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Observation of Field-Induced Electron Emission in Porous Polycrystalline Silicon Nano-Structured Diode

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Field-induced electron emission properties of porous poly-silicon nano-structured (PNS) diodes were investigated as a function of anodizing conditions, including morphological analysis, various kinds of top electrode thickness and the measuring substrate temperature. Also, the vacuum packaging process was performed by the normal glass frit method. The PNS layer was formed on heavily-doped n-type $< 100 >$ Si substrate. Non-doped poly-silicon layer was grown by low-pressure chemical vapor deposition (LPCVD) to a thickness of 2mm. Subsequently, the poly-silicon layer was anodized in a mixed solution HF (50 wt%): ethanol (99.8 wt%) = 1:1 as a function of anodizing condition. After anodizing, the PNS layer was thermally oxidized for 1 hr at 900 °C. Subsequently, the top electrode was deposited as a function of Au thickness using E-beam evaporator and, in order to establish ohmic contact, thermally evaporated Al was deposited on the back side of a Si substrate. The prepared PNS diode was packaged using the normal vacuum sealing method. After the vacuum sealing process, the PNS diode was mounted on the PC measurement table. When a positive bias was applied to the top electrode, the electron emission was observed, which was caused by field-induced electron emission through the top metal.

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I. INTRODUCTION

Previously [1,2], we have evaluated operation of a the porous poly-silicon nano-structured diode in an Ultra High Vacuum (UHV) chamber as a field-induced cold cathode. The PNS diode is composed of an ohmic contact, a Si-substrate, a PNS layer and a thin metal film electrode. Electrons are emitted through the top electrode into vacuum under the condition that positive bias voltage is applied to the top metal electrode. This phenomenon is one of the key aspects in this work and the key technology in the potentiality of the applications as a cold cathode device for future Flat Panel Display (FPD). The PNS diode has several advantages as a field-induced cold cathode. The angle dispersion of emitted electrons is negligible, and the emission current is quite insensitive to the vacuum pressure. In addition, the PNS diode inherits a basic FED advantage as a high performance field emitter. Hence, it has potential not only in application as cold cathode but also to an optically applied device [3,4]. First of all, the most important advantage of the PNS diode consisted of simple structure and no need for complicated processes or even a large area emitter. In this study, we have estimated the dependence of emission properties as a function of anodizing conditions including morphological analysis, various kinds of top electrode thickness and the measuring substrate temperature. In addition, we have compared the electron emission properties of the PNS diode in a UHV chamber with those after a packaging process.

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II. EXPERIMENTAL

The PNS layer was formed on heavily-doped (0.001-0.005 Ω·cm) n-type $< 100 >$ Si wafer. A non-doped poly-silicon layer was grown by low-pressure chemical vapor deposition (LPCVD) to a thickness of 2 mm. Sub-

Table 1. Anodizing condition.

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

sequently, the poly-silicon layer was anodized in a mixed solution HF (50 wt%): ethanol (99.8 wt%) = 1:1 as a function of anodizing condition [5]. The various kinds of anodizing condition are summarized in Table 1. After anodizing, the PNS layer was thermally oxidized for 1 hr at 900 °C. Then, the 20 nm, 30 nm, 45 nm thickness of Au films was deposited using an E-beam evaporator. In order to make ohmic contact, thermally evaporated Al was formed on the backside of the Si-substrate. The prepared PNS diode was placed into an ultra high vacuum (UHV) chamber for measurement of the emission properties. Simultaneously, another prepared PNS diode was packaged using vacuum packaging technology. Because of the glass frit sealing step, the packaging process was performed in a furnace at high temperature. Hence, the temperature dependence of the PNS diode's emission properties was followed using a hot plate in the UHV chamber. Both the PNS diode in the UHV chamber and the packaged PNS diode were applied to the top Au electrode as a function of positive voltage. The anode electrode set above the top electrode was kept at a positive voltage of 300 V. The distance between top electrodes of both PNS diodes was about 1mm, using a glass spacer. The diode current and the emission current were measured using the Keithley 237 Source Measuring Unit. Figure 1 shows a schematic diagram of the measurement system.

III. RESULTS AND DISCUSSION

1. Morphological analysis as a fabrication process step, and effect of anodizing condition

In order to analyse surface morphology as a fabrication process step, scanning electron microscopy (SEM) measurement was performed. As shown in Figure 2, SEM was used to investigate the surface morphologies as a function of the fabrication step. The PNS layer formed at a current density of 10 mA/cm^2 for 20 sec shows a large number of pores with an average width of several nm. After the oxidation step, we can check that the pore widths of the PNS layer were decreased on increasing the thickness of the oxide.

Figure 3 shows the I-V characteristics of the PNS diode deposited with 20 nm thickness of Au film under various kinds of anodizing conditions. Electron emission properties of the fabricated PNS diode were characterized in an UHV chamber at a base pressure of 1×10^{-5} torr. Prior to the test, the PNS diode was not heated and maintained the same pressure. The anode plate was 1mm above the top electrode and biased to + 300 V. The voltage applied to the top Au electrode varied from 0 to + 20 V. In this figure, we can see that the PNS electron emitters fabricated at a current density of 10 mA/cm^2 have a lower turn-on voltage and a higher emission current compared to that of the others. So, we can consider that electron emission properties of PNS diode strongly depend on the anodizing condition.

In order to define each PNS diode's emission properties, the turn-on voltage and the maximum emission current of the PNS diode as a function of anodizing condition are summarized in Figure 4. We can find that the PNS diode of ♯ 1 and ♯ 4 has a higher electron emission current, but the turn-on voltage is much higher. The PNS diode of ♯ 7 and ♯ 8 also has a higher turn-on voltage than the others. In the case of ♯ 5, the PNS diode has the lowest turn-on voltage and the highest maximum emission current compared to the others. Thus, we can confirm that the anodizing condition of ♯ 5 is the most effective condition for field-induced electron emission.

2. Effect of Au thickness of a top electrode, and measuring substrate temperature

The emission properties of the PNS diode under various kinds of Au film thickness are shown in Figure 5. In this figure, we can see that the emission current decreased on increasing the Au film thickness. Hence, we

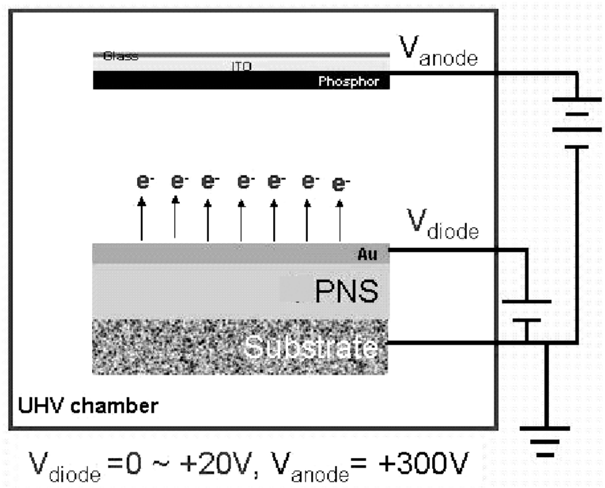

Fig. 1. A schematic diagram of the measurement system.

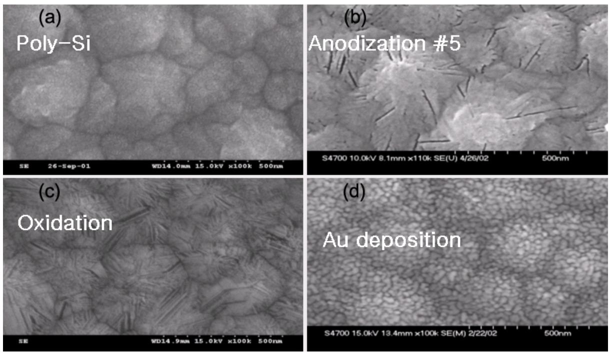

Fig. 2. SEM micrographs for the fabricating process step. (a) The surface of non-doped polysilicon. (b) The morphology of porous polysilicon nano-structure (c) Surface view of PNS after oxidation. (d) The formation of Au on oxide.

can consider that the thick-Au film as a top electrode causes a reduction in emission current. Figure 6 shows that the I-V characteristics of PNS diode were measured as a function of the substrate temperature (<450 °C). On increasing the substrate temperature, the emission current was decreased by the thermally-induced effect. We could not measure the emission current at substrate temperature of over 300 °C. After measurement, we see that the emission current was reduced compared to that of the initial case. In general, when two different materials make intimate contact with each other, diffusion occurs across the interface. The diffusion in semiconductor-related applications precedes the intermetallic formation, grain growth and solid solution formation. The diffusion of one species into another strongly depends on the temperature since the phenomenon is a thermally activated process [6]. Thus, from this phenomenon, we can consider the diffusion probability of Au film. Also, we estimate that the top electrode of thin Au film (20 nm) slightly diffused into the oxide. Since this is so, the thermally-induced phenomenon affected the electron emission properties.

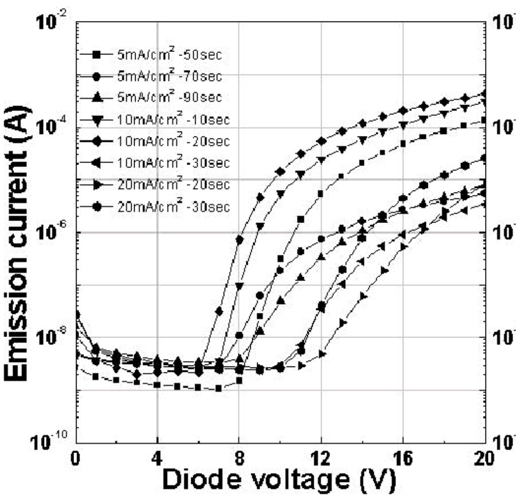

Fig. 3. The I-V characteristics of the PNS diode as a function of anodizing condition.

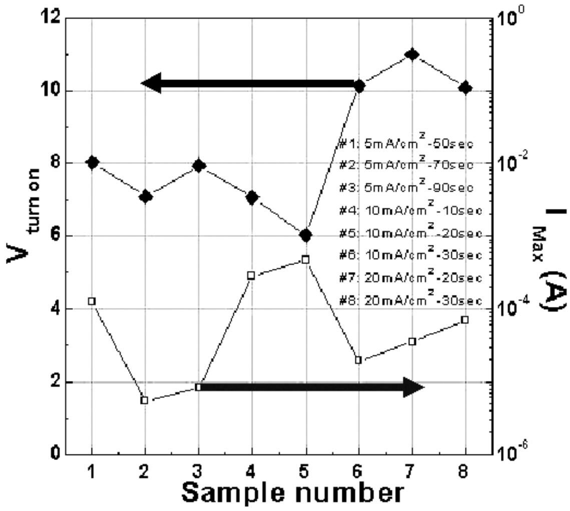

Fig. 4. Turn-on voltage and the maximum emission current of PNS diode as a function of anodizing condition.

3. Electron emission properties of the packaged PNS diode

The emission properties of the PNS diode under different conditions have been investigated. The prepared PNS diode was measured in a UHV chamber and also

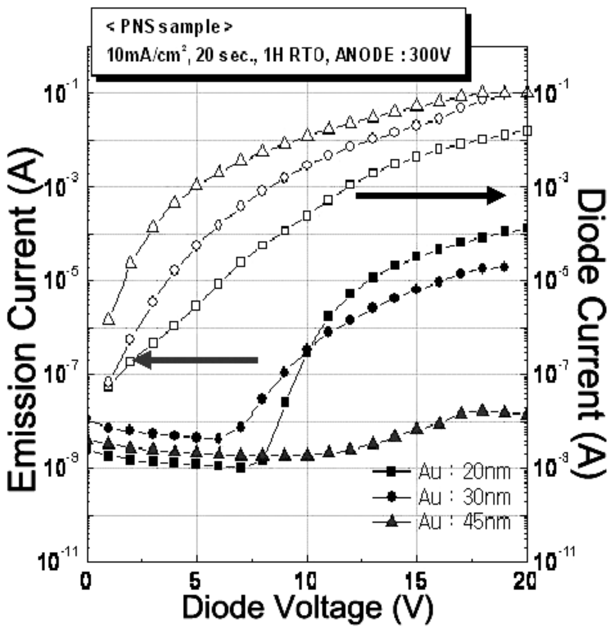

Fig. 5. Current-voltage characteristics as a function of Au film thickness.

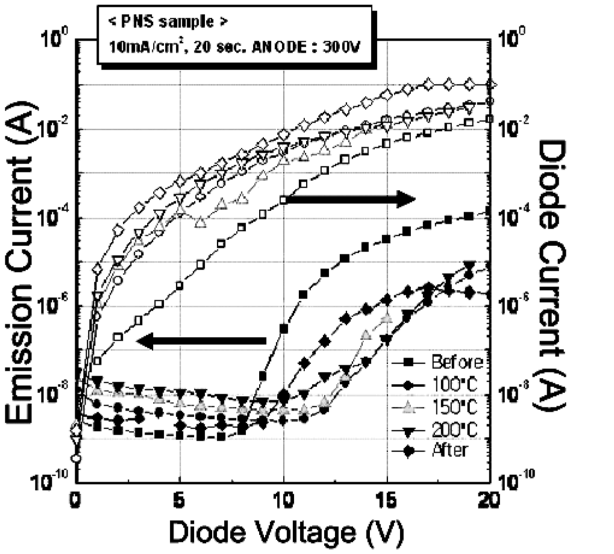

Fig. 6. Current-voltage characteristics of PNS diode as a function of substrate temperature.

measured after a packaging process, respectively. For a PNS diode in a UHV chamber, Figure 7 shows the light emission image on an anode phosphor. An Au electrode was patterned into a 10 mm square and it was confirmed that the light emitting image showed a good emission uniformity. For a PNS diode after a packaging process, Figure 8 shows the light emission image in a packaged glass plate. In the case of the packaged PNS diode, there was no significant difference of light emission pattern in the figures. However, as we were shown in Figure 9, the I-V characteristics were too different to compare the PNS diode in UHV chamber. The emission begins at $\sim$ 10 V and increases very slowly. A high emission current density of 10 μAcm^{-2} was obtained at an anode voltage of 300 V. Such a result is very reasonable, because some layers of the PNS diode were changed by the thermally-

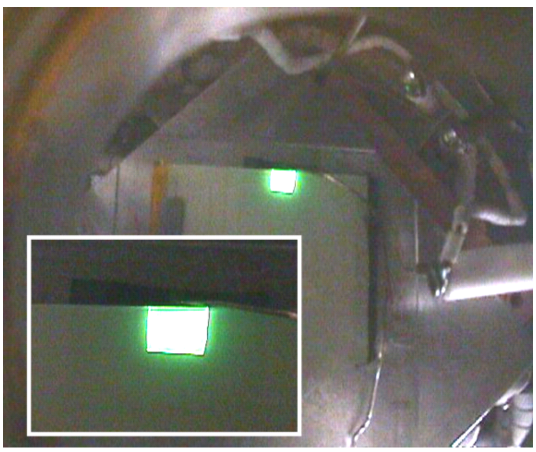

Fig. 7. Light emission pattern of PNS diode in UHV chamber.

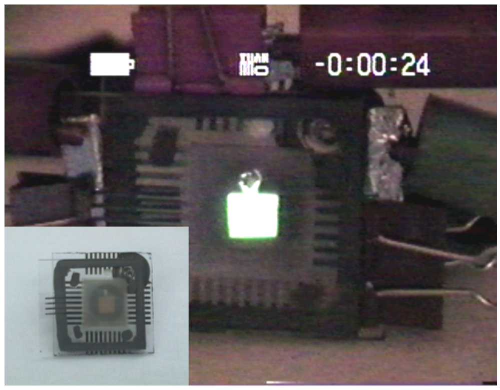

Fig. 8. Light emission pattern of the PNS diode after packaging process.

induced phenomenon during the packaging process, but the difference in the emitted electron image is negligible. Thus, research into this phenomenon is going to develop under various kinds of process condition.

IV. CONCLUSION

Some kinds of PNS diodes' fundamental properties were investigated. The PNS diode was fabricated on the Si-substrate by means of an electrochemical anodizing technique, and the electron emission properties were analysed as a function of both the measuring temperature and the thickness of Au film. Also, the packaging process was performed using a normal glass frit process. As a result, we can see that the electron emission properties were strongly dependt on the anodizing condition and the top electrode properties as a function of thickness and substrate temperature. However, we can also

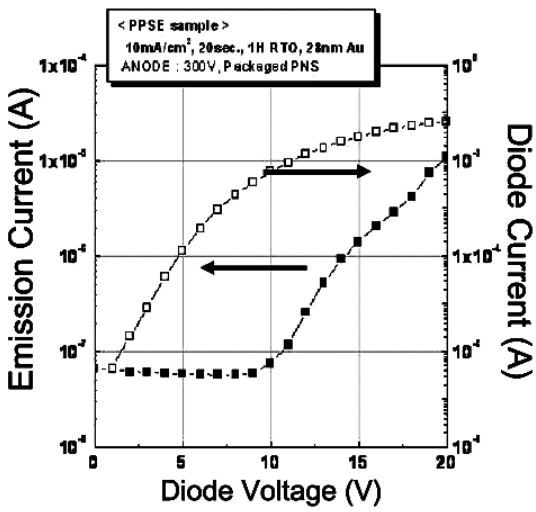

Fig. 9. Current-Voltage characteristics of PNS diode after packaging process.

state that the emission current decreased on increasing the substrate temperature during the packaging process. From this result, we can estimate that diffusion in thin films depends on the substrate temperature and may be expected to have a special property between thin oxide and thin Au film. The special properties of the packaged PNS diode are, however, negligible. Thus, the PNS diode sufficiently shows the potentiality of application as a cold cathode device for future FPD.

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