2-4 Theory of Field emission

Electron field emission is a quantum mechanical tunneling phenomenon of electrons extracted from the conductive solid surface, such as a metal or a semiconductor. If sufficient electric field is applied on the emitter surface, electron s will be emitted through the surface potential barrier into vacuum, even under low temperature. In contrast, thermionic emission is the hot electron emission under high temperature and low electric field. Figure 2-16 (a) shows the potential barrier of a metal-vacuum system. Here W_0 is the energy difference between an electron at rest outside the metal and an electron at rest inside the metal, whereas W_f is the energy difference between the Fermi level and the bottom of the conduction band. The wok function ϕ is defined as $\phi = W_0 - W_f$. When external electric field is applied, the vacuum energy level is reduced and the potential barrier of the surface becomes thinner as shown in Fig.2-16 (b).Then, an electron having enough energy "W" has a finite probability of passing through the potential barrier of the surface into vacuum. Fowler-Nordheim derives the famous F-N equation (2-5) as follow [Spint-76-5248; Tarntair-01-12]

$$J = \frac{aE^2}{\phi t^2(y)} \exp\left[\frac{-b\phi^{\frac{3}{2}} v(y)}{E}\right] \qquad (2\text{-}5)$$

Where J is the current density (A/cm^2), E is the applied electric field (V/cm), ϕ is the work function (in eV), $a = 1.56*10^{-6}$, $b= -6.831*10^{7}$, $y = 3.7947*10^{-4}E^{1/2}/\phi$, $t^2(y) \cong 1.1$ and v(y) can be approximated as

$$v(y)=\cos(0.5\pi y) \qquad (2\text{-}6)$$

or

$$v(y)=0.95-y^2 \qquad (2\text{-}7)$$

Typically, the field emission current I is measured as a function of the applied voltage V.

Substituting relationships of J=I/α and E=βV into Eq. (2-5), where α is the effective emission area and β is the field enhancement factor at the emitting surface, following equation can be obtained

$$I=\frac{A\,\alpha\beta^{2}V^{2}}{\phi t^{2}(y)}\exp\left[-bv(y)\frac{\phi^{\frac{3}{2}}}{\beta V}\right] \qquad (2\text{-}8)$$

Then taking the log. Form of Eq. (2-8)

$$\log\left(\frac{I}{V^{2}}\right)=\log\left[1.54*10^{-6}\frac{\alpha\beta^{2}}{\phi t^{2}(y)}\right]-2.97*10^{7}\left(\frac{\phi^{\frac{3}{2}}v(y)}{\beta V}\right) \qquad (2\text{-}9)$$

From Eq. (2-9), the slope of a Fowler-Nordheim (F-N) plot is given by

$$\text{Slope}=2.97*10^{7}\left(\frac{\phi^{\frac{3}{2}}}{\beta}\right) \qquad (2\text{-}10)$$

The parameter β can be evaluated from the slope S of the measured F-N plot if the work function ϕ was known

$$\beta\cong-2.97*10^{7}\left(\frac{\phi^{\frac{3}{2}}}{S}\right) \qquad (2\text{-}11)$$

Emission area α can be subsequently derived from Eq.(2-9)

$$\alpha=\left(\frac{I}{V^{2}}\right)\frac{\phi}{1.4*10^{-6}\beta^{2}}\exp\left(\frac{-9.89}{\sqrt{\phi}}\right)\exp\left(\frac{6.53*10^{7}\phi^{\frac{3}{2}}}{\beta V}\right) \qquad (2\text{-}12)$$

For example, electric field at the surface of a spherical emitter of radius r concentric with a spherical anode of radius r = d can be represented analytically by

$$E = \frac{V}{r}\left(\frac{r+d}{d}\right) \tag{2-13}$$

Though a realistic electric field in the emitter tip is more complicated than above equation, we can multiple Eq. (2-13) by a geometric correction factor β' to approximate the real condition.

$$E_{tip} = \text{function of } (r, d) = \beta' \frac{V}{r}\left(\frac{r+d}{d}\right) \tag{2-14}$$

Where r is the tip radius of emitter tip, d is the emitter-anode distance and β' is a geometric correction factor

For very sharp conical tip emitter, where d >> r, E_{tip} approaches to $\beta'(\frac{V}{r})$. And for r >> d, E_{tip} approaches to $\beta'(\frac{V}{r})$ which is the solution of the parallel-plate capacitor and for a diode operation in a small anode-to-cathode spacing.

As the gated FEA with vary sharp tip radius, Eq. (2-14) can be approximated as

$$E_{tip} = \beta'\left(\frac{V}{r}\right) \tag{2-15}$$

Combining E=βV and Eq. (2-15), subsequently

$$E = \beta V = \beta'\left(\frac{V}{r}\right) \text{ and } \beta' = \beta r \tag{2-16}$$

The tip radius r is usually in the range from a few nm to 50nm, corresponding to the parameter β' ranging from 10^{-1} to 10^{-2}.

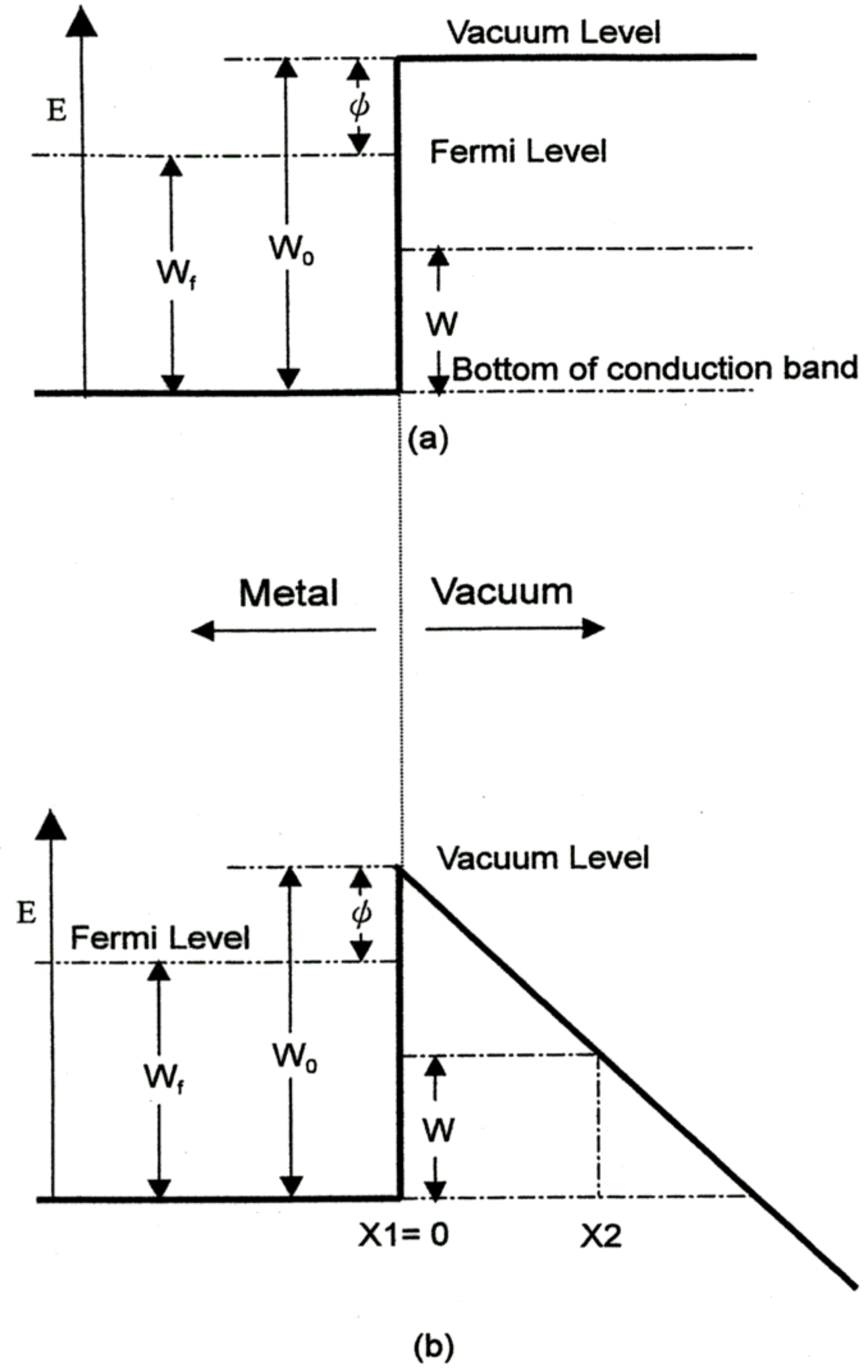


Fig. 2-16 Energy diagrams of vacuum-metal boundary [Tarntair-01-12]

(a) without external electric field

(b) with an external electric field

2-5 Overview of field emission device

The phenomenon of field emission is the emission of electrons from a cold cathode under an intense electric field by quantum mechanical tunneling. The cold cathode emitters has two advantages in contrast to the thermoinic emitters , one is avoid high temperature operation; another it can offer long life time for operation. The devices that operate as described above as called vacuum state device or vacuum microelectronics (VME). Vacuum state device compare with solid state device has many advantages. The remarkable advantages such as fast drift velocity, associated transit time, radiation hardness and temperature insensitivity. For example, the saturation drift velocity is limited to less than $3*10^{7}$ cm/sec in all semiconductors, whereas the saturation electron velocity in vacuum is limited theoretically to $3*10^{10}$ cm/sec and practically to about $6\text{-}9*10^{8}$ cm/sec. The comparison between vacuum microelectronics and solid-state electronics are summarized in Table 2-4.

Nowadays, many VME devices were achieved develop in many process such as flat panel displays, microwave power tubes, electron/ion sources, e-beam lithography, e-beam memories, and excitation devices. The most remarkable field emission potential of CNTs and CNCs is in the field emission display (FED). The FED utilize electrons are emitted from an array of micro-cathodes and are accelerated to phosphor screen anode consisting of many pixels as shown in Fig.2-17. FED has many advantages including high brightness, wide viewing angle, and wide operation temperature range and response time of video rate. Table 2-5 list the comparison of various kinds of flat panel display devices such as liquid crystal display (LCD), electroluminescent display (ELD), vacuum fluorescent display (VFD), plasma display panel(PDP), organic light emitting display (OLED). In the past, all kinds of the cone-shape field emitter arrays have developed. One of these, the Spindt cathode emitter device was developed by C. Spindt and reported at IEEE Conference in 1966. The configuration of Spindt cathode emitter array is showed in Fig.2-18. Typically, the cone height and thickness of dielectric layer about 1 μm, the tip radius about 200 Å, the aperture diameter about 0.5 μm, and the tip to tip spacing from 1 to 5 μm. The array functions as a field emission source of electrons when a positive potential is applied to the gate relative to the tips. No external heat is needed. These Spindt emitters have compatible process with IC devices and due to the size of emitter are in micro scale, so it is easy fabricate in large size and uniformity field emitters. The general requirements of the cold cathode emission are low voltage operation, high current density, small size, compatibility with micro fabrication process and ultra-vacuum processing.

Table 2-4 Characteristics of solid state and VME device [Zhu-2001-7].

Properties	Solid-State Devices	VME Devices
Current density	10^4-10^5 A/cm^2	~$2*10^3$ A/cm^2
Voltage	> 0.1V	>10 V
Structure	Solid /solid interface	Solid/vacuum
Electron transport		
Medium	Solid	Vacuum
Ballistic	< 0.1µm, Low temp.	100% Ballistic
Coherence	Length < 0.1µm	Length >> 0.1µm
Lens effect	Difficult	Easy
Noise		
Thermal noise	Random motion of carriers	Comparable
Flicker noise	Surface/interface effects	Worse
Shot noise	Fluctuation in generation/ Recombination rates of carriers	Comparable
Electron energy	< 0.3 eV	Several to 1000 eV
Cuttoff frequency	< 20 GHz (Si) < 100 GHz (GaAs)	< 100-500 GHz
Power	Small	Large
Radiation hardness	Poor	excellent
Temperature sensitivity	-30 ± 50 ℃	< 500℃
Fabrication /materials	Well established(Si) Establish (GaAs)	Not well establish

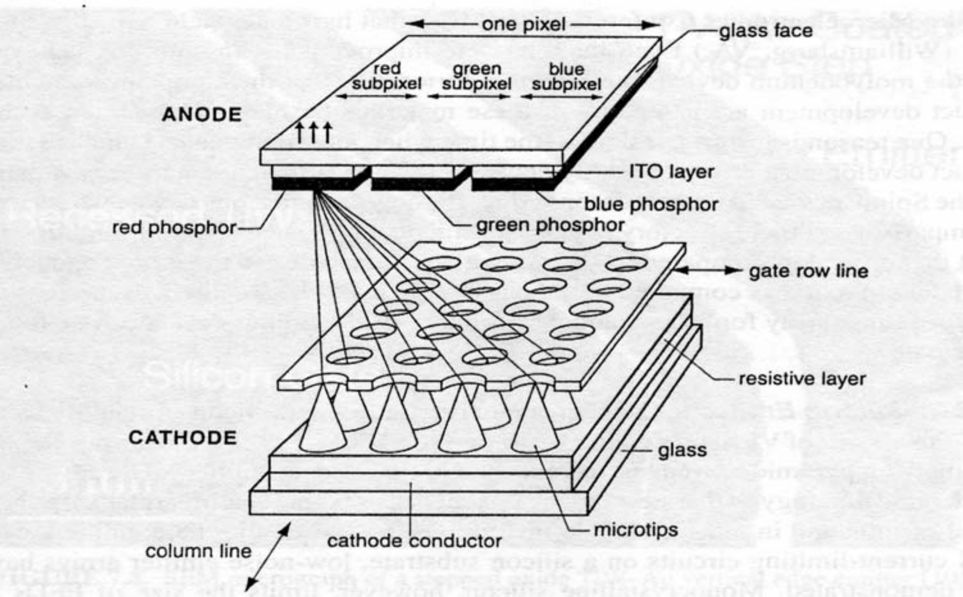


Fig.2-17 Perspective view of an FED in which one emitter array is shared by a red, green, and blue subpixel. [Zhu-2001-293]

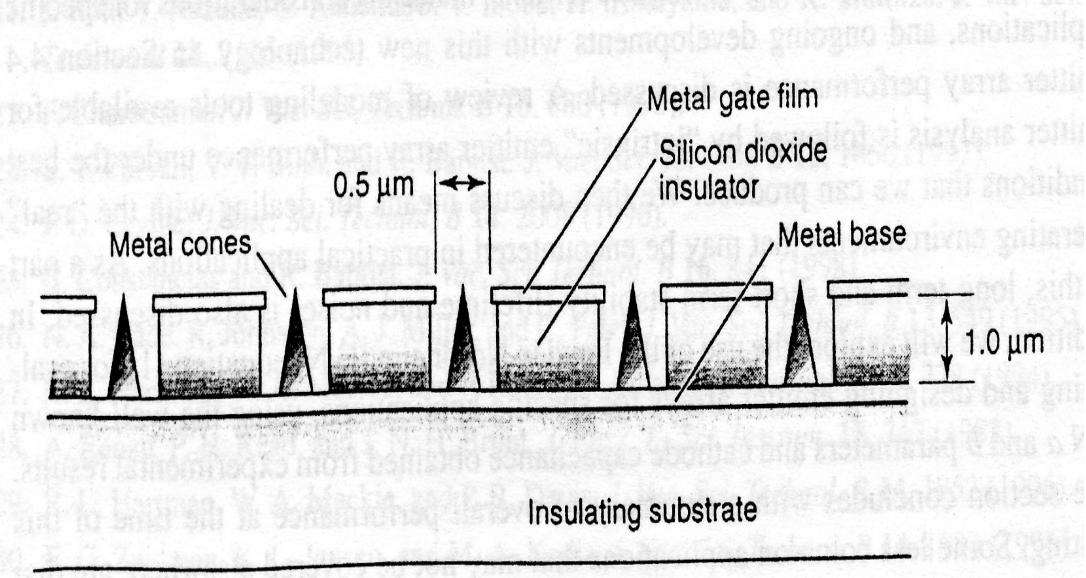
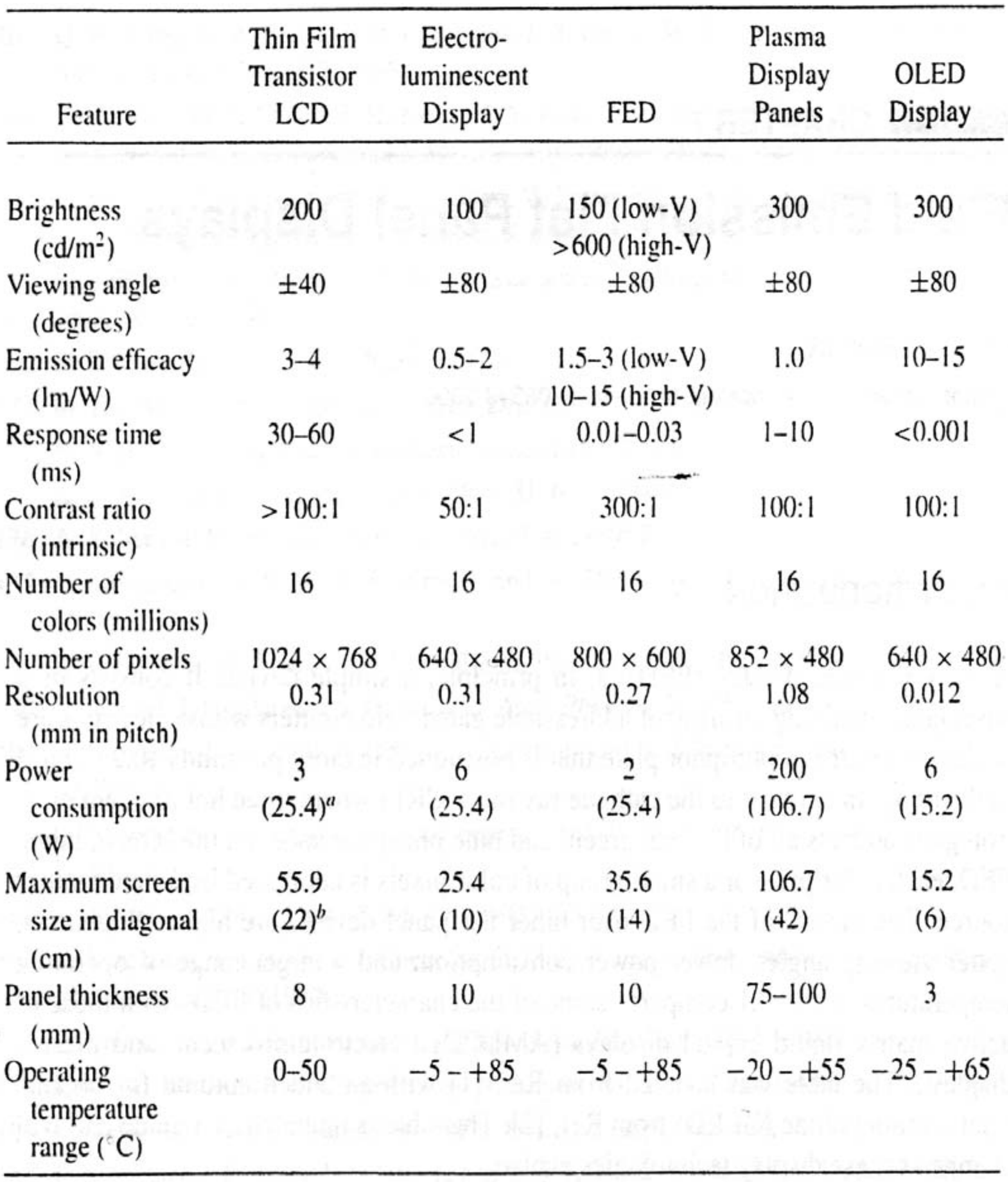


Fig.2-18 The Spindt microfabricated field emitter arrays [Zhu-2001-106]

Table 2-5 Comparison of FED with other Flat Panel Displays [Zhu-2001-290]



Feature	Thin Film Transistor LCD	Electro-luminescent Display	FED	Plasma Display Panels	OLED Display
Brightness (cd/m^2)	200	100	150 (low-V) >600 (high-V)	300	300
Viewing angle (degrees)	±40	±80	±80	±80	±80
Emission efficacy (lm/W)	3–4	0.5–2	1.5–3 (low-V) 10–15 (high-V)	1.0	10–15
Response time (ms)	30–60	<1	0.01–0.03	1–10	<0.001
Contrast ratio (intrinsic)	>100:1	50:1	300:1	100:1	100:1
Number of colors (millions)	16	16	16	16	16
Number of pixels	1024 × 768	640 × 480	800 × 600	852 × 480	640 × 480
Resolution (mm in pitch)	0.31	0.31	0.27	1.08	0.012
Power consumption (W)	3 (25.4)[a]	6 (25.4)	2 (25.4)	200 (106.7)	6 (15.2)
Maximum screen size in diagonal (cm)	55.9 (22)[b]	25.4 (10)	35.6 (14)	106.7 (42)	15.2 (6)
Panel thickness (mm)	8	10	10	75–100	3
Operating temperature range (°C)	0–50	−5 – +85	−5 – +85	−20 – +55	−25 – +65