Electron Emission Theory for LCD Backlight

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Abstract

We considered most general electron emission caused by temperature as well as electric field with a free electron gas model. The total electron emission current density comes from field emission effect where electron energy is lower than vacuum and from thermionic emission effect where electron energy is higher than vacuum. The total electron emission current density is shown as a function of temperature for constant electric field, and as a function of electric field for constant temperature.

1. Introduction

Electron emission has been considerable interests in LCD backlight such as Hot Cathode Fluorescent Lamp and Carbon Nanotube (CNT) backlight, and Field emission display. Thermionic emission is well-known that electrons in metal get enough thermal energy to come out of the metal [1]. The electrons in metal make tunneling through the barrier which becomes thin in high electric field. It is called field emission or Fowler-Nordheim tunneling. The tungsten tips applied by high voltage are examples for the field emissions. The electric field in the tip is proportional to the applied voltage and inversely proportional to the radius of the tip [2]. CNTs have been used for electron sources due to the small radius, order of $10\,\overset{o}{A}$, consequently lower critical voltage to emit electrons. CNTs have been developed to field emission display and backlight for liquid crystal display. It turns out that the tip of CNT becomes about 1500 K when electrons come out of the surface [3]. It is expected that CNT shows field emission and some thermionic emission because of high temperature effect.

In this paper we consider most general electron emission case which involves temperature and electric field effect together. In the zero temperature limit our unified theory of the electron emission is compared with Fowler-Nordheim equation and shows deviation as electric field increases. The total current density is shown in terms of electric field for constant temperature and in terms of temperature for constant electric field.

2. Theory

Free electrons in metal obey Fermi-Dirac distribution and the electron density in 3-dimensions in terms of energy can be written as

$$n(E) = \frac{8\sqrt{2}\pi m^{3/2}\sqrt{E}}{h^3(1+\exp(-\frac{E-E_F}{k_B T}))} \qquad (1)$$

where E_F represents Fermi energy, E the energy of electron, m the mass of electron, h Plank constant, and k_B Boltzmann constant.

The unified theory of field emission and thermionic emission is considered at arbitrary temperature and electric field. Fig. 1 shows a systematic diagram for the unified electron emission theory. The electron density distribution follows Eq. (1) for a given temperature. At zero bias the electrons below vacuum can not make tunneling due to infinite thickness barrier. The thickness of the barrier is changed by potential energy, V(x)=-eFx, due to the applied electric field as shown in Fig. 1. The electrons having energy, which is lower than vacuum, make tunneling into vacuum through the thin barrier caused by the electric field and make field emission. The electrons having energy, which is higher than vacuum, have enough thermal energy to overcome work function and make thermionic emission.

The total current density of electron emission can be expressed as

$$J = J_F + J_T \tag{2}$$

where J_F represents the current density of the field emission in which electrons come out of metal surface by electric field and J_T the current density of the thermionic emission in which electrons come out of metal surface by thermal energy.

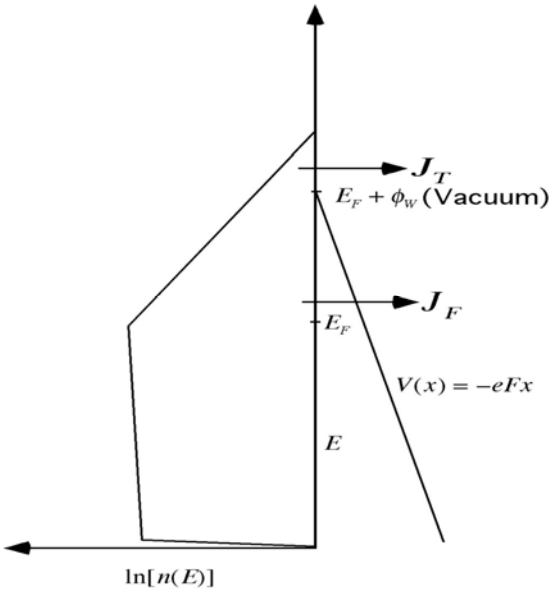

Fig.1. A cartoon for the unified theory of field emission and thermionic emission.

The field emission current density is

$$J_F = \int_0^{E_F+\phi_w} en(E)v_x(E)D(E)dE \tag{3}$$

where ϕ_w is work function, v_x is electron velocity in x-direction, and D is electron tunneling coefficient. The energy range of electrons in Eq. (3) is considered from zero to vacuum where the electron tunneling is possible.

Using Eq. (1) the current density of the field emission, Eq. (3) can be expressed as [4]

$$J_F = \frac{4\pi mek_BT}{h^3}\int_0^{E_F+\phi_w}\int_0^{\infty}\frac{dy}{e^{(\frac{E-E_F}{k_BT})+y}+1}D(E)dE \tag{4}$$

Eq. (4) is simplified to

$$J_F = \frac{4\pi mek_BT}{h^3}\int_0^{E_F+\phi_w} D(E)\ln(1+\exp(-\frac{E-E_F}{k_BT}))dE \tag{5}$$

The tunneling coefficient, D, in Eq. (5) is given by [5]

$$D = \frac{4\sqrt{E}\sqrt{E_F+\phi_w-E}}{E_F+\phi_w}e^{-4k(E_F+\phi_w-E)^{3/2}/3F} \tag{6}$$

where $k=\sqrt{\frac{8\pi^2 m}{h^2}}$ is electron wave number and F is electric field. The tunneling coefficient increases as the energy of the electron and the electric field increases because the barrier becomes thinner by the applied electric field.

From Eq. (5) and Eq. (6), we get

$$J_F = \frac{16\pi mek_BT}{h^3(E_F+\phi_w)}\int_0^{E_F+\phi_w} dE\sqrt{E}\sqrt{E_F+\phi_w-E} \times \ln(1+\exp(-\frac{E-E_F}{k_BT}))e^{-4k(E_F+\phi_w-E)^{3/2}/3F} \tag{7}$$

The current density of the field emission, Eq. (7), can be solved numerically. It turns out that the field emission doesn't depend much on temperature for the high value of the work function and the Fermi energy.

From now we show Fowler-Nordheim approximation in the zero temperature limit, which is the integration approximation. The total electron density of the emission doesn't match well with that of Fowler-Nordheim even in low temperature. The reasons for the discrepancy were that they used two kinds of approximations.

The first approximation is zero temperature limit. The factor, $\ln(1+\exp(-\frac{E-E_F}{k_BT}))$ becomes $\frac{E_F-E}{k_BT}$, which is very good approximation since the electron energy is lower than the Fermi energy in zero temperature limit. This approximation is not good when the electrons appear above Fermi energy for the most field emission cases in which the tunneling current of the electron makes heating on the tip even in low temperature environments. The electron energy can be considered up to the Fermi energy level at zero temperature limit. Considering electrons filled up to Fermi energy in zero temperature limit, Eq. (7) can be written as

$$J_F = \frac{16\pi mek_B T}{h^3(E_F+\phi_w)}\int_0^{E_F} dE\sqrt{E}\sqrt{E_F+\phi_w-E}$$
$$\times(E_F-E)e^{-4k(E_F+\phi_w-E)^{3/2}/3F} \qquad (8)$$

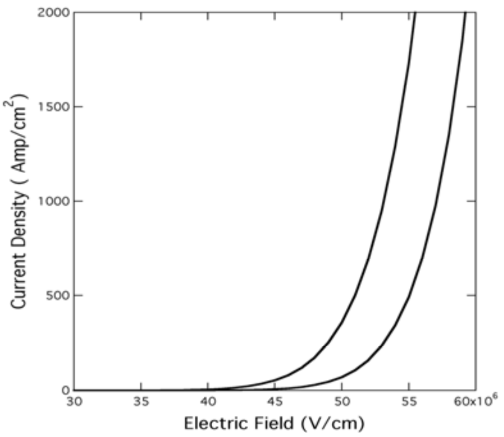

Fig. 2. The Integration approximation by Fowler-Nordheim.

The electron tunneling mainly comes from around Fermi energy level, so the electron energy can be expanded as $E = E_F - x$. Eq. (8) can be expressed in terms of x

$$J_F = \frac{16\pi mek_B T}{h^3(E_F+\phi_w)}\sqrt{E\phi_w}e^{-4k\phi_w^{3/2}/3F}\int_0^{\infty} dx x e^{-2xk\sqrt{\phi_w}/F} \qquad (9)$$

where the integration range from zero to Fermi energy is approximated from zero to infinity.

The 2nd approximation comes from that the exponential term in Eq. (9) is big enough to make an integration approximation. They found the analytical solution from Eq. (9) by the first order approximation as [5]

$$J_F = \frac{e}{2\pi h}\frac{\sqrt{E_F}}{(\phi_w+E_F)\sqrt{\phi_w}}F^2 e^{-4k\phi_w^{3/2}/3F} \qquad (10)$$

This is the well-known Fowler-Nordheim equation.

Fig. 2 shows the Integration approximation by Fowler-Nordheim. The bottom graph shows Eq. (8) and the top graph shows Eq. (10) after the integration approximation. Here work function is 5 eV and Fermi energy is 4 eV. The deviation between the numerical solution of Eq. (8) and the integration approximation of Eq. (10) increases as the electric field increases. When the exponential term in Eq. (8) becomes small, the deviation becomes large: As the Fermi energy and the work function become small and the electric field becomes large, the deviation becomes large.

Electrons above vacuum make thermionic emission, as shown in Fig. 1. The current density of thermionic emission is

$$J_T = \int_{E_F+\phi_w}^{\infty} en(E)v_x(E)dE \qquad (11)$$

where the integration range is considered from vacuum to infinity and the tunneling coefficient of electron is approximated to 1.

The current density of the thermionic emission, Eq. (11) can be written as

$$J_T = \frac{4\pi mek_B T}{h^3}\int_{E_F+\phi_w}^{\infty}\int_0^{\infty}\frac{dy}{e^{(\frac{E-E_F}{k_B T})+y}+1}dE \qquad (12)$$

Eq. (12) becomes

$$J_T = \frac{4\pi mek_B T}{h^3}\int_{E_F+\phi_w}^{\infty}\ln(1+\exp(-\frac{E-E_F}{k_B T}))dE \qquad (13)$$

Since $\ln(1+\exp(-\frac{E-E_F}{k_B T}))$ becomes $\exp(-\frac{E-E_F}{k_B T})$ in this integration ranges in which the electron energy is much higher than the Fermi energy, Eq. (13) is simplified to

$$J_T = \frac{4\pi mek_B T}{h^3}\int_{E_F+\phi_w}^{\infty}\exp(-\frac{E-E_F}{k_B T})dE \qquad (14)$$

where the electrons having higher energy than vacuum can make thermionic emission. Eq. (14) can be solved analytically to

$$J_T = \frac{4\pi mek_B{}^2}{h^3}T^2 e^{-\phi_w/k_B T} \qquad (15)$$

This result is the same as the well-known thermionic emission. The thermionic emission increases exponentially as the work function decreases.

The current density of the total electron emission consists of the current density of the field emission,

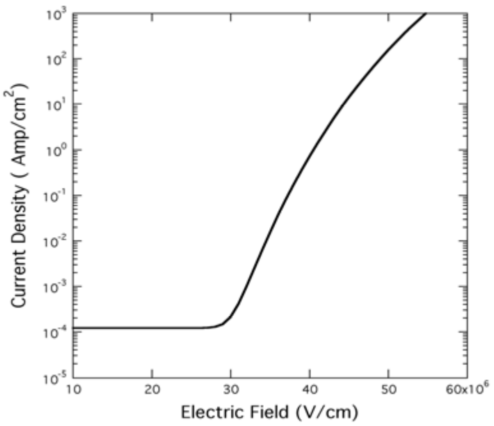

Fig. 3. The current density of electron emission is shown as a function of electric field for the temperature of 2000 K.

Eq. (7), and the current density of the thermionic emission, Eq. (15), in which we can calculate Eq. (7) numerically. Fig. 3 shows the current density of the electron emission as a function of electric field at the temperature of 2000 K for work function and Fermi energy are 5 eV and 4 eV, respectively. Below the electric field of 3×10^7 V/cm the thermionic emission is dominant and above the electric field of 3×10^7 V/cm the field emission becomes more important. Fig. 4 shows the current density of electron emission as a function of temperature for the electric field of 4×10^7 V/cm. The current density of the total electron emission below the temperature of 1500 K comes mainly from field emission effect and is added by thermionic emission effect as temperature increases above the temperature of 1500 K. The current density of the total electron emission increases rapidly from 2500 K as the temperature increases because the number of the electrons, which are thermally excited above vacuum, becomes much higher than that of the electrons, which make tunneling.

The unified theory of field emission and thermionic emission can be applied to the electron emission of the metal which depends on the temperature as well as the electric field. This unified theory will be useful for low work function materials in which the Fower-Nordheim approximation shows deviation. It will be also useful to understand the electron emission from CNT whose temperature becomes above 1500 K.

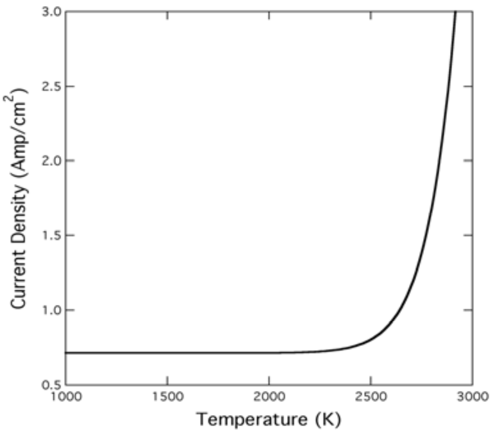

Fig. 4. The current density of electron emission is shown as a function of temperature for the electric field of 4×10^7 V/cm.

3. Summary

We constructed the unified theory of field emission and thermionic emission with a free electron gas model. The unified theory of field emission and thermionic emission shows that the electrons having energy, which is higher than vacuum, have enough thermal energy to overcome work function and make thermionic emission, and the electrons having energy, which is lower than vacuum, make tunneling through the thin barrier caused by the applied electric field and makes field emission. The total current density of electron emission increases as temperature increases above 1500 K for constant electric field. The total current density of electron emission increases as electric field increases above 3×10^7 V/cm for constant temperature.

4. References

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