to provide the anode with voltages from 0 to 30 kV. A value of corresponding emission current was monitored with a 4-digit indicator with the power supply.

3. RESULTS AND DISCUSSION

These Cs_3Sb photocathodes have emission mode of reflection, in which light is incident on the photocathode and electrons are emitted backwards. In this case, the thickness of the photocathode is less critical in the reflective mode. Precise control of the diffusion process is not required for the thickness of the produced photocathode.

Figure 3 shows a change of emission current of the Cs_3Sb emitter in the panel device as a function of an operation time. Cu film 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/m. As shown in Fig. 3, the emission current density did not fluctuate in response to the excitation light. It was decreased with time. The initial current was as high as 111 A, corresponding to current density of 14 A/cm^2. After 95 hours of operation, it was decreased to a value of 80 A, corresponding to current density of 10 A/cm^2. This indicated that the emitter was gradually degraded in QE during the device operation. It appeared that the degradation behaviour occurred at standard running conditions partly related to gradual change of the crystalline Cs_3Sb microstructure by evaporating Cs under continuous optical and electrical stresses.

Figure 4 shows emission current of the panel device with green phosphor coated ITO anode plate. Measurement conditions were the same as those for Fig. 3. The initial current was as high as 109 A, similar to the value in Fig. 3. After 95 hours of operation, it was decreased to 51 A, corresponding to current density of 6.4 A/cm^2. The degradation rate was much faster. Possible explanations for such difference lie in anode plates. During device operation, it is clear that outgassing from the phosphor coated plate is much larger than that from the Cu film coated plate. The outgassing might have

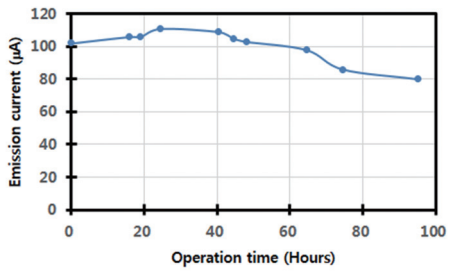

Fig. 3. Emission current vs. operation time plot of a Cs_3Sb emitter based panel device with Cu anode plate.

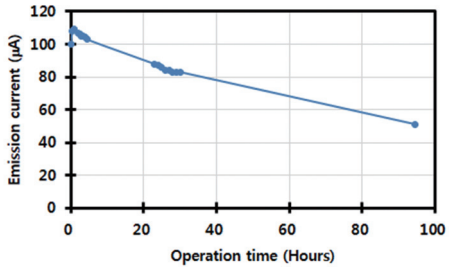

Fig. 4. Emission current vs. operation time plot of a Cs_3Sb emitter based panel device with a green phosphor anode plate. The initial current was decreased to a level half of the initial value after 95 hours of operation.

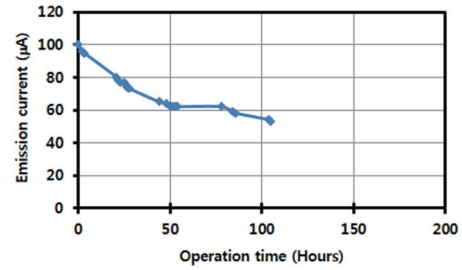

Fig. 5. The second successive emission profile with extended 50% decay lifetime in the initial current after 105 hours of operation.

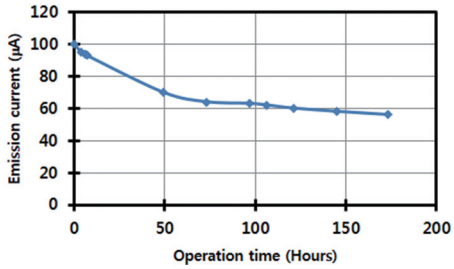

Fig. 6. The third successive emission profile with more extended 50% decay lifetime after 173 hours of operation.

affected the vacuum level of the device, resulting in fast degradation of the emission current. This indicates that vacuum level is an important factor for the device operation.

In Fig. 4, the initial current level was 109 A. It was gradually decreased to 51 A after 95 hours with stable emission characteristics. At this point, we raised the input light until the current level read was 100 A again in order to investigate the emission characteristics of the photocathode emitter in the device. Interestingly, it was observed that the initial current was gradually decreased to 53 A after 105 hours of operation (Fig. 5). This indicates that the second successive emission profile is similar to the previous one with an extended lifetime to reach the same emission current.

We adjusted the input light again to reach the current level of 100 A. The third successive emission profile was also similar to the previous one with current starting from 100 A. It was decreased to 56 A after 173 hours of operation, resulting in more extended decay lifetime (Fig. 6).

One possible explanation for the mechanism observed is that the Cs vapors might have evaporated from the original Cs_3Sb surface under optical and electrical stresses for the device operation and presented as residual Cs vapors in the device [9], reacting with

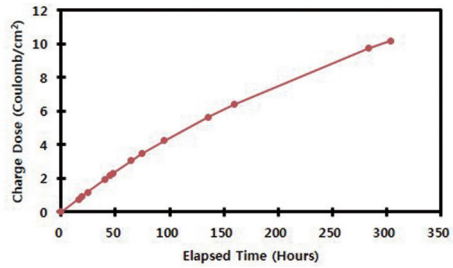

Fig. 7. Cumulative charge doses as a function of elapsed time during operation of the device with Cu film coated anode plate. The third successive emission profile shows more extended 50% decay lifetime after 173 hours of operation.

partially degraded Cs_3Sb surface to form a fresh Cs_3Sb surface under operating conditions. This is a kind of re-cesiation process.

Another important factor that might have affected the operation of a phosphor coated panel device is outgassing from phosphors. The rate of outgassing is usually high in the first part of the device operation. It then decreases with an extended operation time. Regarding the extended decay lifetime, reactive Cs vapors might have also reacted with the outgassing species, resulting in better vacuum conditions and inducing less degradation of the photocathode due to less vacuum contaminants. These indicate that the Cs_3Sb emitter based evacuated panel device might have potential of having a long lifetime as long as proper vacuum pressure levels are maintained.

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 was determined by the time of operation and the average current. Figure 7 shows cumulative charges deposited on a unit area in coulomb/cm2 as a function of time. The cumulative charge dose was increased with time, contrary to current density. The charge doses deposited on a phosphor plate were almost the same as those deposited on Cu anode plate as a function of time. Hence, charge dose was almost the same with respect to operation time regardless of anode conditions when the same excitation light was used for the panel device. This indicates that the photo-responsivity of a photocathode might be identical to excitation light source and that emitter degradation depends on the cumulative charge dose at constant anode voltage.

4. CONCLUSIONS

This paper described the production of Cs_3Sb photocathode using a simple non-vacuum experimental setup and the in-situ fabrication of a successive panel device. The produced Cs_3Sb photocathode emitters were stable during the operation of panel device. Acting as flat emitters, Cs_3Sb photocathodes showed property of vertical directionality in electron emission. Measured parameters of the panel device such as emission current, decay lifetime, and charge dose exhibited stable electrical characteristics without fluctuation. Therefore, Cs_3Sb photocathode emitters in the panel device have high emission current with extended lifetime via re-cesiation process, making them as suitable cathode materials for general panel device applications.

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