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Improvement of porous polysilicon nano-structured emitter for vacuum packaged devices

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Porous polysilicon (PPS) emitters were fabricated by depositing an Au thin film on a thermally oxidized polysilicon and their emission properties were examined. The emission properties were also measured for the emitters with various Au thicknesses and the vacuum packaged devices were then developed. The experimental results show that the electrical performances of PPS emitters decreased, because high-temperature packaging process will lead to thermally induced phenomenon between thin layers. We have carried out optimal-thickness variation in Au thickness to improve electron emission properties of PPS emitters packaged. When PPS emitters packaged was driven directly, the field-induced electron emission through anode phosphor was observed.

1. Introduction

Many types of cold cathodes have been developed for applications to vacuum microelectronic devices including high frequency and harsh-environment electronic devices, and a flat panel display. The cold cathodes are expected to have high current density at a low extraction voltage and to be stable in operation for the above-mentioned applications. Since the discovery of porous polysilicon (PPS) emitters [1–3], much research effort has been devoted to characterize PPS emitters. Based on extraordinary anodizing technique on a Si substrate, many applications have been proposed [4–6]. Among them, the application in field electron emission is the most attractive.

Recently, an efficient and stable cold emission cathode fabricated from porous polysilicon was proposed by the Koshida *et al.* [2] and it is called "BSD"-Ballistic electron Surface-emitting Display. Fig. 1 shows the proposed quasi-ballistic electron drift model. Firstly, electrons are injected from the substrate due to thermal excitation. Because drift length of electron in silicon nanocrystallites is much longer than bulk silicon [7], probability of collision between drifting electron and nanocrystallite is considerably small. The PPS layer holds most of the applied voltage to the diode, because there are thin oxide skins on the surfaces of the nanocrystallites and silicon grains due to a rapid thermal oxidation. Hence, injected electrons are accelerated by the strong electric field (average electric field intensity in the PPS region may reach about 10^5 V/cm for a bias of several tens of volts) and drifted in the PPS layer toward the surface. Electrons arrived at the surface are regarded as hot electrons which have much higher kinetic energy than those at the thermal equilibrium, and then, electrons are ejected to the vacuum through a thin Au film. The remaining grains of the polysilicon act as heat sink, through which the heat occurred by collisions with electrons and silicon atoms escapes.

Generally, PPS emitter composed of an ohmic contact, a silicon/glass substrate, a PPS layer and a metal

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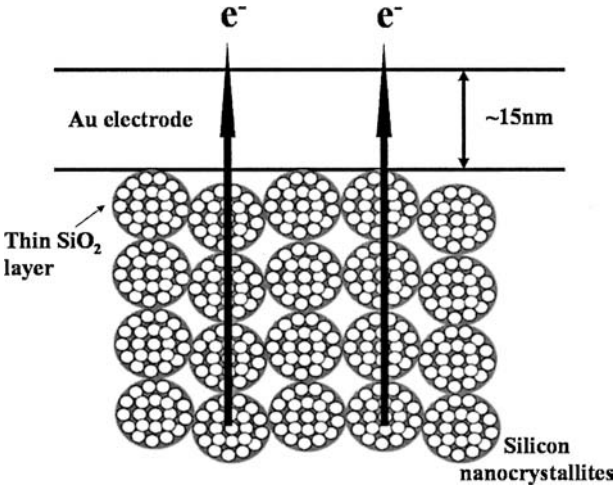

Figure 1 Proposed quasi-ballistic electrons drift model of the PPS surface emitting cold cathode [2].

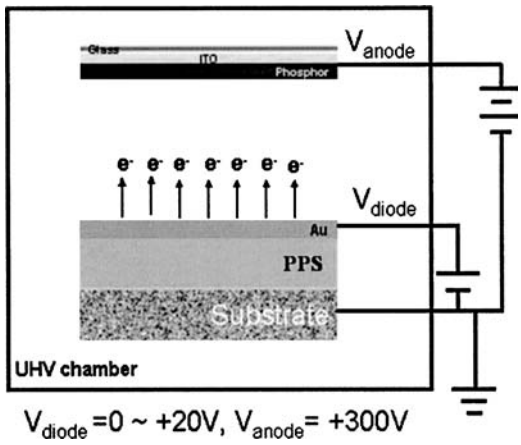

Figure 2 A schematic diagram of the measurement system.

thin film electrode has several advantages, compared to other cold cathodes. The angle dispersion of electrons emitted is negligible, and the emission current is quite insensitive to the vacuum pressure [8]. In addition, the PPS emitter inherits basic FED advantages like a high performance field emitter.

The purpose of this paper is to investigate the dependence of PPS emitter properties on various anodizing conditions and to optimize packaging process. The fabrication process was optimized as a function of various conditions to improve the emission properties. We also packaged PPS emitters using vacuum packaging process. The resulting properties are discussed.

2. Experiments

The PPS layer was formed on the heavily doped N-type Si [100] wafers with a resistivity less than 0.005 Ωcm. Intrinsic polysilicon was increased to the thickness of 2 μm by low-pressure chemical vapor deposition (LPCVD). The anodization was carried out in the solution of HF (50%): ethanol = 1:1 at current densities of 5–20 mA/cm^2 for 5–10 s under no-illumination. Various kinds of anodizing conditions were summarized in Table I. After anodizing, the PPS layer was thermally oxidized for 1 h at 900 °C. Au with various thicknesses (20, 30 and 45 nm) was thereby deposited on a PPS to form an extraction gate electrode using e-beam evaporator. The area of an Au layer was about 1 cm^2. To make ohmic contact, Al evaporated thermally was formed on the backside of a Si substrate. The emitters were mounted into the vacuum chamber evacuated to a pressure of 1×10^{-5} Torr for measurement of the emission properties as a function of anodizing condition. The anode electrode was set above the top electrode and kept at a positive voltage of 300 V. The height of anode electrode was about 1 mm, where the glass spacer was used.

TABLE I Anodizing condition

	Anodizing condition	
Sample no.	J (mA/cm^2)	Time (s)
#1	5	50
#2	5	60
#3	5	70
#4	10	10
#5	10	20
#6	10	30
#7	20	20
#8	20	30

After the analysis of the emission properties, packaging process was performed. Emission currents of PPS emitters decreased, because high-temperature packaging process will lead to thermally induced phenomenon. Therefore, we proceed with the pre-experiment for effect of temperature in the ultra high vacuum (UHV) chamber and analyze the changed property of Au using Auger Electron spectrometer (AES) and Scanning Electron Microscopy (SEM). All measurements were performed using the Keithley 237 Source Measure Unit. Fig. 2 shows a schematic diagram of measurement system.

3. Results and discussion

To analyze the interface features as a function of anodizing condition, scanning electron microscopy (SEM) measurement was performed. The cross-section between a PPS layer and a Si substrate is shown in Fig. 3. The PPS layers were formed at current densities of 10, 20, 30, and 40 mA/cm^2 for 20 s, respectively. As current density increased, the anodized depth was increased to the thickness of a Si substrate. The most important feature of the shown figure was a gap between thin layers. As the size of a gap increased, it affected the current flow in PPS layers. It was found that these features of a Si substrate reduce the electron emission properties of PPS emitters.

Fig. 4 shows the I-V characteristics of PPS emitters, which were deposited with an Au film of 20 nm thickness, under various kinds of anodizing conditions. Electron emission properties of PPS emitters were characterized in an UHV chamber at a base pressure of 1×10^{-5} Torr. Prior to the test, PPS emitters were not heated and maintained the same pressure. The anode plate was 1 mm above the top electrode and biased to 300 V. The voltage applied to the Au top electrode varied from 0 to 20 V. As shown in this figure, PPS

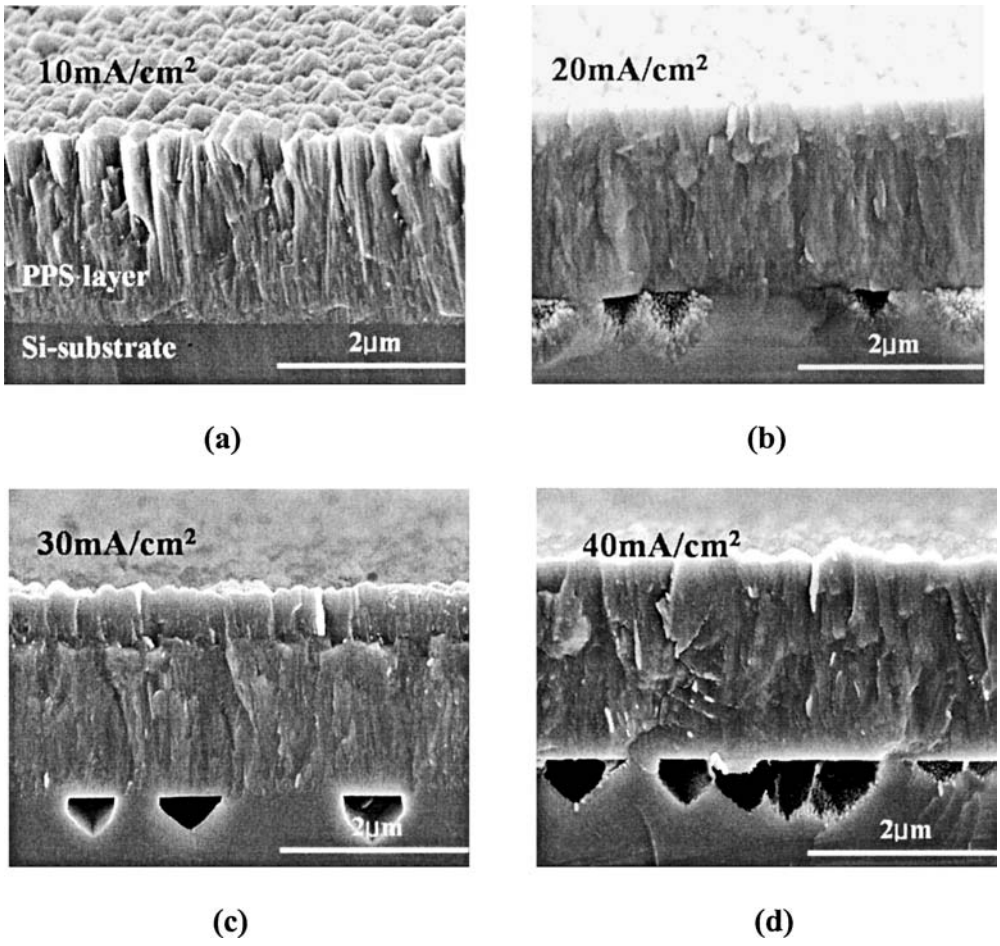

Figure 3 SEM images as a function of anodizing current for 20 s: (a) 10 mA/cm^2, (b) 20 mA/cm^2, (c) 30 mA/cm^2, and (d) 10 mA/cm^2.

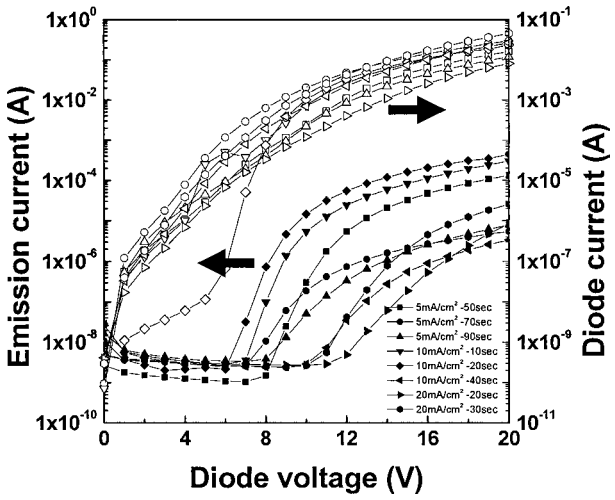

Figure 4 The current-voltage characteristics of PPS emitters as a function of anodizing condition.

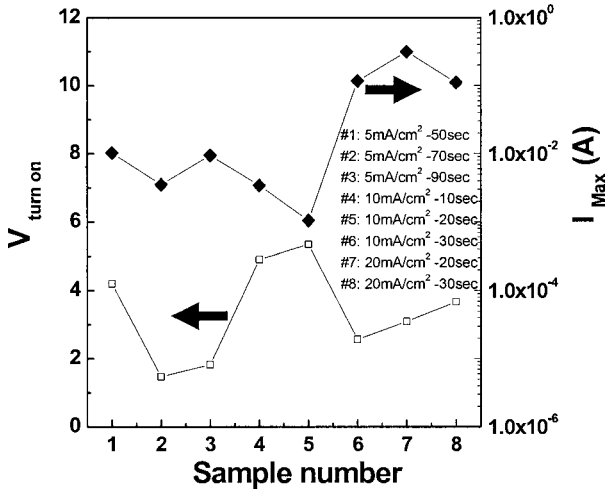

Figure 5 Turn-on voltage and maximum emission current of PPS emitters as a function of anodizing condition.

emitters fabricated at current density of 10 mA/cm^2 has a lower turn-on voltage and a higher emission current than others. As mentioned previously, electron emission properties of emitters strongly depend on the anodizing condition related to the size of a gap in PPS layers.

To define the emission properties of each emitter, the turn-on voltage and the maximum emission current as a function of anodizing condition were summarized in Fig. 5. It is found that the emitters of #1 and #4 have a higher electron emission current but much higher turn-on voltage than others. The samples of #7 and # 8 also have the highest turn-on voltage. The sample of #5 also has the lowest turn-on voltage and the highest maximum emission current. We confirm that the anodizing condition of #5 is the most effective condition for electron emitters.

The emission properties under various kinds of Au film thicknesses are shown in Fig. 6. As shown in this figure, we see that the electron emission properties

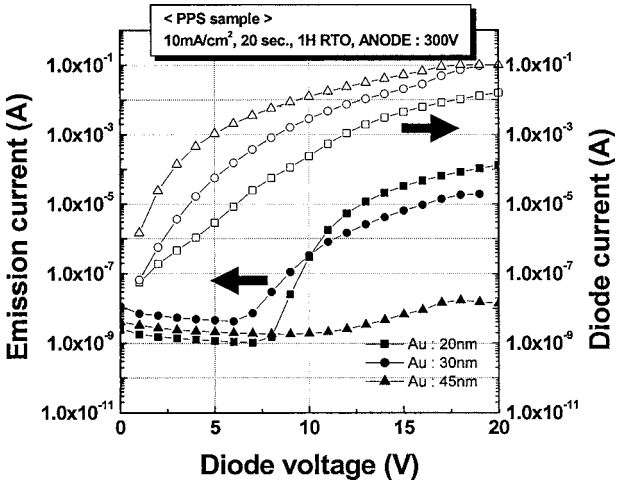

Figure 6 The current-voltage characteristics as a function of Au film thickness.

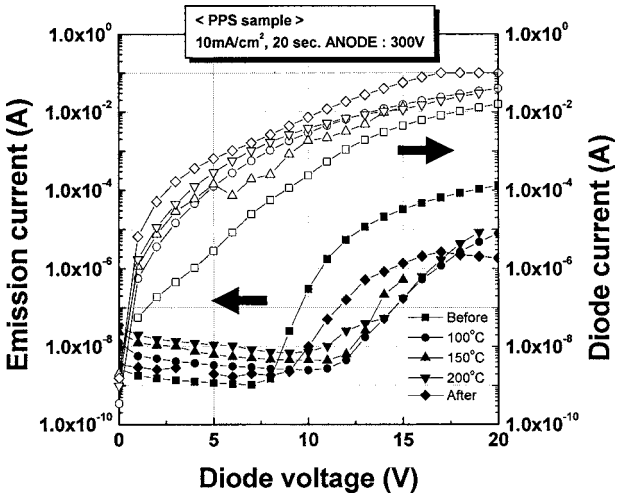

Figure 7 The current-voltage characteristics of PPS emitters as a function of substrate temperature.

under the same condition for anodizing depend mainly on the Au thickness. As increases the thickness of Au film, the injected electrons, which were accelerated by the electric field, cannot pass the gate electrode. It is also shown that the optimal thickness suitable for packaging process is acquired through the emitted electron behavior.

Fig. 7 shows the electron emission properties of PPS emitters as a function of the substrate temperature (<450 °C). As the substrate temperature increased, the emission current decreased owing to the thermally induced effect. In addition, we could not measure the emission current at the substrate temperature over 300 °C. After measurement, the value of emission current was clearly reduced, compared to that of initial case. To analyze the changed surface properties, SEM measurement was performed. In case of as-fabricated PPS surface in Fig. 8(a), we can discriminate between the grain boundaries. However, in case of packaged PPS surface, we cannot clearly discriminate between the grain boundaries in Fig. 8(b). Also, we can observe that Au leave the trace of reflow of Au film. Hence,

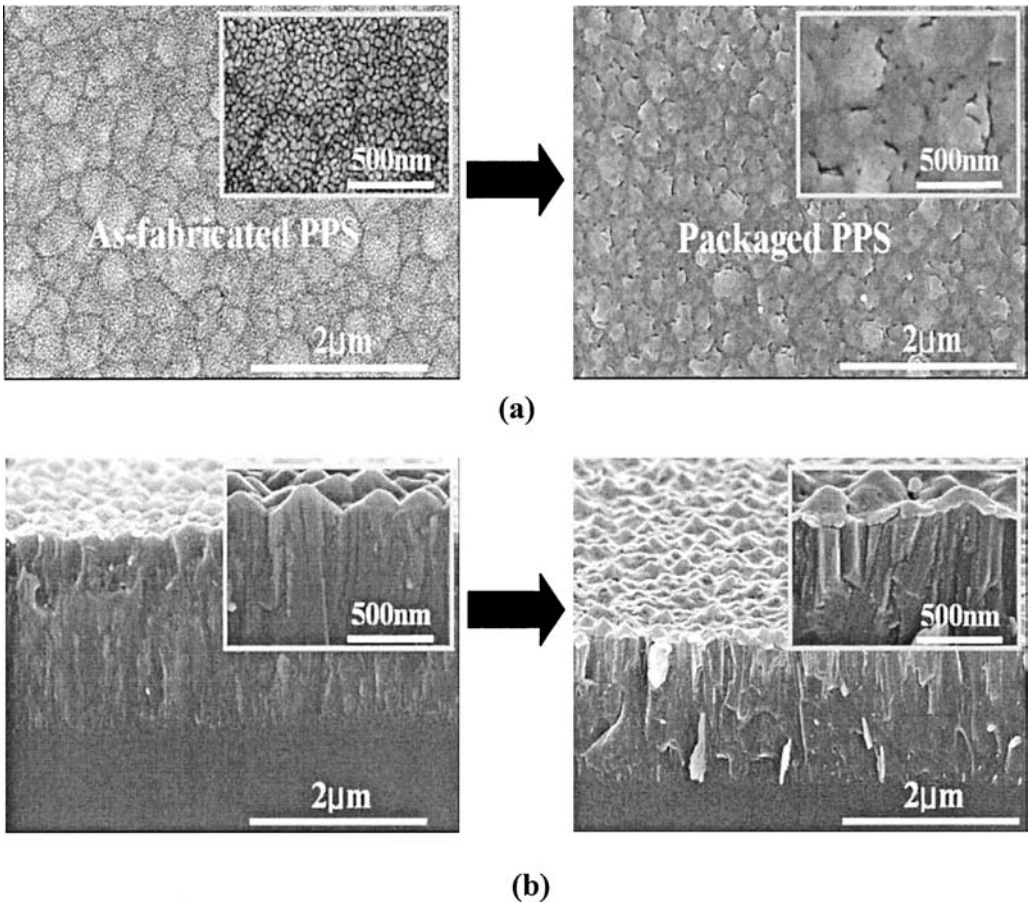

Figure 8 SEM images for the changed morphology of Au due to anneal treatment: (a) Surface view and (b) cross-section view.

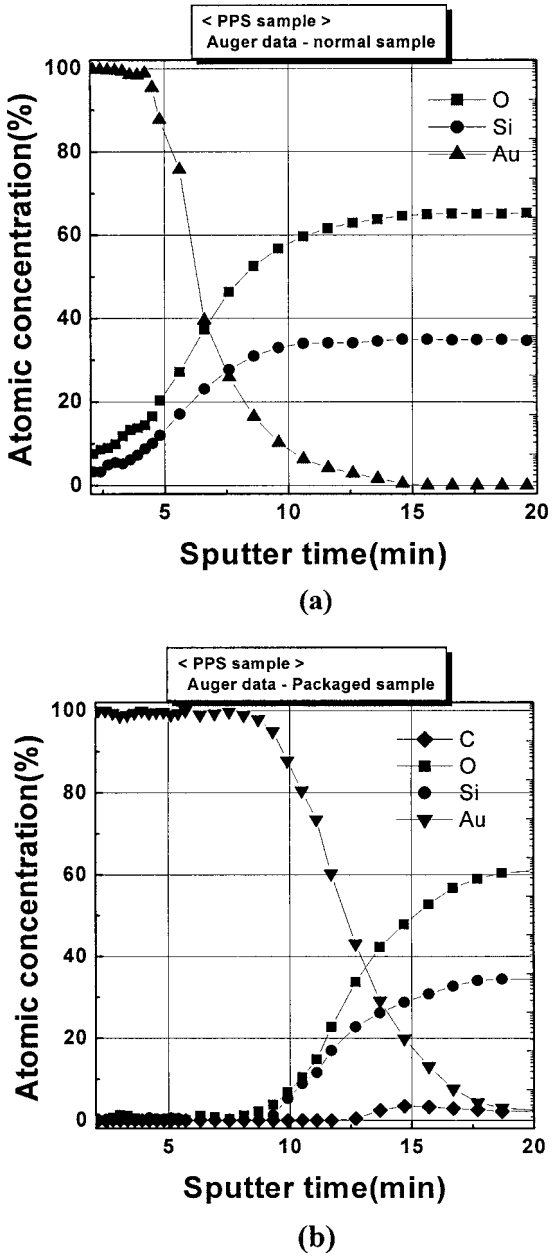

Figure 9 The depth profile of Au onto PPS emitter using AES: (a) As-fabricated PPS emitter and (b) annealed PPS emitter.

we can consider that Au film was changed during the temperature analysis.

In general, when two different materials make intimate contact each other, the diffusion occurs across the interface. The diffusion in semiconductor-related applications precedes the inter-metallic formation, grain growth and solid solution formation. In addition, the diffusion of one species into another depends strongly on the temperature, since it is a thermally activated process [9]. The thermally induced phenomenon therefore affected the electron emission property [10, 11]. After the temperature analysis, Auger Electron Spectrometer (AES) measured the slightly diffused Au. AES is a surface analytical technique, which provides information about surfaces and interfaces. AES can be used for determining the composition of a surface, mapping the spatial distribution of the surface constituents, and obtaining an in-depth profile of these constituents into the bulk of the material. Therefore, we made use

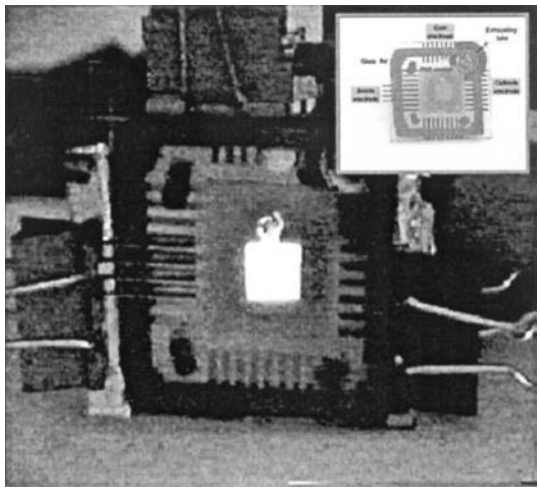

Figure 10 Light emission pattern of PPS emitter packaged.

of AES to analyze the depth profile of Au onto PPS emitter. As shown in the Fig. 9, the sputtering rate (20 Å/min) depends on the atomic weight of material being removed. With the Au as a top-electrode layer under the high temperature conditions, more diffuses than that of initial PPS emitter under the room temperature condition. Thus, we modified and optimized the top-electrode thickness suited for vacuum packaging process.

Fig. 10 shows the light emission image in PPS emitter packaged. As mentioned above, the top electrode layers of PPS emitters were changed owing to the thermally induced phenomenon during the packaging process. Although thermally induced phenomenon (which we call diffusion) strongly occurred, we modified and optimized the top-electrode thickness suitable for vacuum packaging process.

4. Conclusions

We have fabricated porous polysilicon emitters by depositing an Au thin film on an oxidized PPS layer and developed the vacuum packaged emitters. In this study, the properties of electron emission and diffusion occurred in the PPS emitters during packaging process were reported. The main focus of this paper was to analyze the electron emission properties of PPS emitters as a function of anodizing condition and to optimize the Au thickness suitable for packaging process. As a result, the electron emission properties depended strongly on the anodizing condition. In addition, electron emission properties of PPS emitter packaged were affected by the properties of top electrode under various kinds of thicknesses and substrate temperature. We considered the diffusion probability of Au film and modified the thickness of Au film related to diffusion. We confirm that PPS emitters can potentially be applied to a cold cathode device for future FPD.

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