Characteristics and Circuit Model of a Field Emission Triode

Jung-Hyun Nam, Jeong-Don Ihm, Jong-Duk Lee, Yeo-Hwan Kim, and Kyu-Man Choi

Abstract

A circuit model for a field emission triode has been proposed. The model parameters have been extracted from the fabricated silicon tip array and verified by comparing with the results simulated by circuit simulator (SPICE). The cut-off frequency can be calculated from the parametric capacitance and the transconductance values extracted from measurements. For the field emission triode, the capacitance of 3.45 fF/tip and the transconductance of 0.94 nS/tip have been measured under the emission current of 4.1 nA/tip. From these values, the cut-off frequency is predicted to be 43 kHz but the measured one came out to be 6kHz. because of the parasitic capacitance components.

I. Introduction

A field emitter array as an electron source may become available by combining the micro-fabrication techniques with the superiority of vacuum as a transport medium. A number of researches have been carried out on the fabrication and the DC test of field emission triodes. However it is also important to analyze the AC characteristics of them for the applications including field emission display and RF power amplifier[1]. From that analysis, various characteristics of the field emission triodes such as optimal operating point, transient state response, delay, frequency response, and input/output current can be predicted.

In this paper, a circuit model of the field emission triode is proposed and the numerical values of parameters related to the model are extracted. The values of these parameters can be estimated analogically from the MOSFET model which is adapted for the field emission triode. In this model, field emission parameters are strongly dependent on the structure of the field emission triode and the work function of the tip material because the electron transport in the vacuum device is ballistic.

The fabrication process of silicon field emitter array, which is used for the field emission triode modeling, is based on isotropic silicon dry etching, tip-sharpening oxidation, and nitride side-wall masking oxidation[2]. The fabricated field emission triode has physical parameters of 1 μm oxide isolation layer thickness, 1.6 μm gate hole diameter, and 1.5 mm distance between the gate and the anode. Figure 1 is the SEM photo image showing the cross sectional view of the single field emitter and figure 2 is the measured F-N plots for a single tip and a 256-tip array.

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II. Circuit Modeling of a Field Emission Triode

The model parameters superimposed on the basic structure of a field emission triode are shown in figure 3. In the notations, T means the internal node supposed to be located at the tip apex. R_G and R_C represent the line resistances of the gate and the cathode, respectively and their values are less than 10Ω. R_{GC} represents the modeling resistor parameter for the leakage current component through the thermally grown silicon dioxide layer separating the gate from the cathode and the extracted value from the measured I-V characteristics is about $1\times10^9\Omega$. The resistance of the silicon tip, R_{tip} can be approximated by equation (1), if the silicon tip is assumed to be a truncated cone.

$$R_{tip} = \frac{\rho h}{\pi R r} \tag{1}$$

where is the resistivity of a silicon tip, R is the radius of tip base, r is the radius of tip, and h is the height of tip. The tip used in this modeling has $\rho = 5\times10^{-3}$ Ωcm, h = 1.2 μm, R = 0.5 μm, and r = 0.05 μm. From these values, R_{tip} is calculated to be 760 Ω/tip.

The capacitance between the gate and the cathode, C_{GC} is mainly composed of the isolating silicon dioxide capacitance and calculated to be 3.45 fF/tip from the gate area and the silicon dioxide layer thickness. C_{GC} is the largest capacitance value in the model parameters and its value is nearly independent of the gate bias voltage because the oxide layer is so thick that the

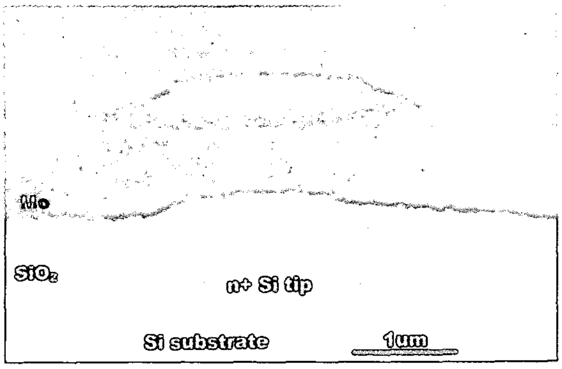

Fig. 1. A SEM photo image of the silicon-tip field emission triode fabricated by the isotropic silicon dry etching[2].

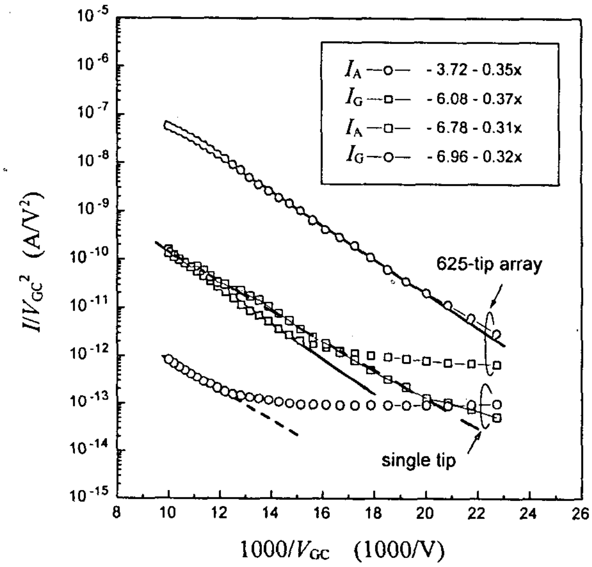

Fig. 2. The measured F-N plots for a single tip and a 625-tip array. I_A and I_G represent the anode current and the gate current respectively. The straight lines are for the modeling of the emission current equations and the resultant offset and slope values are arranged in the legend box of the figure.

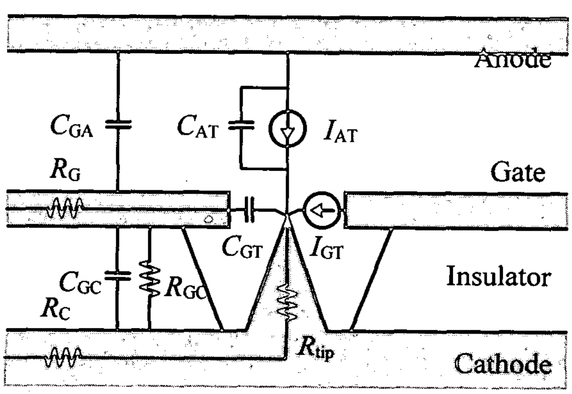

Fig. 3. The physical structure and the equivalent circuit model of a field emission triode.

silicon depletion capacitance can be ignored. The main effect of this capacitance is limiting of the speed at which the gate voltage can be modulated and reducing the gate-to-tip voltage under high frequency operating condition in combination with R_{tip}. The capacitance between the gate and the anode is represented by C_{GA} and is can be determined from the distance between the gate and the anode plate. C_{GT} represents the capacitance between the gate and the tip and it can be calculated from the total surface charge induced on the tip by gate voltage, which is equal to the surface integral of the electric flux density due to the gate voltage[3]. The calculated value for C_{GT} is 0.041 fF/tip, while the measured one is 0.1~0.4 fF/tip[4]. The difference between the calculated and the measured values might be caused by the surface roughness of the real tip. Thus the calculated value should be multiplied by a surface enhancement factor. C_{AT} represents the capacitance between the anode and the tip and is calculated to be about 4.24×10^{-4} fF/tip using the same method for C_{GT}.

The dependent current sources I_{AT} and I_{GT} in the circuit model represent the emission current due to the electric field created by the potential difference between the tip and the gate. The anode current I_{AT} is one portion of the emission current received by the anode, while the gate current I_{GT} is another by the gate. I_{AT} can be characterized by Fowler-Nordheim equation[3] in the form of ;

$$I_{AT}= aV_{GT}^2\exp\left(-\frac{b}{V_{GT}}\right)\begin{cases} a\cong1.54\times10^{-6}\frac{\alpha}{\phi}\exp(9.89/\sqrt{\phi}) \\ b\cong6.53\times10^{-7}\phi^{3/2}/\beta \end{cases} \quad (2)$$

where V_{GT} is the voltage between the gate and the tip in [V], α is the emitting area in [cm^2], ϕ is the work function of tip material in [eV], and β is the geometric factor in [cm^{-1}] depending on the electrode configuration. From the measured F-N plots in the figure 2, the vertical axis intercept I and the slopes S can be extracted and the values of a and b can be calculated from I and S using the following equations.

$$I = \log a$$
$$S = -\frac{b}{1000}\log e \quad (3)$$

For a single tip, a and b for anode current are 1.66×10^{-7} A/V^2 and 713.7 V, respectively and a for gate current is about 1/1000 of that for anode current.

For the simplicity, the noise current generated by the secondary electron emission from the anode[5] is ignored. The noise component in the field emission current is dominated by 1/f flicker noise below 100 kHz and by shot noise above 100 kHz[5-7].

A small signal equivalent circuit in which the dependent current sources are represented as transconductance components is used to analyze the AC characteristics of a field emission triode. But the analytical analysis with the full circuit model parameters is very complicated. Using theoretical and experimental techniques,

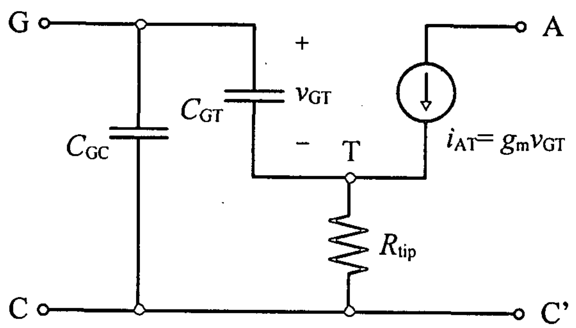

Fig. 4. The simplified small signal equivalent circuit model for a field emission triode.

a representative numerical value was obtained for each parameter. These results show that the values of some quantities such as R_G, R_C, R_{GC}, C_{GA}. C_{AT}, and I_{GT} are small enough to be negligible in normal operation of the field emission triode. The remained circuit model parameters are shown in the simplified small signal equivalent circuit shown in figure 4.

From the equation (2), the small signal transconductance g_m is written as follows;

$$g_m = \frac{\partial I_{AT}}{\partial V_{GT}} = \frac{I_{AT}}{V_{GT}}\left(2+\frac{b}{V_{GT}}\right) = a(2V_{GT}+bv)\exp\left(-\frac{b}{V_{GT}}\right) \quad (4)$$

Thus the g_m monotonously increases with the increasing V_{GT}. The transconductance of a single tip as a function of the gate voltage is shown in figure 5. The solid line in the figure represents the calculated values from the equation (4) and the relation of $V_{GC} = V_{GT} + I_{AT}R_{tip}$ under DC condition and the dots are the measured ones. The figure shows a good agreement between the calculated and the measured transconductance.

The cut-off frequency f_T can be defined as a frequency at which the common source short circuit current gain comes to unity and it can be written as equation (5) using the simplified small signal model in figure 4.

$$f_T = \frac{g'_m}{2\pi(C'_{GC}+C_{GT})} \quad (5)$$

where g'_m and the C'_{GC} are expressed as the equations of (6) and (7)

$$g'_m = g_m + 4\pi^2 f_T^2 R_{tip} C_{GC} C_{GT} \quad (6)$$

$$C'_{GC} = C_{GC}(1+g_m R_{tip}) \quad (7)$$

g'_m and C'_{GC} are the corrected values of g_m and C_{GC} because of the tip resistance, R_{tip}. From the above equation and the model parameter values, the correction errors for g_m and C_{GC} are less than 0.01% and the cut-off frequency of the single tip with the emission current of 1 μA/tip is calculated to be about 4.4 MHz. The total transconductance and the total capacitance of a field emitter array are proportional to the number of tips in the array, so simple increase of the number of tips does not improve f_T.

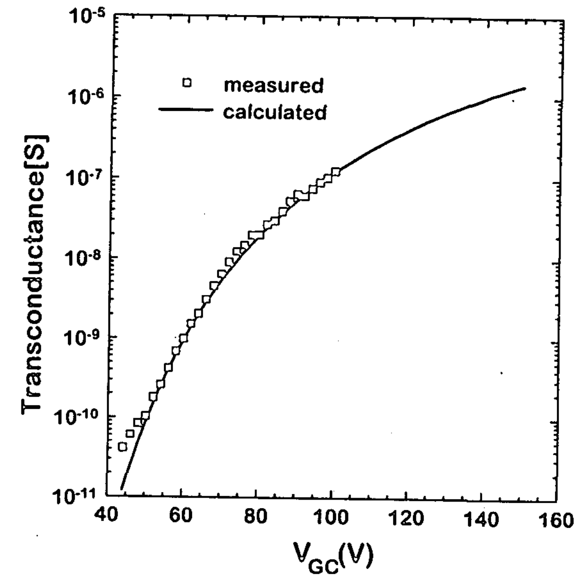

Fig. 5. Transconductance of a single tip as a function of the gate voltage.

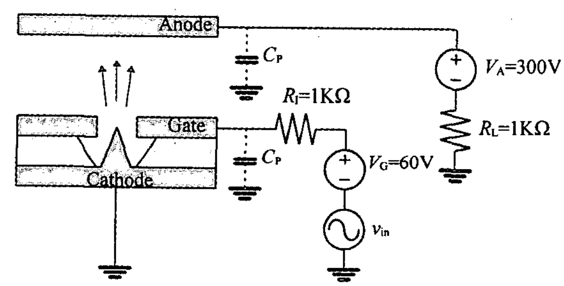

Fig. 6. A schematic diagram for measuring the AC response of the field emission triode.

For improving f_T, g_m should be increased by optimizing the tip emission characteristics or by choosing the operating point of higher gate bias voltage, and the capacitance value should be decreased by the increase of the emitter packing density[8-9].

III. Measurement and Circuit Simulation

Comparison of the measurement and the SPICE simulation result was conducted to verify the equivalent circuit model. The AC characteristics of the fabricated field emission array with 625 tips has been tested with the gate bias voltage of 60 V as shown in figure 6. Under these bias conditions the DC anode current is measured to be 4.1 nA/tip and the g_m and f_T are predicted to be 0.94 nS/tip and 43 kHz, respectively. Small signal sinusoidal input voltage is added to the gate bias voltage and the magnitudes of the input and output current are measured at the resistor of 1 kΩ connected serially to the gate and the anode bias voltage sources.

Figure 7 shows the measured AC current gain as hollow square

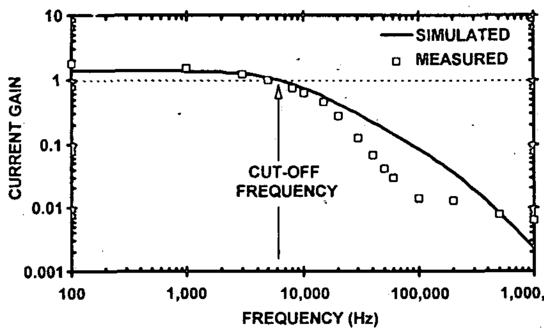

Fig. 7. The AC current gains measured from the field emission triode and simulated by using SPICE with the full model parameters and the external components including parasitic capacitors originated from the measurement setup.

dots. The measured cut-off frequency is 6 kHz, which is about 1/7 of the one predicted by the simplified small signal model. This discrepancy is due to the large parasitic capacitors originated from the measurement system including the probe station in the ultra-high vacuum chamber and the line cables as represented by C_P's in figure 6. By the measurements with various load resistor values, C_P's for our measurement system come out to be about 600 pF per a probe. In figure 7, the SPICE simulation result with the full model parameters in the figure 1 and the external components including the parasitic capacitors in figure 6 is plotted as a solid line. The figure shows that the simulated output is nearly same as the measured one up to the cut-off frequency. Over that frequency, the output magnitude decreases rapidly and it reaches the measurement limit over the frequency of 100 kHz. From this comparison, it can be concluded that the parameters for the circuit model are reasonable.

IV. Conclusion

A circuit model for a field emission triode has been developed and the parameters of the equivalent circuit model have been analyzed. The parameters are composed of the resistance, the capacitance, and the current sources depending on the gate voltage. Each parameter value can be obtained theoretically and experimentally. A simplified small signal equivalent circuit model has been developed to analyze the AC characteristics. From this model, the cut-off frequency is proportional to the ratio of the transconductance, which is strongly dependent on the anode current and the gate bias voltage, to the total gate capacitance. It can be known that the anode current per tip or the tip density should be increased to make the cut-off frequency higher. The former is more effective but the high anode current will deteriorate the reliability of the emission tips. SPICE simulation and measurement have been conducted to verify the developed model. The results reveal a good agreement but the parasitic elements originated from the testing setup are affecting the frequency responses.

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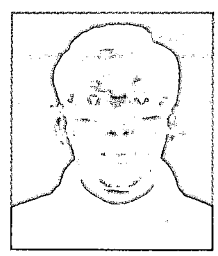

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