Relationship between work function and current fluctuation of field emitters: Use of SK chart for evaluation of work function

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The relation between the work function and current fluctuation was investigated for various kinds of emitters: element metals, transition metal nitrides, and diamonds. Since these deposited emitters have no good standard, it is difficult to distinguish the effect of work function and the other physical parameters such as apex radius. In order to distinguish these effects, we propose a unique technique of the SK chart and plotting the Fowler–Nordheim characteristics in the SK chart in accordance with the magnitude of the noise power: SKN plot. The SKN plot clearly exhibits the relation between physical parameters and current fluctuation and it was found that the emitter with lower work function shows lower current fluctuation.
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I. INTRODUCTION

In order to realize vacuum microelectronics devices, it is necessary to establish the method for evaluation of field emitters. We have been investigating the emission stability of various kinds of field emitters which include those made of element metals,[1–5] transition metal nitrides,[6,7] and boron-doped diamonds.[8] When comparing the characteristics between these materials, we should know the difference of the physical parameters for each emitter, for example, apex radius r_a or work function ϕ. However, derivation of this information is generally difficult because the field emitter has three unknown parameters of r_a, ϕ and emission area α, despite the fact that obtained values are only two: current and voltage. In order to obtain ϕ, it has been necessary to calibrate r_a with a well defined needle emitter. However, deposited field emitters have no good standard, unlike the conventional bulk field emitters. In order to overcome these difficulties, we have proposed a technique for estimation of field emitters using a two-dimensional diagram SK chart[2,9] of which abscissa and ordinate are the intercept and slope of the Fowler–Nordheim (FN) plot. Since the effects of r_a and ϕ on the emission characteristics are clearly distinguished in this chart, relationship between the physical parameters of field emitters and emission property will be known easily. It should be noted that the equi-ϕ curve on SK chart does not agree with the theoretical calculation based on the smooth surface.[9] Accumulation of the FN data begins to clarify the empirical relation between the slope and intercept.[10] Using this chart, we have reported an empirical relation between ϕ and normalized noise power P_N of the nickel deposited field emitters.[2] In this article, we report that this relation is seen for various kinds of emitters.

II. EXPERIMENTAL PROCEDURE

A. Analyzed emitters

We have analyzed various kinds of field emitters as listed in Table I. Since the details of the measurement have already been published, we depict the reference for each emitter. All the measurements were performed in ultrahigh vacuum (UHV) of 10^{-7} Pa, pumped by a sputter ion pump. Field emission measurements were performed very carefully after the aging of several hours.

B. Measurement of the emission characteristics

The current–voltage characteristics were recorded in an $X-Y$ recorder or a personal computer through an analog or digital current meter. In all the experiments, the difference in emitter-collector gap causes a significant deviation of the location in the SK chart, thus we precisely controlled the gap. Measurements of the needle emitters and the diamond emitters were performed with the device which can control the electrode gap by piezoelectric device. For nitrides and Spindt-type emitters, the collector was fixed. The current fluctuation was recorded in a personal computer through a digital current meter.

We repeated current–voltage characteristics and current fluctuation measurements of various currents, typically 0.4 nA, 40 nA, and 4 μA. In this article, current fluctuation at 40 nA extraction will be argued. The current fluctuation was also recorded to PC through the digital current meter. P_N was calculated in the following manner.[2] A current fluctuation curve of which absolute intensity was normalized by the average current, was converted to power spectral density by Fourier transform. Integrating the power spectral density from 0.2 to 2 Hz, we obtained the value of P_N. Although the frequency range is narrow, this is adequate because the noise power spectrum is generally proportional to $f^{-\gamma}$, where $1<\gamma<2$, which means high frequency component is small as compared with the low frequency component.

C. SK chart

The FN characteristics were converted to points in the SK chart[2] with their slopes and intercepts. Figure 1 shows the typical example of the SK chart, together with the interpretation of this chart. The plotted data were obtained by Ni deposited W needle emitter. The emission characteristics de-

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TABLE I. Various kinds of emitters evaluated in the present study.

Emitter material	Emitter type	Collector	d_{EC} (μm)	Reference
Ni	Deposited on W needle	Si substrate	1.5	2
Mo, Ni, Au, Pt	Spindt-type	Si substrate	0.5	3,4
Pt	Spindt-type (CO treated)	Phosphor coated glass	0.5	5
ZrN_x, NbN_x	Deposited on Si pyramid array	Si substrate	4	6.7
B doped CVD diamond	Deposited on flat substrate	Gold ball	1.5	8

viate among this plotted range. The upper right indicates lower ϕ and the lower left indicates higher ϕ. The upper left indicates smaller r_a and lower right indicates larger r_a. In this chart, one FN characteristic is converted to a point. Some researchers evaluated their emitter with this chart.[11,12] One of the important things is that the distribution of FN characteristics in this chart does not obey the theoretically derived distribution,[9] as described earlier. The theoretical curve for the emitters with various r_a and the same ϕ should distribute along a vertical line. However, the experimentally obtained data distribute transversely. In a previous article,[2,9] we described the equi-ϕ line with inversely proportional relation between S and K. The empirical relation seems to have linear relation with a negative slope.[5,12] This linear relation is considered to be equi-ϕ line.[13] We also argued the relation between the parameters which gives linear relation,[13] but currently quantitative arguments are not possible. The relation which has already been shown by prior work is, however, almost linear if the distribution does not scatter too much so we partially use the equi-work function line in this article. It should be noted that in the SK chart, the relative change of the apex radius can be read, but if there is a large change in emitter-collector geometry or difference in gap between these electrodes, a simple comparison would not be possible.

D. Plot of noise power data on SK chart: SKN plot

In order to investigate the relationship between the physical parameters and stability, one of the easiest ways is to make the ''SKN plot.'' In the SKN plot, the size of the plot is in accordance with the magnitude of P_N: a larger plot means a higher P_N. Plotting in such a way, can visually estimate the relation between P_N and physical parameters of the emitters.[2]

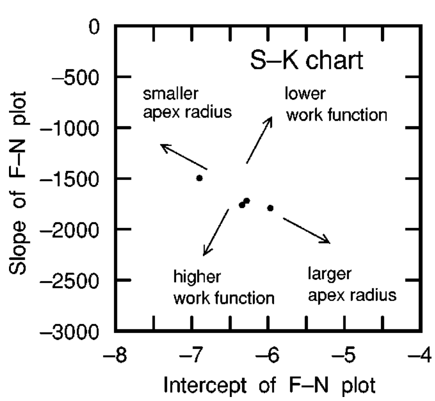

FIG. 1. Example of the SK chart and how to read it.

III. RELATIONSHIP BETWEEN WORK FUNCTION AND CURRENT FLUCTUATION

A. Transition metal nitride field emitters

First, we describe the results of the transition metal nitride emitters, because the work function of these materials can be controlled by controlling the nitrogen composition, as was measured by the Kelvin probe.[13] The ZrN_x and NbN_x emitters were fabricated by depositing these films on a Si pyramid array.[6,7] The relation between the ϕ measured by a Kelvin probe and the P_N was already investigated and the results showed that the emitter with lower ϕ shows lower P_N. Figures 2(a) and 2(b) show the SKN plot for ZrN_x and NbN_x emitters. The number shown in the figure is the estimated ϕ. Solid curves are equi-ϕ line proposed in the previous study, which may be a guide of view. The NbN_x film, as well as ZrN_x film, shows lower P_N for the emitter with lower ϕ. For both materials, P_N depended on ϕ of the emitter.

B. Spindt-type field emitters

Spindt-type cathodes with various metal materials were examined.[3,4] We can compare the emission characteristics among the different cathode materials, and also those of the

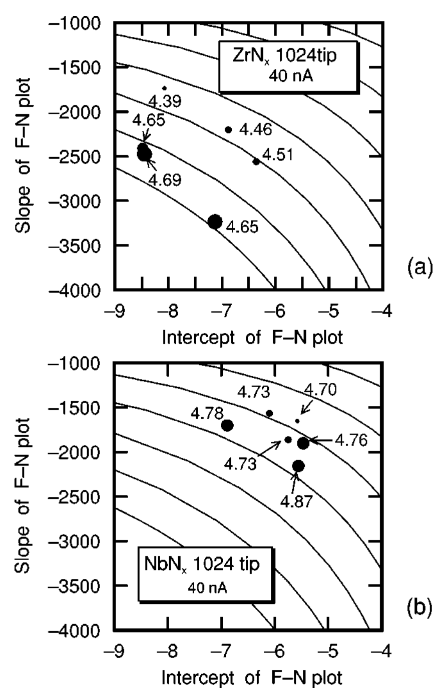

FIG. 2. SKN plot of transition metal nitride field emitters; (a) ZrN_x and (b) NbN_x.

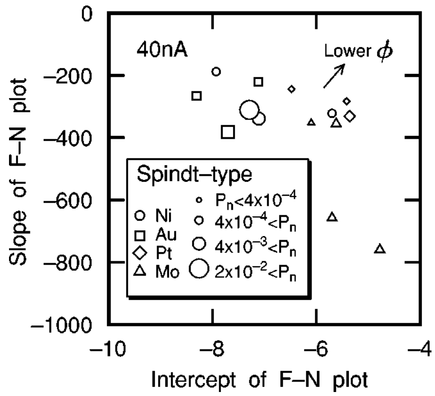

FIG. 3. SKN plot of Spindt-type field emitters with various kinds of materials.

Pt emitters before and after the CO treatment which greatly enhances the emission property.[5,14] Figure 3 shows the SKN plot for different cathode materials. Although the cone half angle of these emitters is different, the noise power of the emitter which is located at the upper right is lower than that at the lower left.

The Pt emitters could be significantly improved by the operation in carbon monoxide ambient.[14] As we have reported, the driving voltage was largely improved and at the same time, current fluctuation was reduced. This is also explained by the location of FN data in the SK chart.

C. Boron-doped diamonds

Boron-doped diamond film field emitters were prepared by microwave plasma chemical vapor deposition, on a flat silicon substrate. Details of the preparation conditions are shown elsewhere.[8] The films with different boron concentration were prepared, and also the surface treatments were made to have hydrogen- or oxygen-terminated surface for each sample. The measurement was done with a gold ball as a collector. Figure 4 shows the SKN plot for these emitters. The solid and open marks indicate the hydrogen- and oxygen-terminated diamonds. P_N did not depend on the boron concentration but depended on the surface treatment: P_N of the hydrogen-terminated film was of the order of 10^{-6}, and that of the oxygen-terminated film was of the order of 10^{-5}. In this case as well, the emitter with lower ϕ indicates the lower P_N.

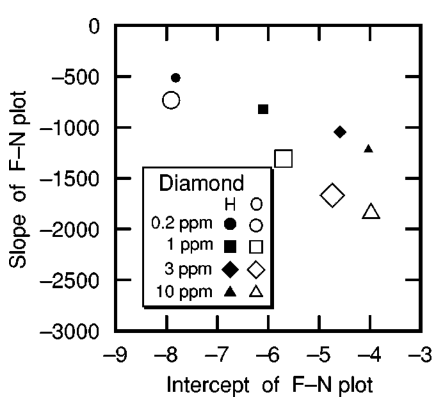

FIG. 4. SKN plot of boron-doped diamond thin film field emitters.

IV. DISCUSSION

The SKN plots clearly showed the relationship between ϕ and P_N, that is, current fluctuation. The reason for this strong correlation has not been fully understood. If the current fluctuation is due to adsorption and desorption of molecules on the emitter surface, change in the ϕ of the emission site is a plausible candidate. We have derived the equation

$$\frac{dj}{j} \propto \phi^{1/2}, \tag{1}$$

from the differential of the FN equation.[2] However, this equation underestimates the strong correlation between P_N and ϕ. Furthermore, the current fluctuation is not governed by ϕ only but also depends upon the apex radius. Further investigation on this issue will be necessary.

V. CONCLUSION

We have investigated the empirical relation between ϕ and P_N of various kinds of deposited field emitters with the SK chart. As a result, it was shown that the emitter with a lower ϕ shows lower current fluctuation, for the same kinds of material. In the development of field emission cathode, a material with a lower ϕ is preferred and evaluation can be made by the SK chart.

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