Fabrication of Vacuum Tube arrays with a sub-micron dimension using Anodic Aluminum Oxide Nano - Templates

Sun-Kyu Hwang
Department of Chemical Engineering, Computer and Electrical Engineering Division
Pohang University of Science and Technology
Pohang, Kyungbuk
trainer@postech.ac.kr
Tel: 84-54-279-5957
Fax: 84-54-279-8298

Kun-Hong Lee[1]
1 Department of Chemical Engineering, Computer and Electrical Engineering Division, Pohang University of Science and Technology,
Pohang, Kyungbuk, Korea
ce20047@postech.ac.kr
Tel: 84-54-279-2271
Fax: 84-54-279-8298

Abstract

Vacuum tube arrays (VTA) with a sub-micron dimension were fabricated by using anodic aluminum oxide (AAO) nano-templates. The field emission characteristics of Ni nanowires show a turn-on voltage in the range of 11.0-14.0 V and a field enhancement factor in the range of 560-2790. The distance between the tips of Ni nanowires and the anode was much smaller than that between the tips and the anode of conventional designs.

1. Introduction

Vacuum devices based on field emission have attracted considerable attention in recent years because they have several advantages over solid-state devices. They are robust at ambient temperature and in radiation environment. They have no power dissipation during electron transport because of the ballistic nature of transport in vacuum [1]. Consequently, vacuum devices can generate high power at high frequencies. These characteristics guarantee many applications, including active elements for integrated-circuits[2], flat-panel displays[3], electron guns[4], and microwave power tubes[5].

Most of the field-emission-based vacuum devices are fabricated by following the Spindt's process. However, it requires sophisticated procedures and expensive equipment such as selective etching and electron beam lithography. High voltage is required for the operation of these devices because of the inter-electrode distance of several hundred micrometers. In addition, the Spindt's process is difficult to apply to a large area. To overcome these difficulties, we have used anodic aluminum oxide (AAO) technology, which is capable of controlling the dimensions of the structures such as pore diameter, pore length, and pore density in a few nanometer resolution without using electron beam lithography. Also, AAO technology can also be applied to a large area easily.

In this study, we have fabricated field emitter arrays (FEAs) with an integrated anode by using AAO nano-template. The final purpose of this work is to devise a novel process for fabricating vacuum tube arrays with a sub-micrometer dimension.

2. Experimental

First, a cleaned and electropolished aluminum sheet of high purity (99.999 %) was anodized in a 0.3 M oxalic acid solution at 15 °C for 12 hours. After chemically etching the anodized layer in a mixture of chromic acid and phosphoric acid, the second anodization was performed under the same condition for 30 min. Details of the fabrication process had been reported elsewhere[6]. Subsequent treatment with a 0.1 M phosphoric acid solution at 30 °C for 20 min widened the pores and thinned the barrier layer simultaneously. Ni nanowires were electrochemically deposited in the pores of the AAO

template. The electrodeposition was accomplished in an electrolyte consisting of 5 wt. % $NiSO_4 \cdot 6H_2O$ and 2 wt. % H_3BO_3 by applying ac voltage. The lengths of Ni nanowires were changed by varying the electrodeposition time. The AAO template containing nickel nanowires was sealed using angled evaporation of titanium, which served as an anode of the vacuum tube array.

Figure 1 illustrates the fabrication process in this work.

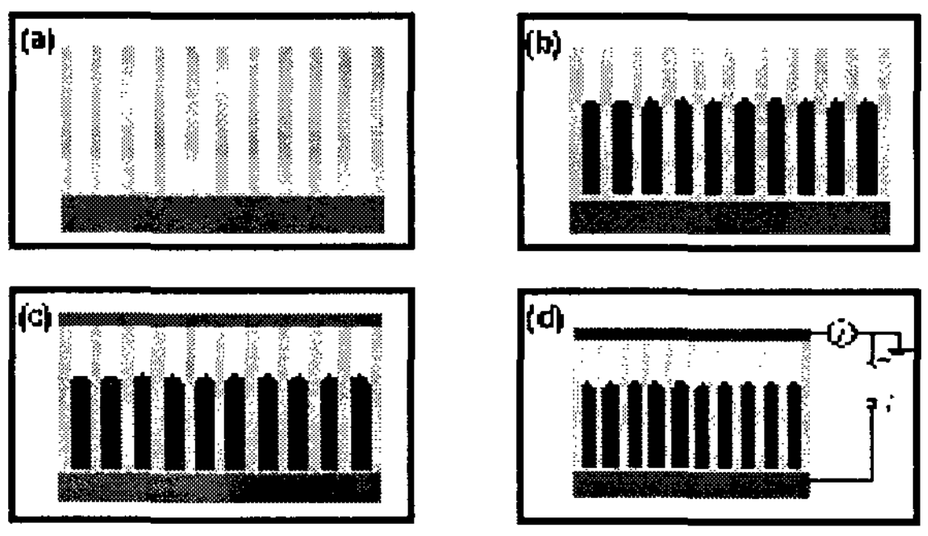

Fig. 1. Fabrication process of integrated diode
(a) AAO template fabrication,
(b) electrodeposition of Ni nanowires,
(c) angled evaporation of Ti to seal the structure,
(d) schematic of a field emission measurement setup

3. Result and Discussion

Figure 2 shows the SEM images of the fabricated vacuum tube arrays.

This figure clearly shows that the lengths of Ni nanowires increase with the deposition time while the uniformity becomes irregular.

That is, when the deposition time is longer, the lengths of nanowires grow uneven as some become longer than others. Thus, the differences in the length between nanowires become greater. This is due to the difference in the thickness of the barrier layer at each pore and due also to the hydrogen evolution caused by water splitting reaction [7].

Titanium layers were used to seal the pores of the AAO templates. Titanium layers also act as the anodes for vacuum tube arrays. It should be noted that titanium is frequently used as a getter material to maintain the vacuum level in a vacuum device. Infiltration of titanium into the pores must be avoided to prevent short circuits. To achieve this goal, angled evaporation with 20 ° was performed.

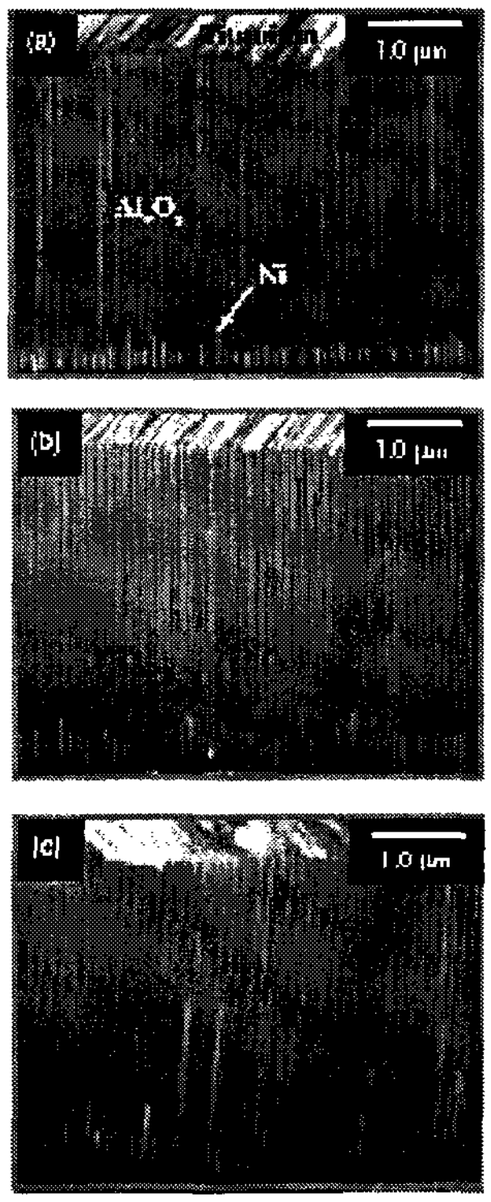

Fig.2.SEM images of integrated diode structure. Ni nanowires were electrochemically deposited in the pores of the AAO template for (a) 60 sec, (b) 150 sec, and (c) 270 sec

The emission characteristics of the vacuum tube arrays (VTAs) were measured. The remaining aluminum under the AAO template acts as a cathode and the titanium layer on top of the AAO template as an anode. Figure 3 presents the typical current-voltage relationship of these vacuum tube arrays. A useful parameter for the comparison of the field emission performances of three different samples is the turn-on voltage, V_{to}. The V_{to} values of three samples are found to be 11.0 V, 12.0 V, and 14.0 V, respectively. These values are much lower than those values previously reported [8-9]. The inter-electrode distances of our samples are less than 3 μm, while those of previous investigators were about several hundred micrometers. Therefore, in our structure, the electric field sufficient for field emission can be supplied to the tips at a low operating voltage. The current-voltage relationship shown in Fig. 3 confirms that the emission current density changes with the inter-electrode distance. As the

electrodeposition time increases, the inter-electrode distance decreases. Therefore, A has a larger emission current density than those of other specimens at the same operating voltage.

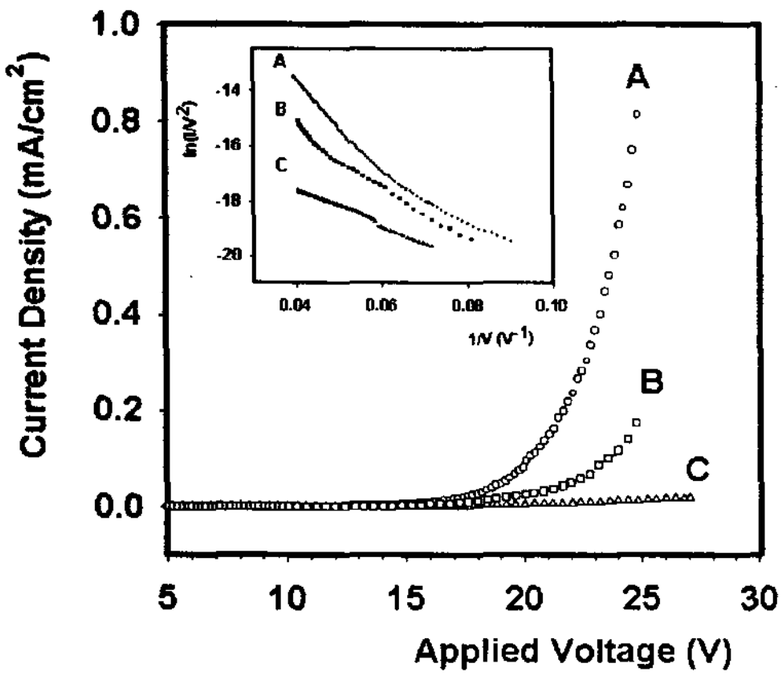

Fig. 3 FE current density vs applied voltage for integrated diode structure (inset plot) Fowler-Nordheim plots

The inset in Fig. 3 shows the Fowler-Nordheim(FN) plots in our samples. The emission data generally agree with the FN relation, confirming that the emission current has indeed come from the field emission. We also estimated the field enhancement factor, β from the slope of the F-N plot. The slope of the F-N plot is equal to $B\varphi^{3/2}d/\beta$, where the constant $B = 6.87*10^9$ V $eV^{-3/2}$ m^{-1}. φ is a work function of Ni nanowire, and d is the distance between Ni nanowires and integrated anode [10]. The work function of the Ni nanowires is assumed to be the same as the bulk nickel having [111] plane (=5.35 eV). Field enhancement factors, β, for A, B, and C were calculated using the above equation, and they were in the range of 560- 2790. These low β values may result from the field screening effect by the high nanowire density about 10^{10} tips/cm^2.

4. Conclusions

We have fabricated vacuum tube arrays with a sub-micrometer dimension by using AAO nano-templates.

Current-voltage characteristics show the turn-on voltages of 11.0-14.0 V and field enhancement factor of 560-2790. This phenomenon is attributed to the fact that the distances between the tips of Ni nanowires and the anodes are much smaller than those between the tips and the anodes of conventional designs.

5. References

[1] Brodie, I.; Schwoebel, P. R., Proc. IEEE, **82,** 7 (1994).

[2] Brodie, I., IEEE Trans. Electron Devices, 36, **11,** 2641 (1989).

[3] Meyer, R.; Ghis, A.; Rambaud, P.; Müller, F., Proc. Japan Display, 513 (1985).

[4] Chang, P.; Kern, D.; Muray, L., IEEE Trans. Electron Devices, 38, **10,** 2284 (1991).

[5] Brodie, I., in Tri Service Microwave Power Tube Conf.(Montetry, CA, 1976).

[6] Hwang, S.-K.; Jeong, S.-H.; Hwang, H.-Y.; Lee, O.-J.; Lee, K.-H., Korean J. Chem. Eng., **19**(3), 467 (2002).

[7] Sautter, W.; Ibe, G.; Meier, J., Aluminium, 50, 143 (1974).

[8] Davydov, D. N.; Sattari, P. A.; AlMawlawi, D.; Osika, A.; Haslett, T. L., J. Appl. Phys. **86,** 3983 (1999).

[9] Govyadinov, A. N.; Zakhvitcevich, S. A., J. Vac. Sci. Technol B **16(3),** 1222 (1998).

[10] Bonard, J. -M.; Salvetat, J. -P.; Stöckli, T.; Forró, L.; Châtelain, A., Appl. Phys. A **69,** 245(1999).