Calculation of Field Enhancement Factor in CNT-Cathodes Dependence on Dielectric Constant of Bonding Materials

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Abstract

The effect of the dielectric constant (ε) of bonding materials in screen-printed carbon nanotube cathode on field enhancement factor was investigated using the ANSYS software for high-efficient CNT-cathodes. The field enhancement factor increased with decreasing the dielectric constant and reaching a maximum value when the dielectric constant is 1, the value for a vacuum. This indicates that the best bonding materials for screen-printing CNT-cathodes should have a low dielectric constant and this can be used as criteria for selecting bonding materials for use in CNT pastes for high-efficient CNT-cathodes

Keywords: Carbon nanotubes, Screen-printing, Dielectric constant, Field enhancement factor

I. Introduction

Numerous efforts have recently been made to use a carbon nanotube cathode (CNT cathode) as an emitter for field emission display (FED). In general, a carbon nanotube cathode can be fabricated by means of chemical vapor deposition (CVD)[1,2], or screen-printing method which is amenable to the mass production[3]. In the manufacture of large area field emission displays, screen printed CNT-FED is more useful in terms of the fabrication process because it can be mass produced more easily at lower costs than that of CVD-process grown CNTs. However, in the case of CNT paste, many technical limitations remain, including difficulties in fabricating high resolution panels, the non-uniform dispersion of CNT powders, poor adhesion between the substrate and CNT layer, low reproducibility caused by numerous manufacturing process steps, and their life time [4]. Therefore, the effects of several bonding materials that are routinely added to improve adhesion between the CNT and substrate with reference to the above technical limitations on field emission efficiency have been reported [5-9]. Choi et al.[5] reported that frit glass shows better field emission characteristics than silver paste but Zhou et al.[9] reported that the contrary is true. Park et al.[6, 7] reported that spin-on-glass(SOG) shows better field emission characteristics than frit glass. Collectively, the above investigations [5-9] showed that a relationship exists between bonding materials and field emission characteristics but the issue of specifically how bonding materials affect field emission characteristics remains unclear. Accordingly, it seems reasonable that the material constant of bonding materials might be related to the field emission efficiency of screen printed CNT cathodes.

In this study, we investigated such a relationship between the dielectric constant of bonding materials and field emission characteristics by means of simulation method.

II. Theoretical Background

Generally, the experimental field emission data are analyzed using the Fowler-Nordheim model. The corresponding F-N plots [Ln [I/V^2] vs. 1/V] indicate Fowler-Nordheim type field emission behavior. The electric field enhancement factor can be derived using the Fowler-Nordheim formula [10]:

$$I \propto aV^2 \exp\left(-\frac{b}{V}\right) \tag{1}$$

$$b = \frac{0.95B\phi^{3/2}}{\beta'} \tag{2}$$

Where β' is the local field conversion factor at the emitting surface, $B = 6.87\times10^7$, Φ is the work function of CNTs (~4.5eV), the electric field enhancement factor(β) can be estimated from the equation [10]:

$$E_{loc} = \frac{\beta V}{d} \tag{3}$$

Where d is the distance between the anode and cathode. The electric field enhancement factor (β) is only related to a geometric parameter such as emitter radius and aspect ratio [11, 12]. This theory could be right for Spindt-type emitter which has the structure as shown in Fig. 1 (a). However, in the case of an emitter type, as shown in Fig. 1(b), the local electric field(E_{loc}) is different from Fig 1(a) and Fig 1 (b) because of the effect of bonding materials used.

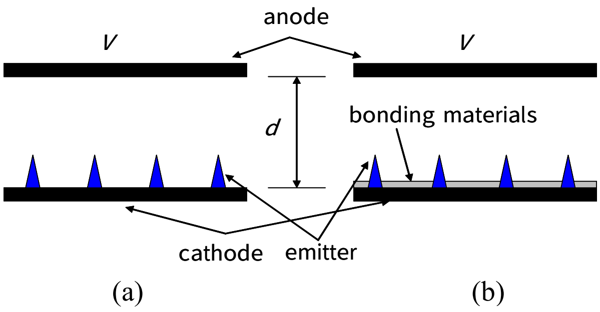

Fig. 1 A schematic structure of a diode type field emission display: (a) a spindt type emitter, (b) screen-printed emitter.

That is to say, the local electric field (E_{loc}) will be decreased because of a lower aspect ratio in the case where bonding materials are conductive, such as silver paste. However, in the case where bonding material is an insulator, such as glass-frit, the local electric field (E_{loc}) will change with the dielectric constant of the bonding materials used.

In order to determine the effect of dielectric constant, we modeled a simplified diode-type field emitter structure and calculated this effect by using the ANSYS software. The detailed results are discussed in the following sections.

III. Simulation Model

Fig. 2 (a) shows a brief geometrical description for a general experimental setup, except for the diameter, height and tip distance of CNTs. In order to apply this to a simulation model, we assumed that the diameter and the height of the CNTs are 20 nm and 15 µm respectively and the thickness of bonding material (paste) used is 10 µm. Although the applied voltage and distance between the anode and cathode electrodes is respectively 1000V and 500 µm in the experimental setup, the applied voltage and electrode distance in simulation model were set at 100V and 50/µm under the same electric field conditions(2V/µm) for convenience of modeling. Fig. 2(b) shows a simplified model used in the simulation. The parameters used are summarized in Table 1. As shown in Table 1, the dielectric constants of bonding materials were varied from 1 to 5. In addition to these dielectric materials, we made calculations for conductive bonding materials such as silver paste as a reference.

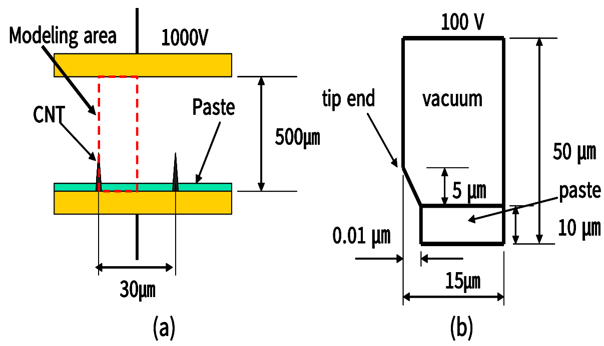

Fig. 2 A geometrical description of the simulations: (a) a general experimental setup, except for the tip distance. (b) a detailed model for the simulation. Paste thickness: 10µm, tip height: 15µm, tip diameter: 20nm, tip distance: 30µm, electric field: 2V/µm (1000V/500µm = 100V/50µm).

Table 1. Summary of the simulation conditions used.

CNT			Bonding materials (insulator)		Vacuum	Applied Voltage (V)	Others
Diameter (nm)	Height (µm)	Tip distance (µm)	Thick (µm)	Dielectric constants (var.)	Dielectric constants		
20	15	30	10	variable 1,2,3,4,5	1	100	- Axis-symmetric - Cathode and CNT tip are electrically conductive materials.

IV. Results and Discussion

Table 2 shows the calculated results for the electric fields at the tip-end of a CNT and at a mid-point between two tips (distance 15㎛) for different dielectric-constant. As described in equation (3), the electric field ratio of the tip to the mid-point ($E_{tip\ end}$ / $E_{distance\ 15}$) could be used as a parameter for the field enhancement factor [10].

Table 2. Calculated results for electric fields with different dielectric constants.

Dielectric constant (ε)	$E_{tip\ end}$ (V/㎛)	$E_{distance\ 15}$ (V/㎛)	$E_{tip\ end}/E_{distance\ 15}$
1.0	47.290	1.970	24.003
2.0	36.919	2.191	16.850
3.0	32.795	2.279	14.391
4.0	30.580	2.326	13.146
5.0	29.198	2.356	12.395
Conductive paste	23.228	2.483	9.355

For the conductive paste, such as conductive bonding materials, we calculated the ratio and obtained a value of 9.355, which is the lowest value found in this study. This result is caused by the contribution of the portion of the CNT tip that protrudes above the surface of the conductive paste. On the other hand, for dielectric materials, the electric field ratio of the tip-end to the mid-point increases with decreasing dielectric constants. Fig. 3 shows that the electric field ratio decreases exponentially with dielectric constant. Accordingly, based on these simulation results, equation (3) should be modified to the following form.

$$E_{loc} \sim \frac{\beta V}{d} \times \exp(-a\varepsilon) \tag{4}$$

Where ε is the dielectric constant of the bonding material and α is a positive constant. According to previously reported experimental results[5, 7, 8], a frit glass shows better field emission characteristics than a silver paste[5] and spin-on-glass(SOG) shows better field emission characteristics than a frit glass[6,7].

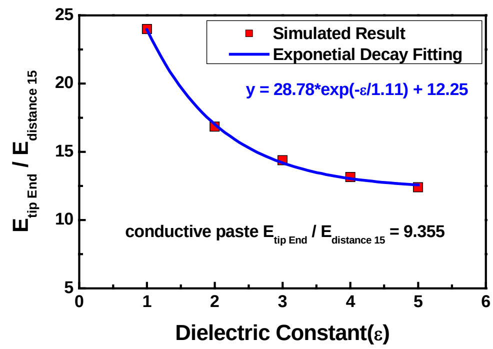

Fig. 3 Electric field ratio versus dielectric constants(square symbol). The result is fitted by using an exponential decay function (solid line).

Although the exact dielectric constants of bonding materials are not known in the above experimental results[5, 7, 8], these values can be estimated using literature[13, 14, 15]. The dielectric constants of lead free frit glass (BaO-ZnO-B_2O_3 system) and spin-on-glass were reported to be 14~20 [13] and 2.2~5.1 at 1 MHz [14, 15] respectively. Kim et al. [13] reported that dielectric constant of lead free frit glass (BaO-ZnO-B_2O_3 system) is slightly higher than conventional lead based frit glass. Although Park et al.[6, 7] reported that the better characteristics of spin-on glass is due to the improvement in the uniformity of the paste layer, these results[6, 7] can be caused by the contribution of lower dielectric constants. Furthermore, Appen and Bresker provided factors from which dielectric constants can be calculated using the following equation [13]:

$$\varepsilon = \frac{1}{100}\sum \varepsilon_i p_i \tag{5}$$

Where p_i represents the portion of the individual oxides in mol % and ε_i is the characteristic factor for each oxide. Therefore, equations (4) and (5) would be very important for technical applications in field emission display.

From this study, we estimate that the current density of a sample made using dielectric materials would be higher than that of conductive materials and lower dielectric-constants materials would show a higher current density.

V. Conclusion

The findings herein indicate that the emission current in a screen-printed CNT cathode is dependent on the dielectric constant of the inorganic bonding materials. This can be used as criteria for choosing the type of bonding materials that can be used in a CNT paste for high-efficient CNT-cathodes.

VI. References

[1] O. M. Küttel, O. Groening, C. Emmenegger, L. Schlapbach, Appl. Phys, Lett. 73 (15) (1998) 2113.

[2] Z. F. Ren, Z. P. Huang, D. Z. Wang, J. G. Wen, J. W. Xu, J. H. Wang, L. E. Calvet, J. Chen, J. F. Klemic, M. A. Reed, Appl. Phys. Lett. 75 (8) (1999) 1086.

[3] W. B. Choi, D. S. Chung, J. H. Kang, H. Y. Kim, Y. W. Jim, I. T. Han, Y. H. Lee, J. E. Jung, N. S. Lee, G. S. Park, J. M. Kim, Appl. Phys. Lett. 75 (20) (1999) 3129.

[4] J. E. Jung, Y. W. Jin , J. H. Choi, Y. J. Park, T. Y. Ko, D. S. Chung, J. W. Kim, J. E. Jang, S. N. Cha, W. K. Yi, S. H. Cho, M. J. Yoon, C. G. Lee, J. H. You, N. S. Lee, J. B. Yoo, J. M. Kim, Physica B 323 (2002) 71.

[5] W. S. Choi, H. Y. Shin, D. H. Kim, B. G. Ahn, W. S. Chung, D. G. Lee, Y. R. Cho, Kor. J. Mat. Res. 13 (2003) 663.

[6] Y. R. Cho, J. H. Lee, S. D. Ahn, B. C. Kim, Y. H. Song, C. S. Hwang, C. H. Chung, K. I. Cho, Vacuum Microelectronics Conference, 2001. IVMC 2001, Proceedings of the 14th International (2001) 67.

[7] J. H. Park, J. S. Moon, J. H. Han, A. S. Berdinsky, J. B. Yoo, C. Y. Park, J. W. Nam, J. W. Park, C. G. Lee, D. H. Choi, Vacuum Nanoelectronics Conference, 2004. IVNC 2004. Technical Digest of the 17th International (2004) 74.

[8] J. H. Park, J. H. Choi, J. S. Moon, D. G. Kushinov, J. B. Yoo, C. Y. Park, J. W. Nam, C. K. Lee, J. H. Park, D. H. Choi, Carbon 43(2005) 698.

[9] X. Zhou, L. Wei, Q. Wang, J. Li, Vacuum Microelectronics Conference, 2003. Technical Digest of the 16th International (2003) 143.

[10] J. Li, W. Lei, X. Zhang, X. Zhou, Q. Wang, Y. Zhang, B. Wang, App. Surf. Sci. 220 (2003) 96.

[11] T. S. Fisher, D. G. Walker, J. Heat Transfer 124 (5) (2004) 954.

[12] R. C. Smith, J. D. Carey, S. R. P. Silva, Vacuum Nanoelectronics Conference, 2004. IVNC 2004. Technical Digest of the 17th International (2004) 176.

[13] D. N. Kim J. Y. Lee, J. S. Huh, H. S. Kim, J. Non-Cryst. Solids. 306 (2002) 70.

[14] Y. Y. Cheng, L. C. Chao, S. M. Jang, C. H. Yu, M. S. Liang, Interconnect Technology Conference, 2000. Proceedings of the IEEE 2000 international (2000) 161.

[15] C. C. Tee, G. Sarkar, S. C. Y. Meng, D. L. H. Yu, L. Chan, Electron Devices Meeting, 1997. Proceedings, 1997 IEEE Hong Kong (1997) 86.