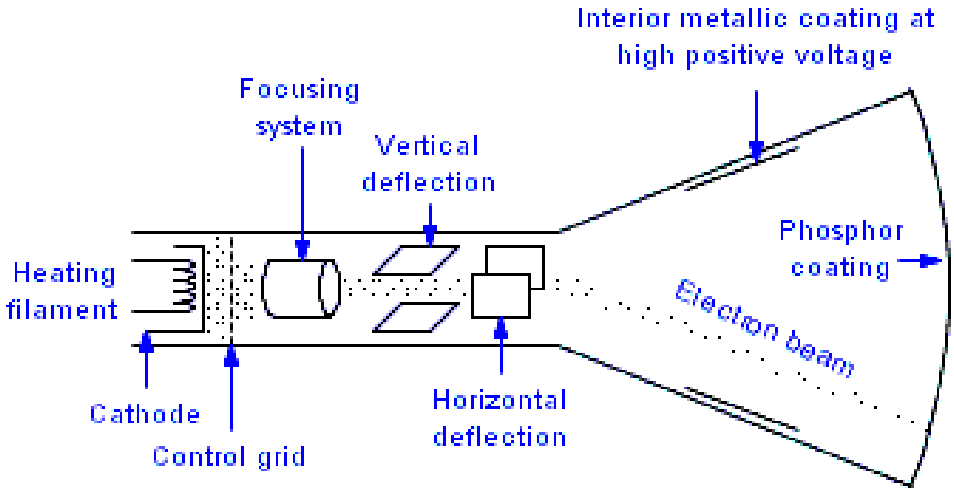
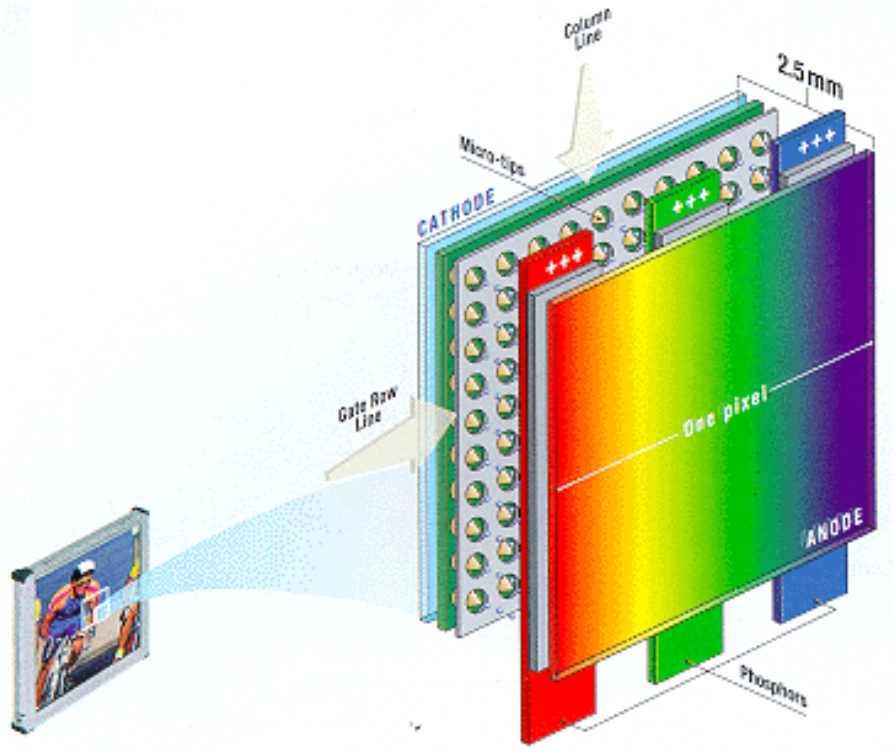


(a)



(b)

Fig. 1-1 The schematic diagram of (a) conventional cathode ray tube (CRT), (b) field emission display (FED)

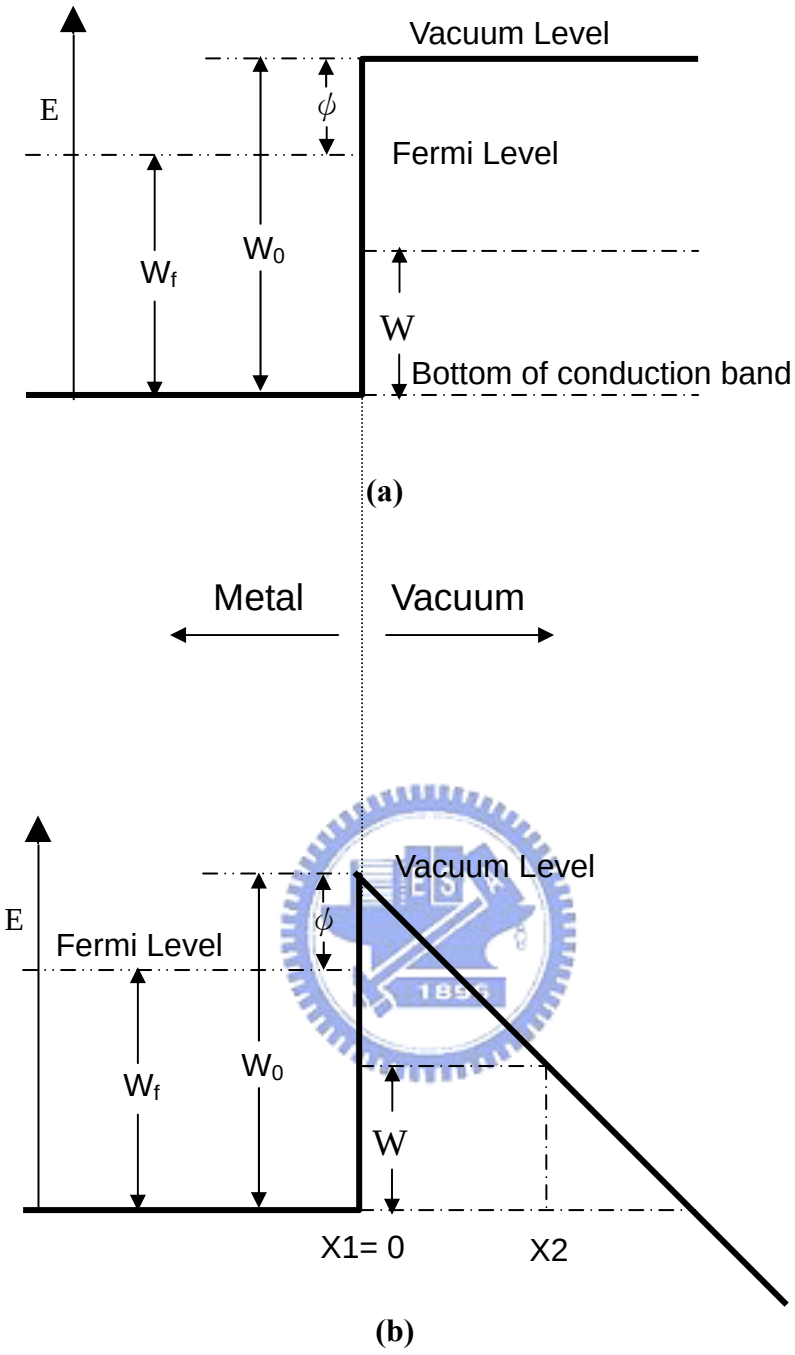
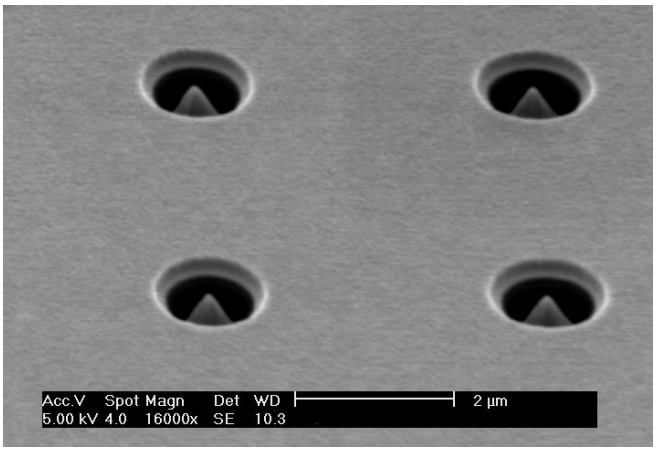
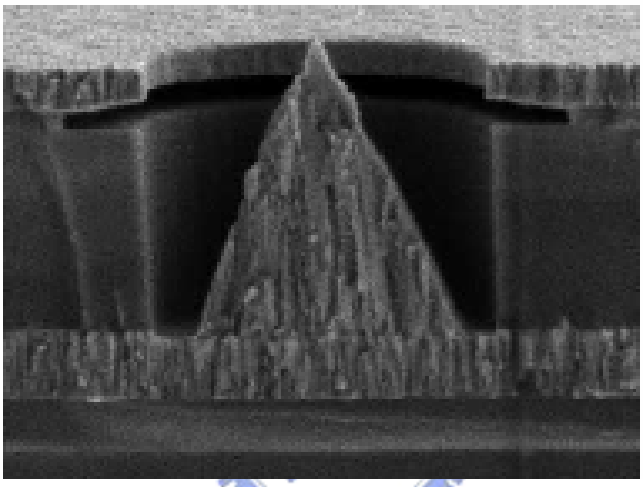


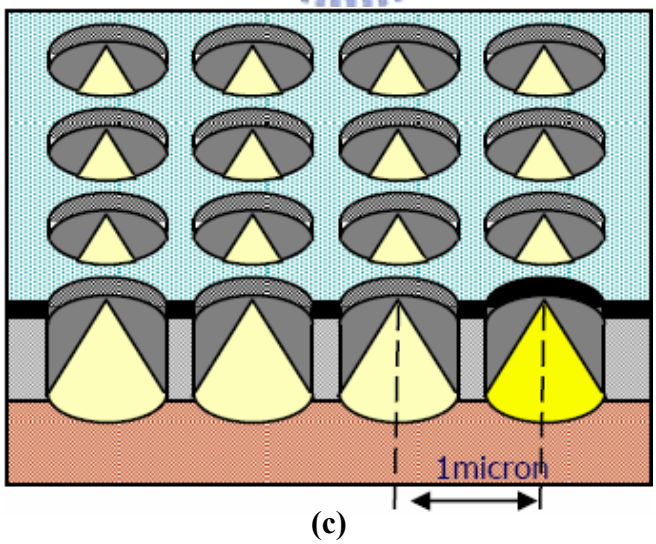
Fig. 1-2 Energy diagrams of vacuum-metal boundary: (a)without external electric field; and (b) with an external electric field



(a)



(b)



(c)

Fig. 1-3 The SEM micrograph of (a) Spindt type triodes array, (b) Spindt type field emission triode, and the schematic image of (c) Spindt type triode array

Motorola 5.6" color FED

(a)

Pixtech 15" color FED

(b)

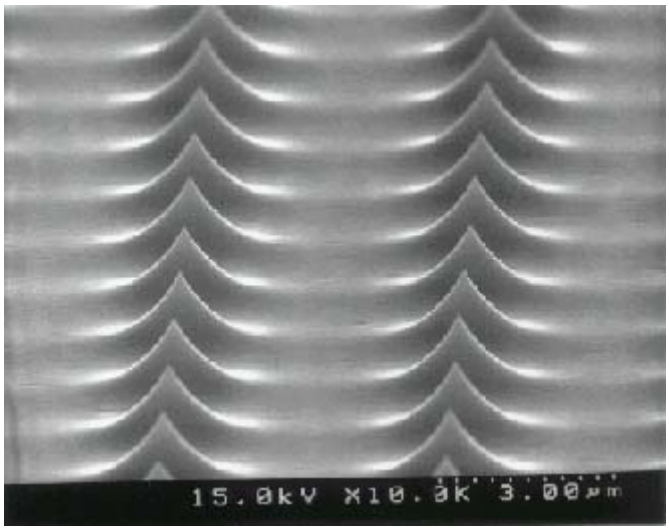
Futaba 7" color FED

(c)

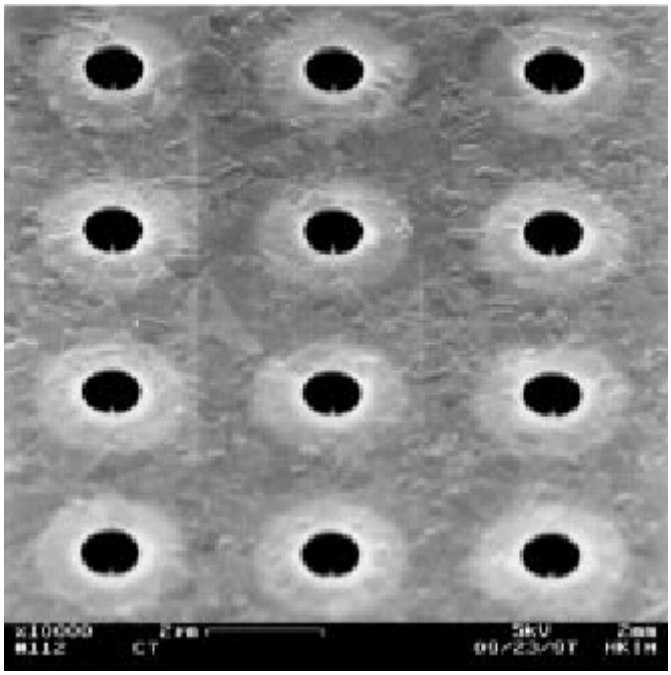
Candescnet 13.1" ThinCRT

(d)

Fig. 1-4 The FED products based on Spindt type field emitters, (a) motorola 5.6” color FED, (b) Pixtech 15” color FED, (c) Futaba 7” color FED and (d) Sony/Candescent 13.1” color FED

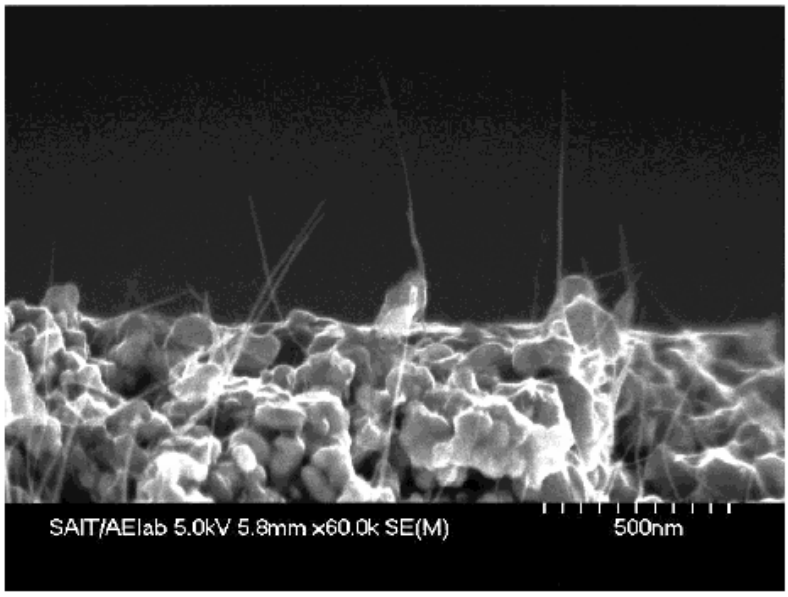


(a)

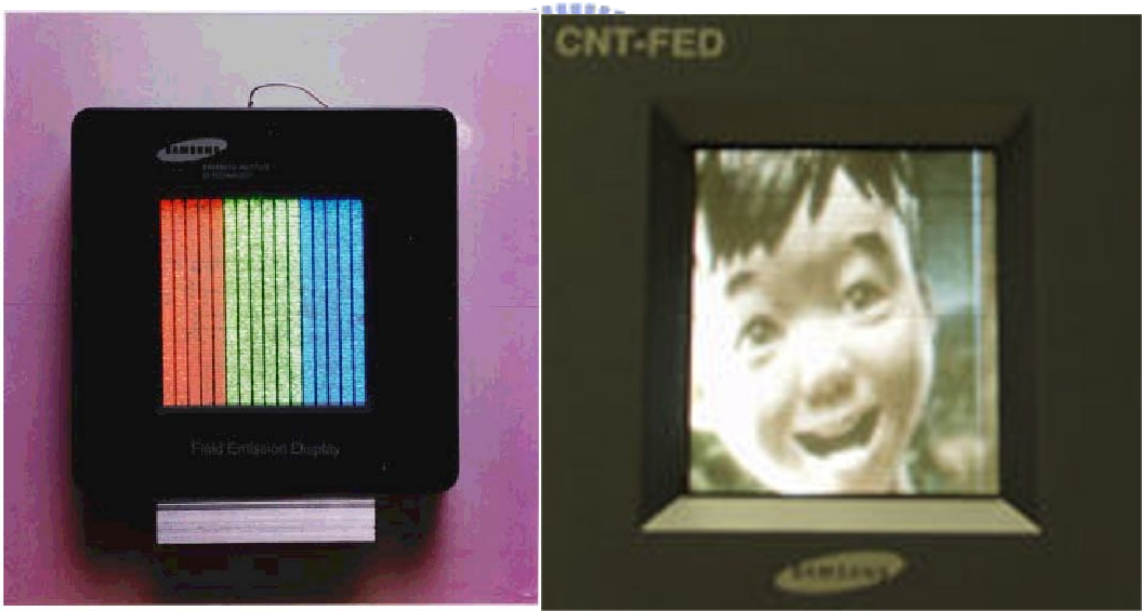


(b)

Fig. 1-5 (a) Si tip formed by isotropic etching and (b) Si tip field emission triodes array formed by CMP

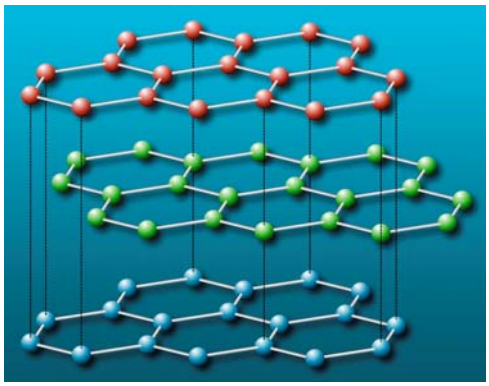


(a)

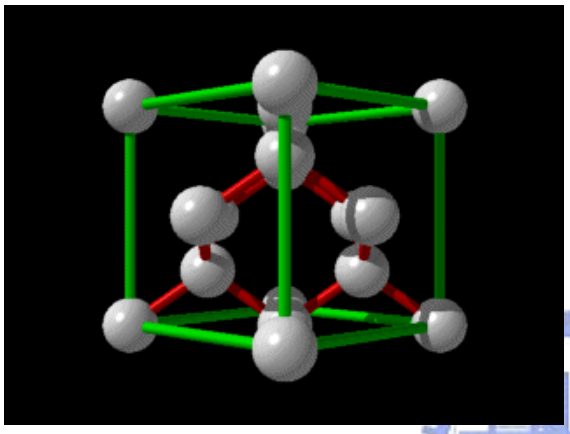


(b) **(c)**

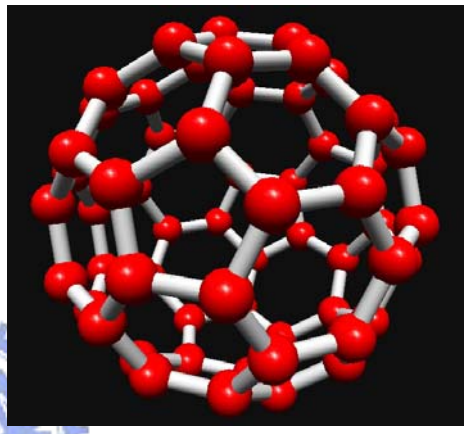
Fig. 1-6 (a) SEM image of CNT cathode from Samsung's FED, (b) a 4.5-inch FED from Samsung, the emitting image of fully sealed SWNT-FED at color mode with red, green, and blue phosphor columns, and (c) a prototype of 5" CNT flat panel display by Samsung



(a)

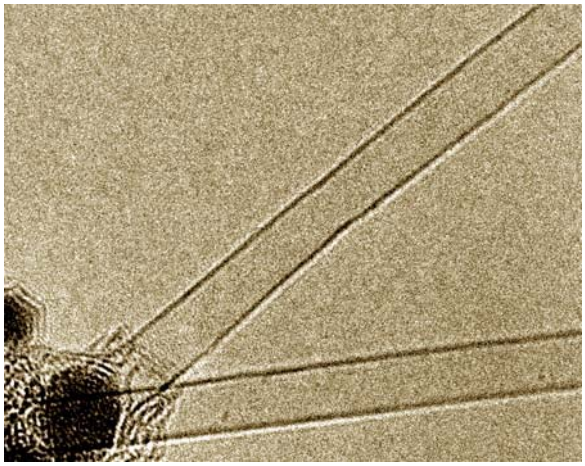


(b)

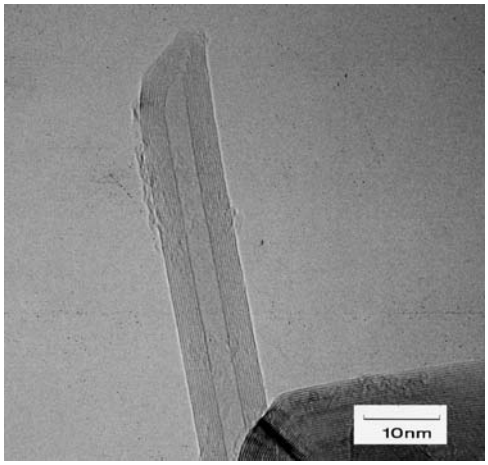


(c)

Fig. 1-7 Structures of carbon (a) graphite, (b) diamond, (c) fullerene



(a)



(b)

Fig. 1-8 TEM images of (a) SWNT, and (b) MWNT

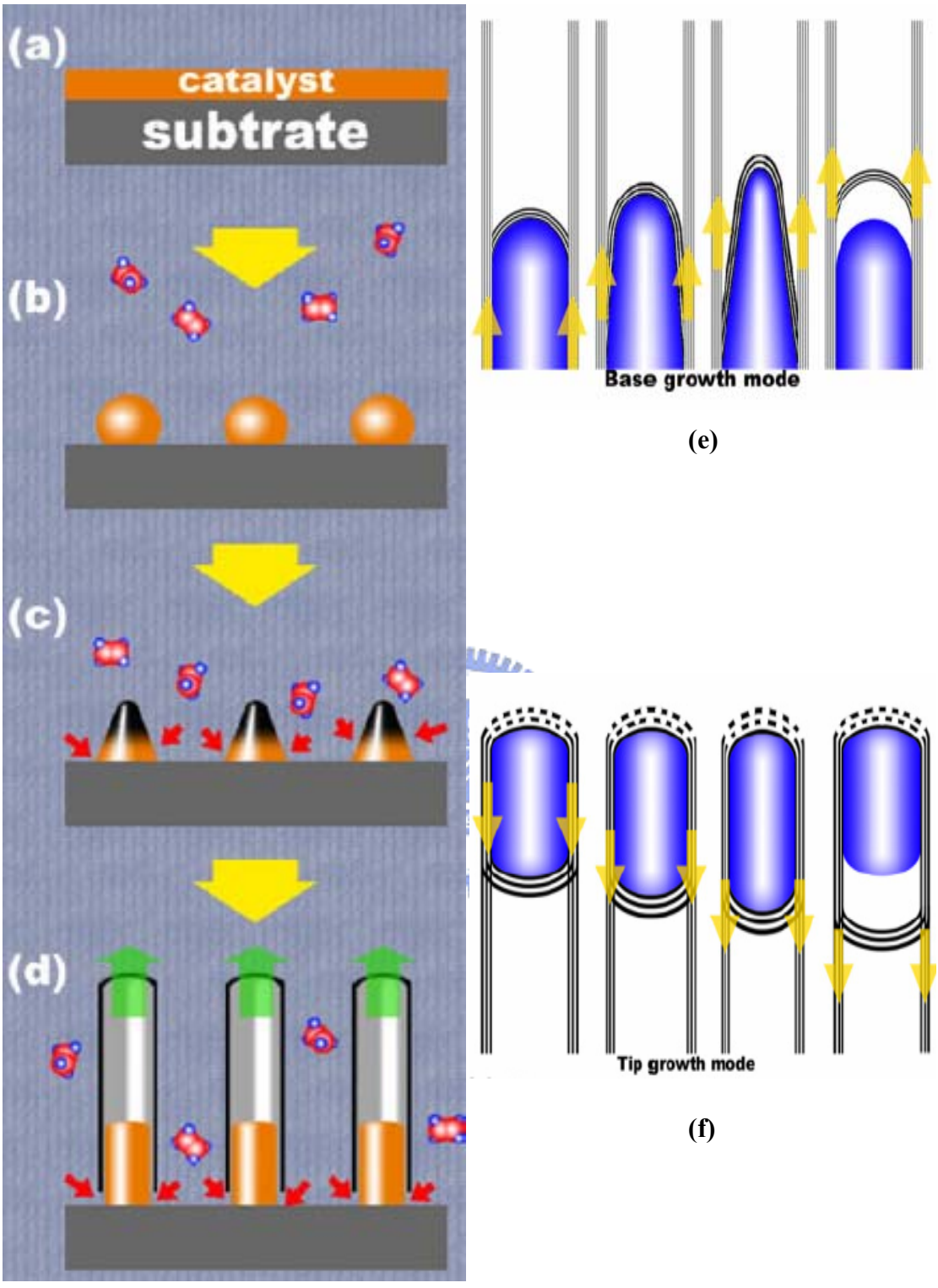


Fig. 1-9 Growth mechanism of CNTs growth (a) catalyst film pre-treatment, (b) carbon source addition, (c) adsorption of carbon atom at the surface of nanoparticles, (d) CNT growth, (e) base growth model, (f) tip growth model

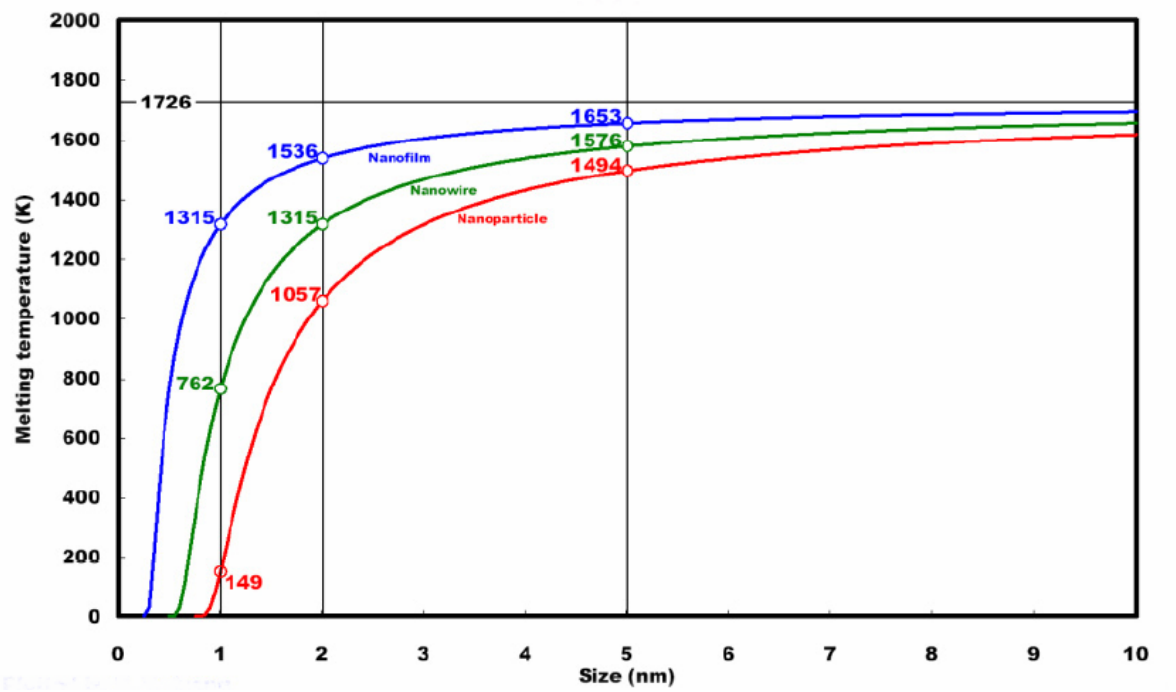


Fig. 2-1 Lindemann criterion

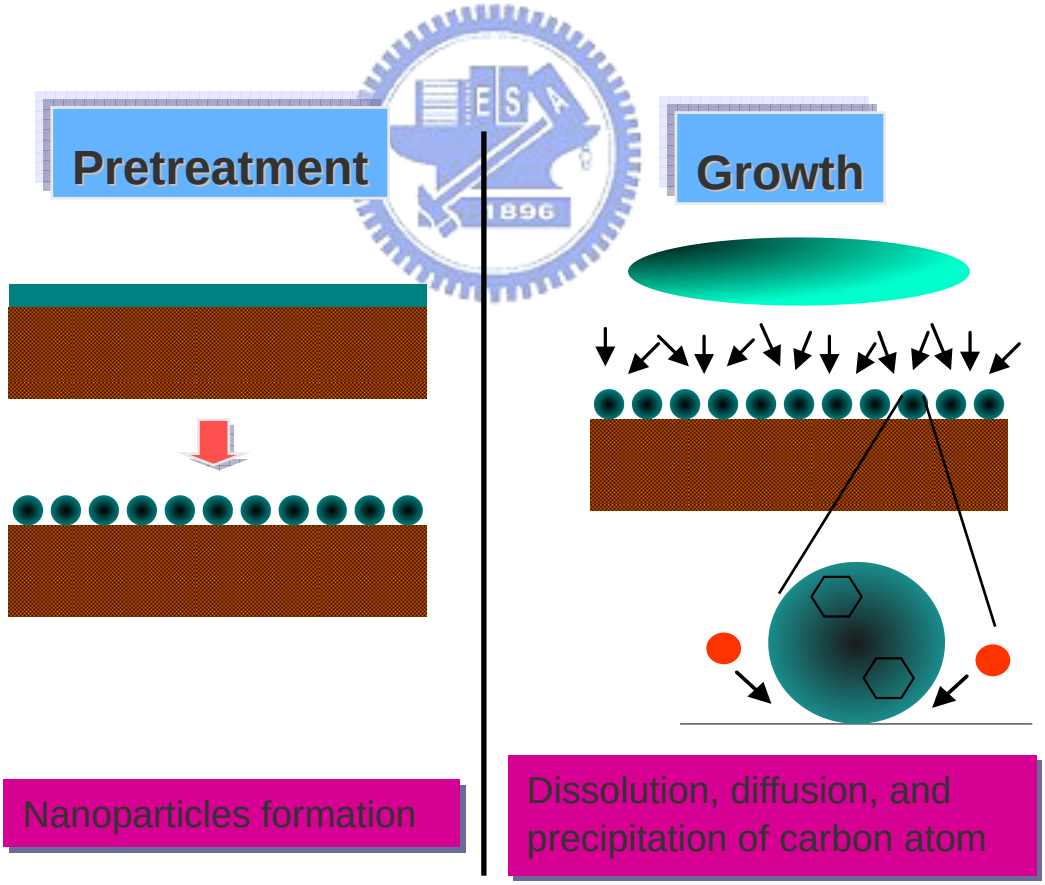


Fig. 2-2 The role of catalyst for CNTs growth

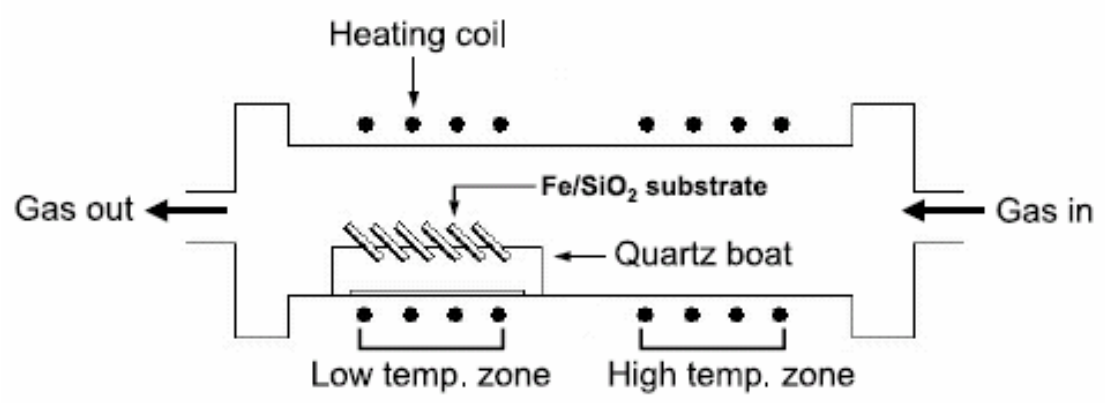


Fig. 2-3 Schematic diagram of the CVD reactor with two different temperature zones

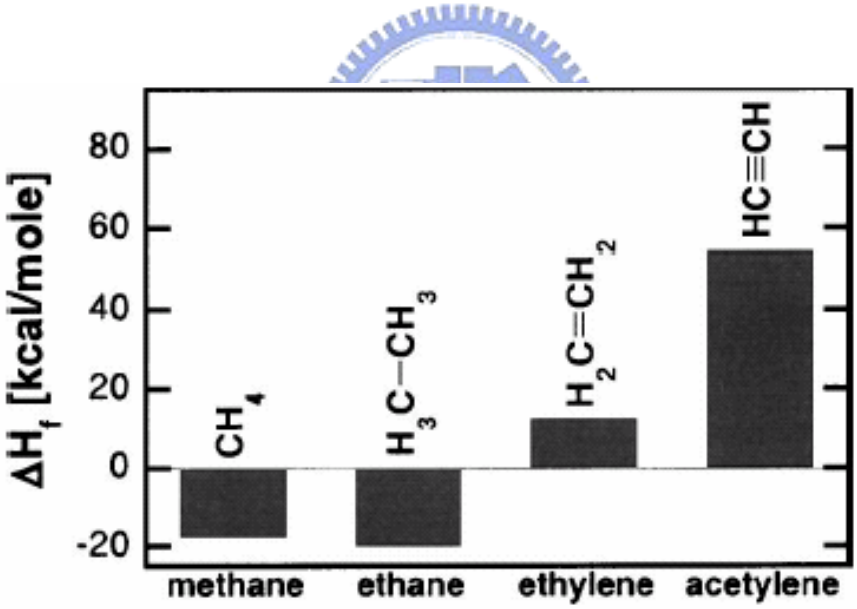


Fig. 2-4 Heat of formation of various hydrocarbon gases

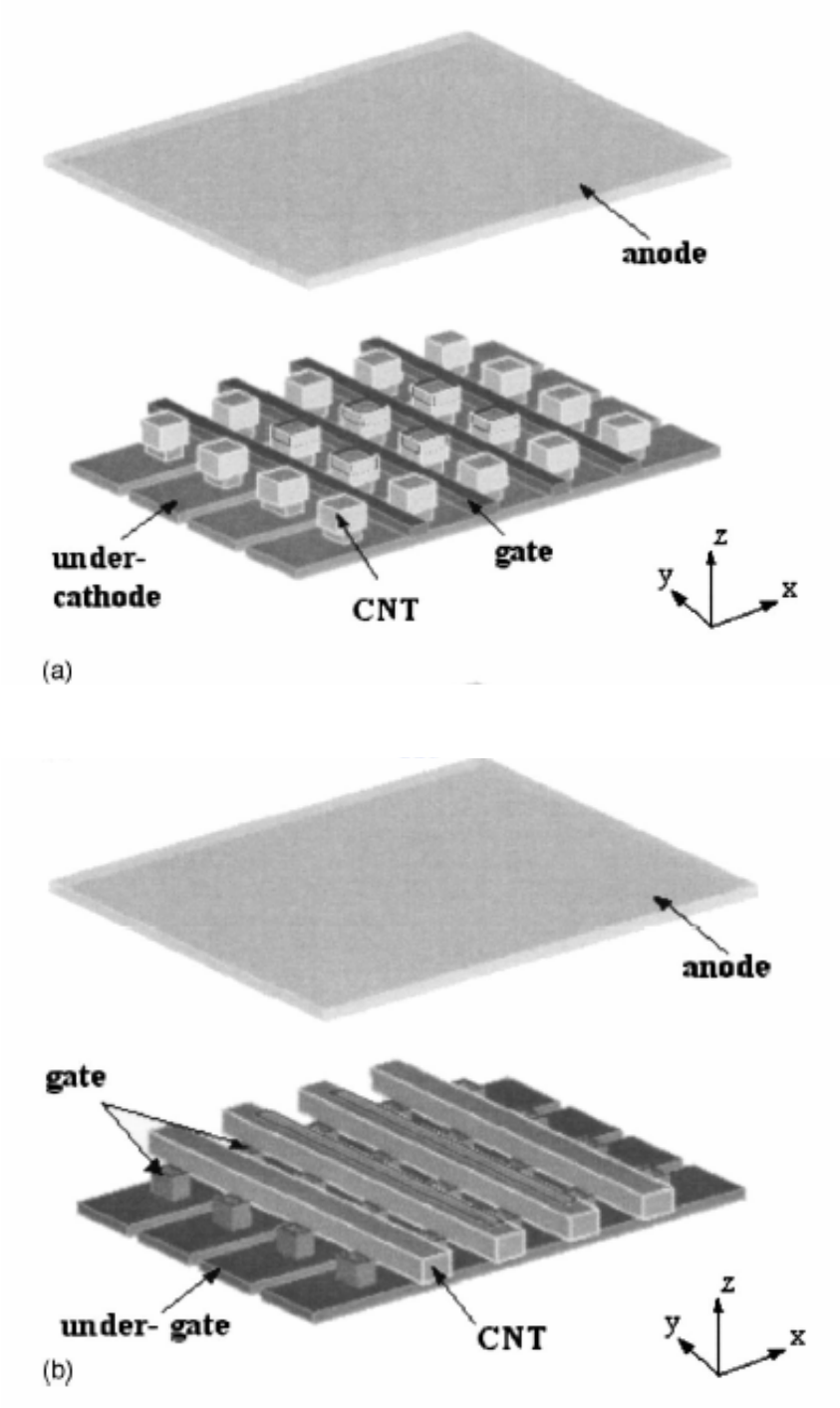


Fig. 2-5 Schematic of (a) planar-gate and (b) under-gate CNT-FED structure

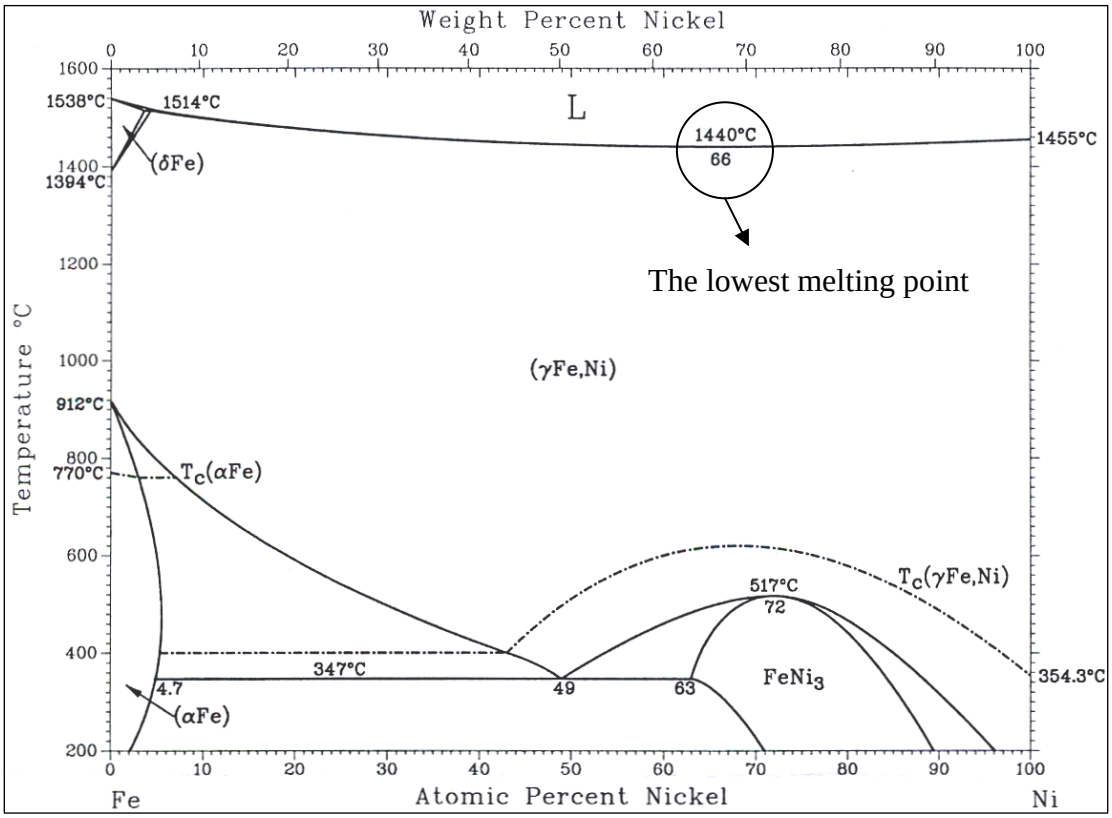
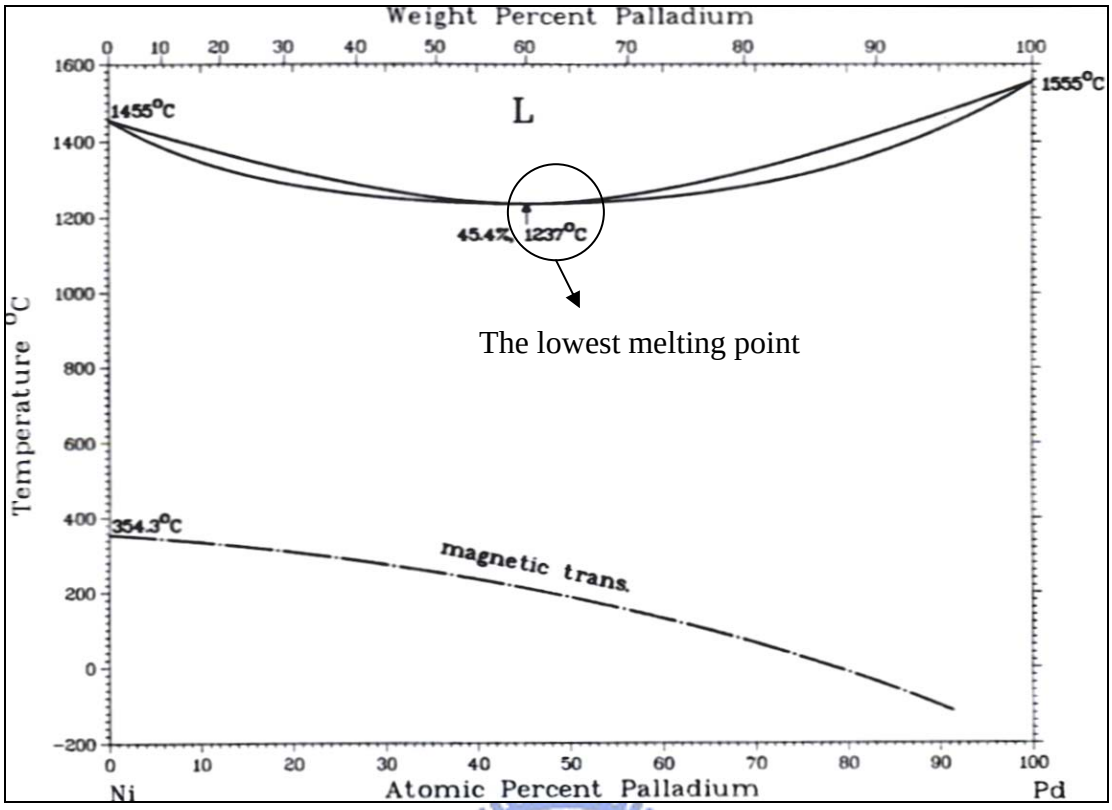
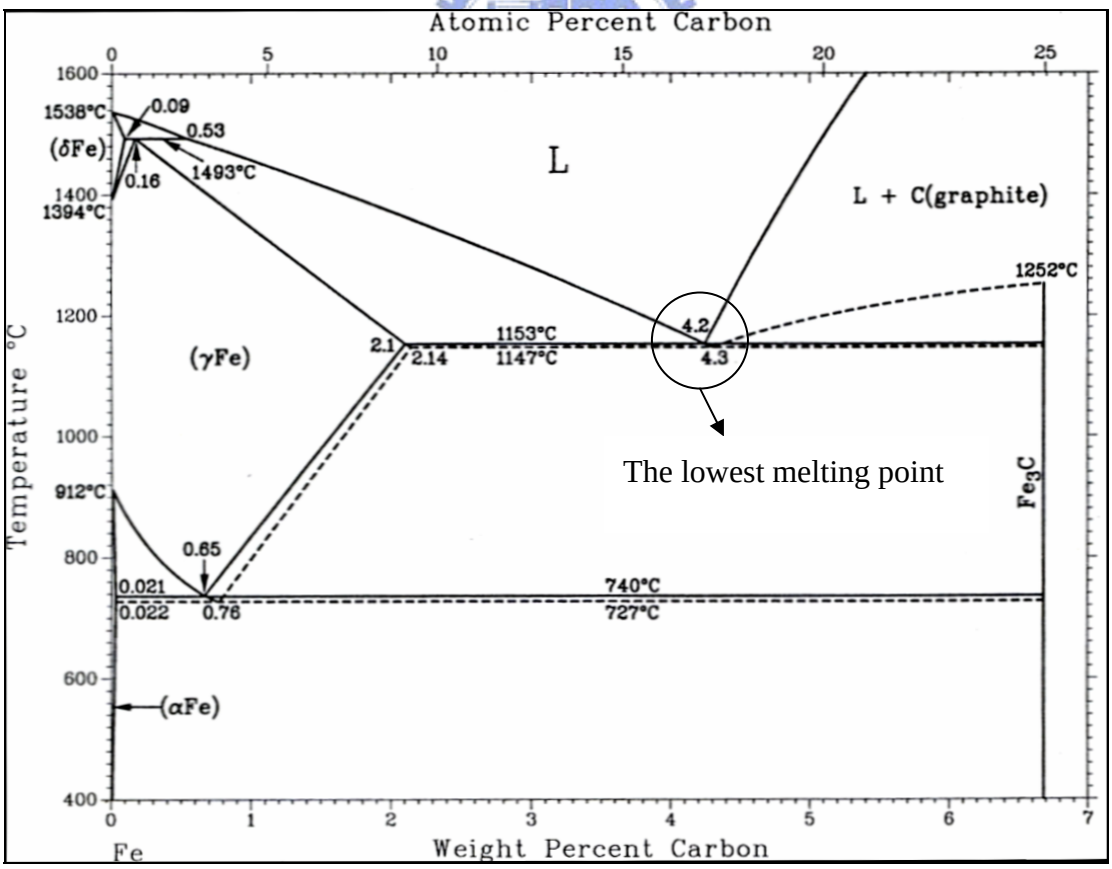


Fig. 2-6 FeNi alloy phase diagram

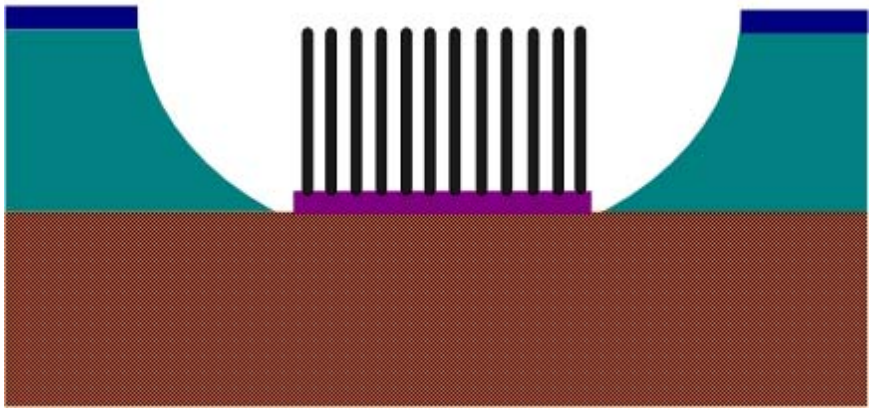


(a)

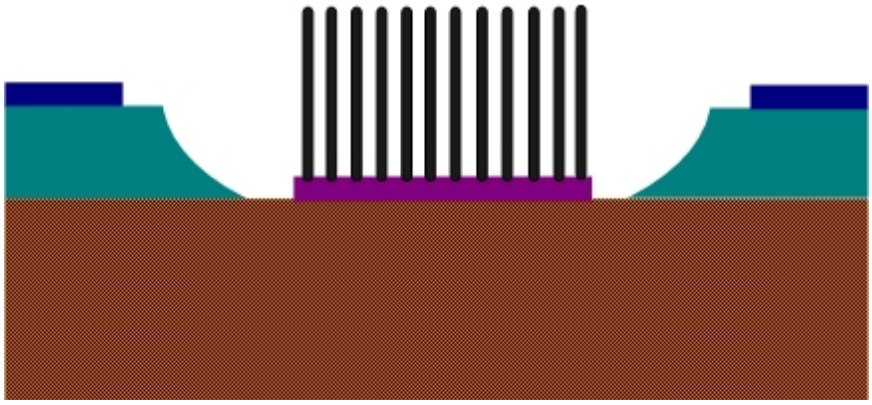


(b)

Fig. 2-7 Phase diagrams of (a) NiPd and (b) FeC alloy



(a)



(b)

Fig. 2-8 Schematic of (a) planar-gate (b) under-gate that we hypothesized

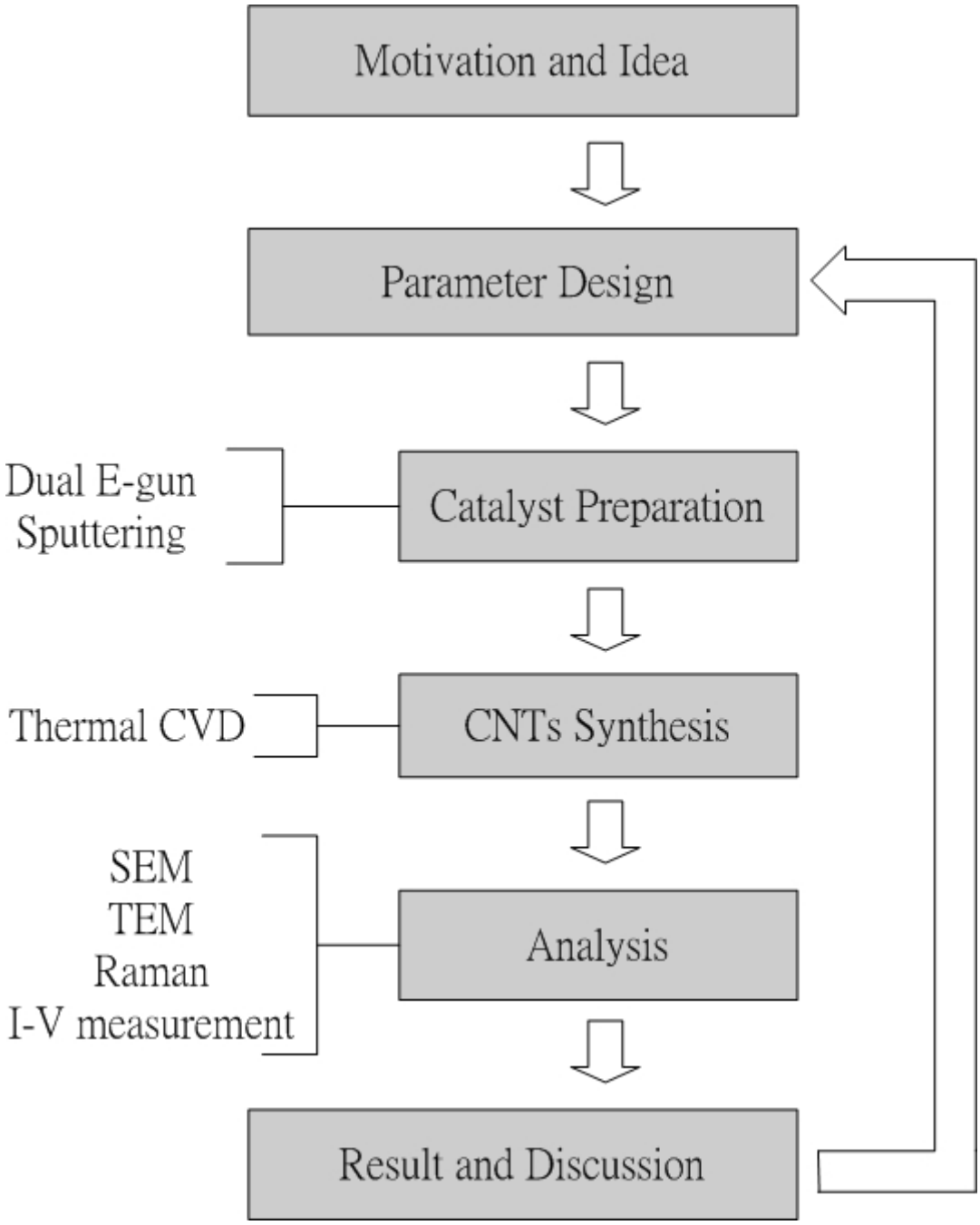
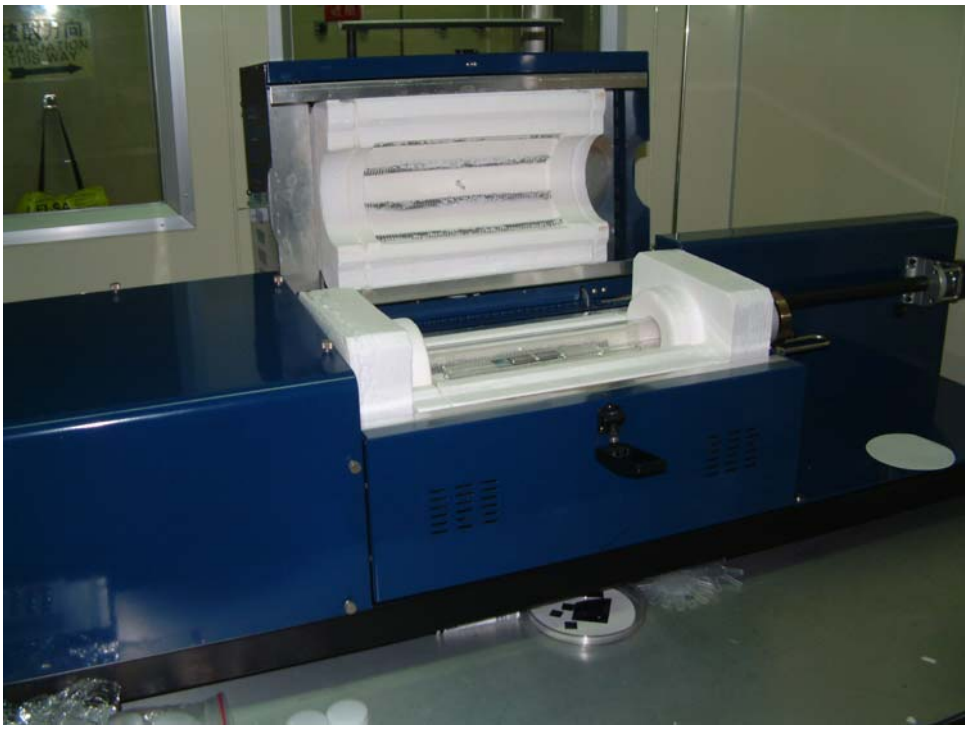
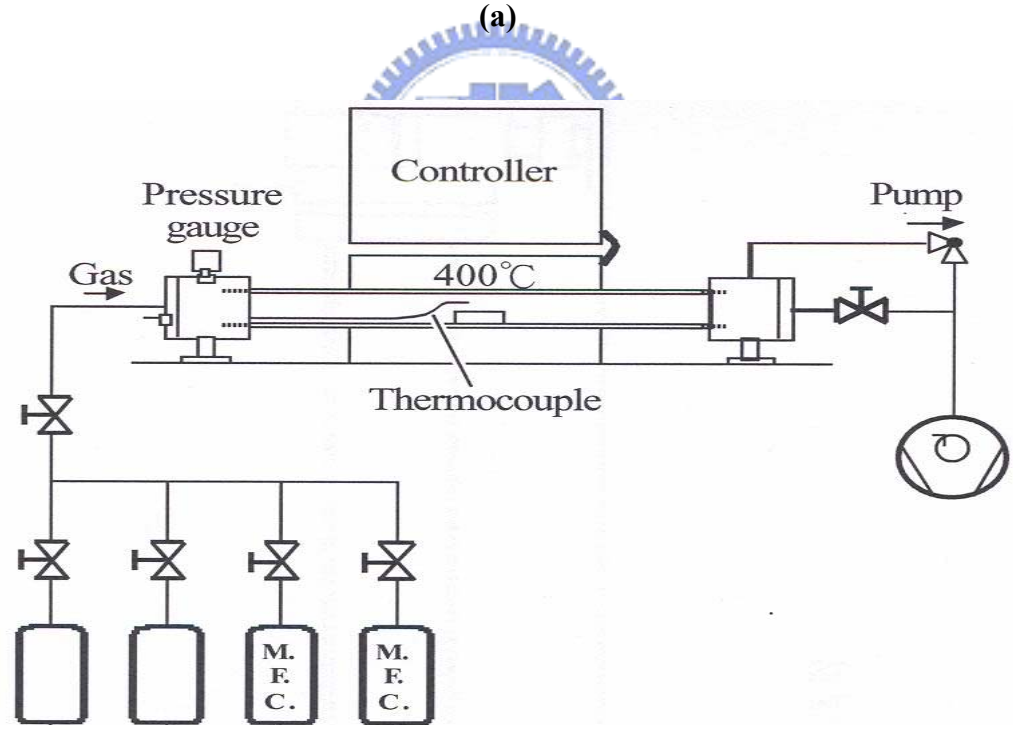


Fig. 3-1 Schematic experimental procedures



(a)



(b)

Fig. 3-2 A (a) photo and (b) schematic picture of thermal CVD

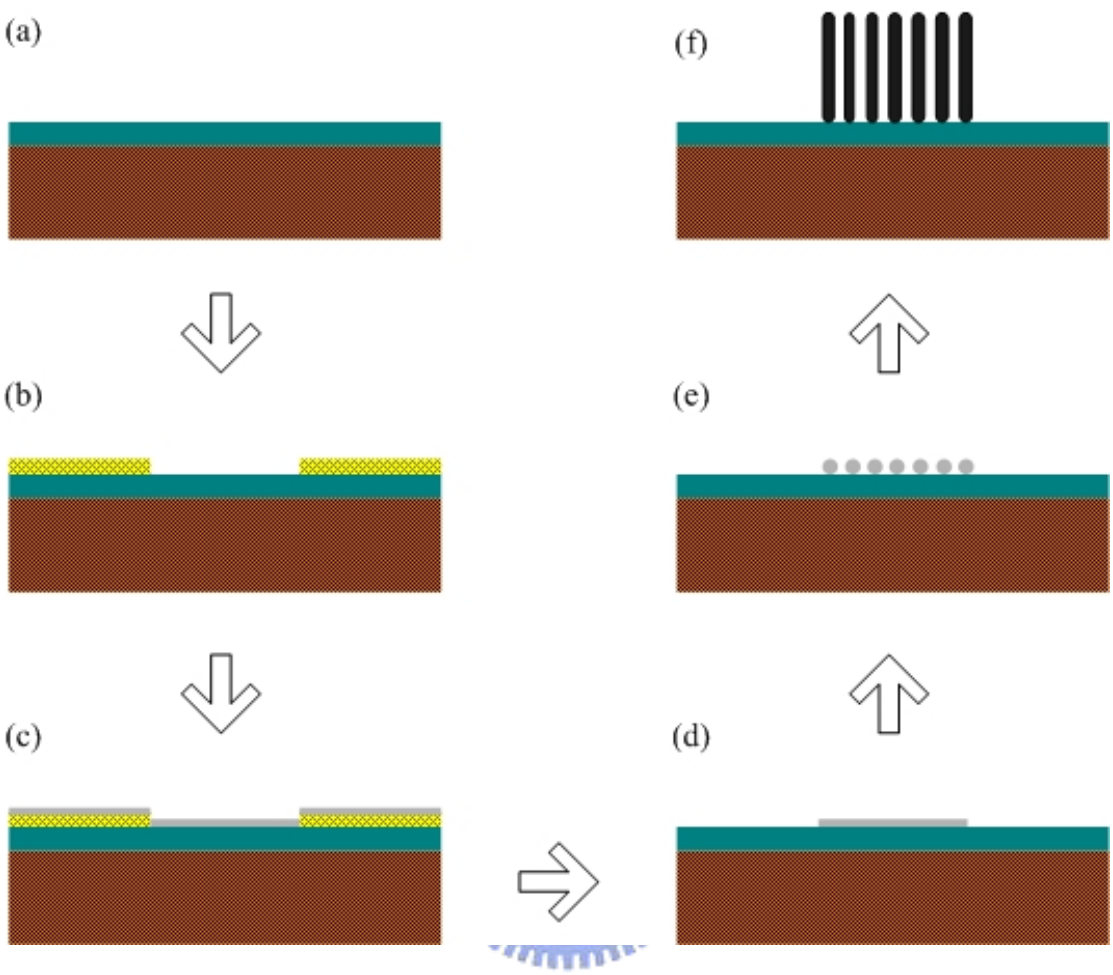


Fig. 3-3 Experimental processes of CNTs grown in diode structure (a) deposit Ti buffer layer on silicon substrate (b) pattern by UV light (c) deposit catalyst metal on Ti buffer layer (d) lift-off photo-resistance (e) pre-treat to form nano-particles (f) grow carbon nanotubes

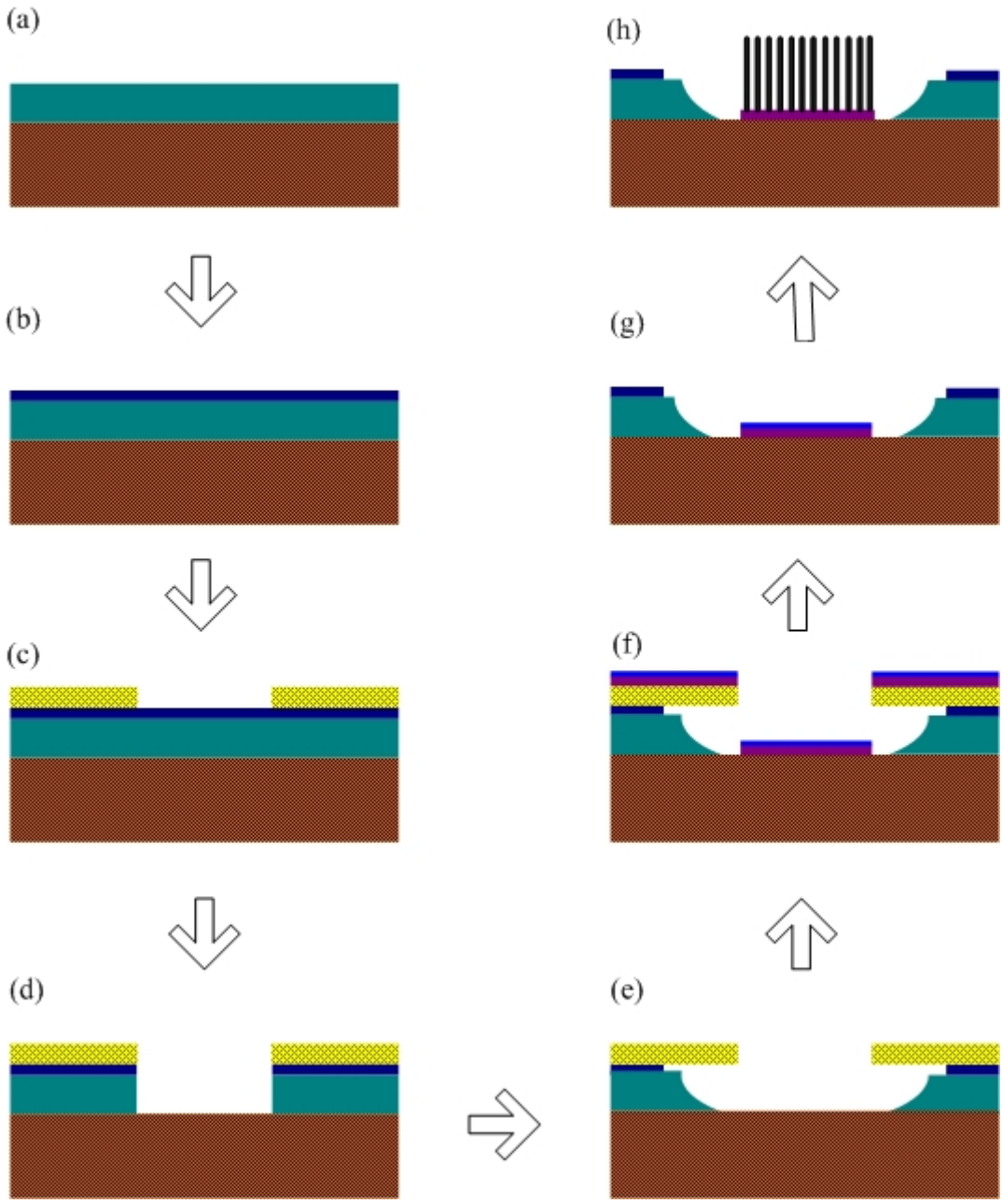


Fig. 3-4 Fabricated procedures of triode structure (a) wet oxidation (b) deposit poly-Si by LPCVD and dope with $POCl_3$ (c) pattern by UV light (d) etching poly-Si and oxide by RIE (e) wet lateral etching (f) deposit Ti buffer layer and catalyst layer (g) lift-off photo-resistance (h) grow carbon nanotubes

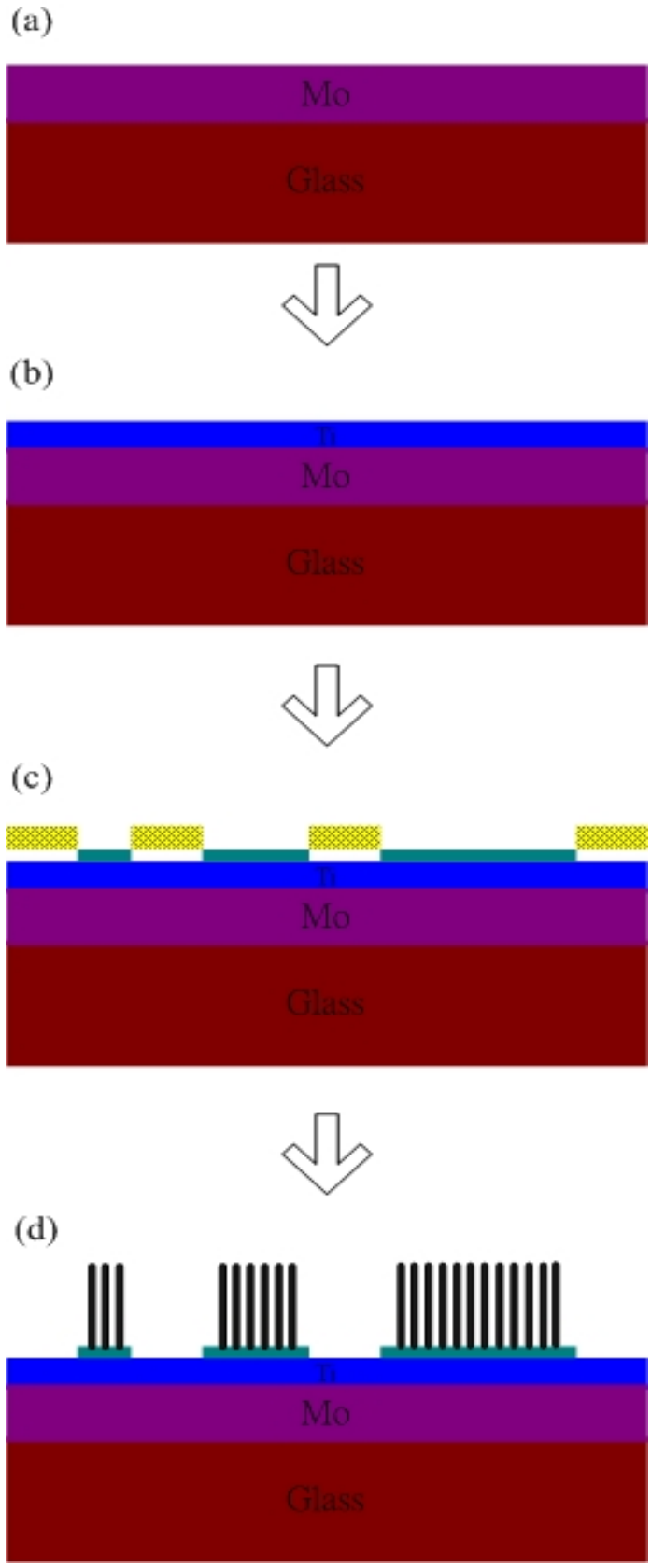
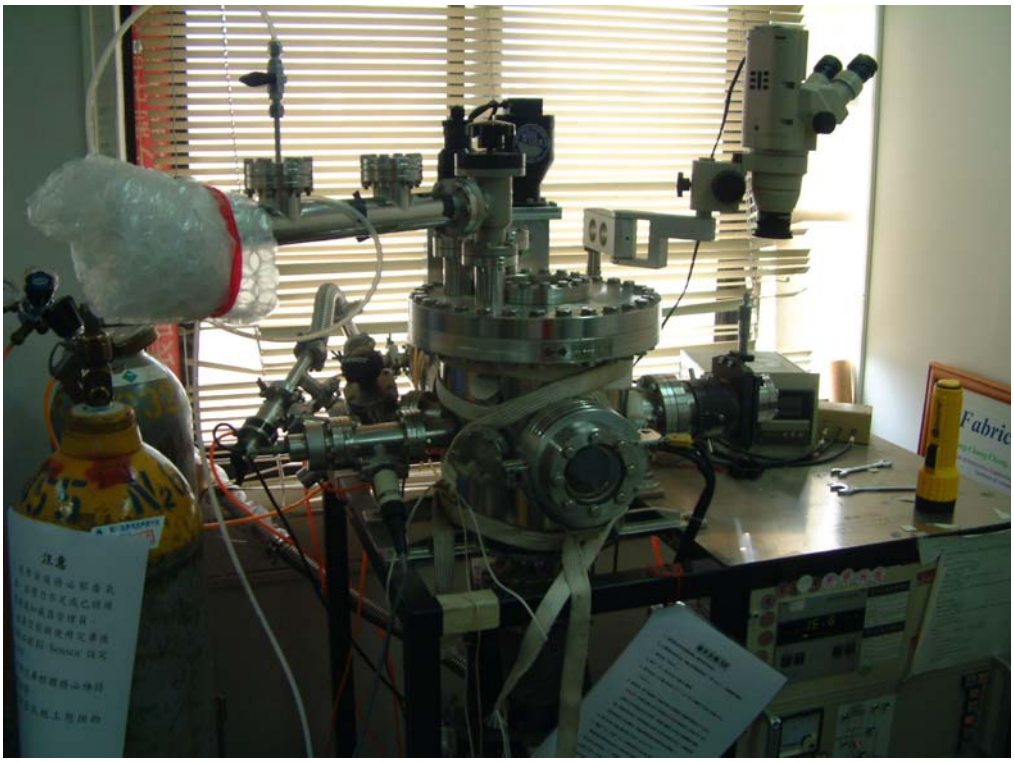


Fig. 3-5 Diode structure of CNT-FED on glass substrate



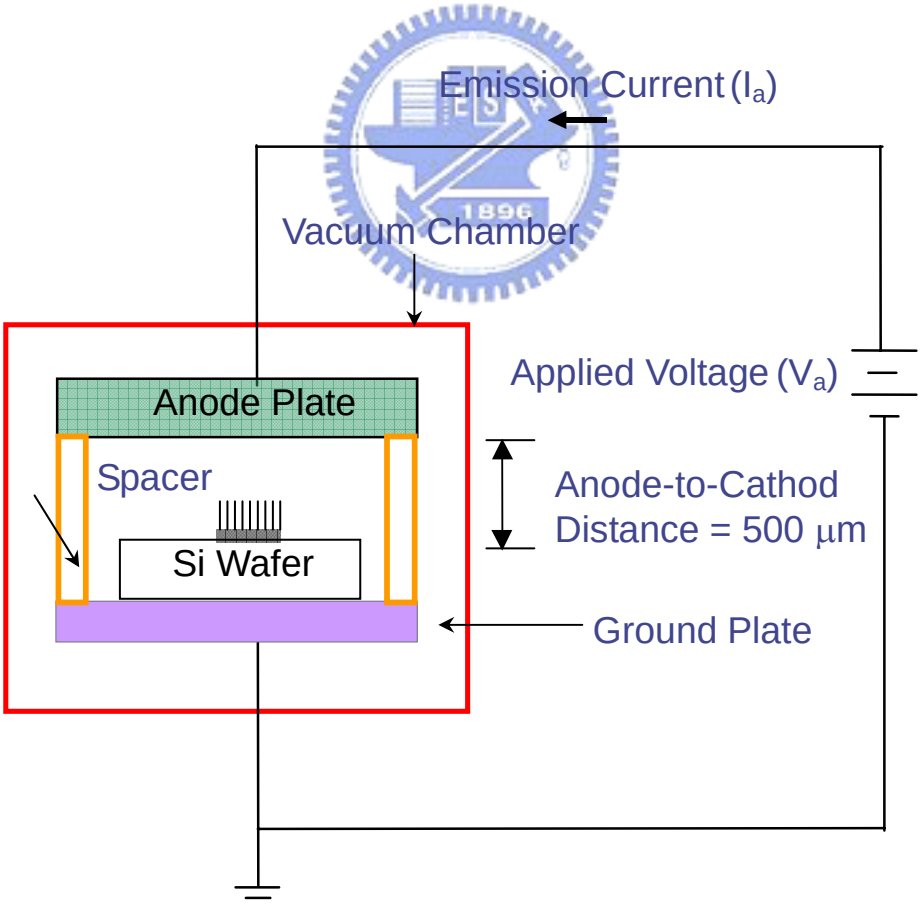


Fig. 3-6 High vacuum measurement system

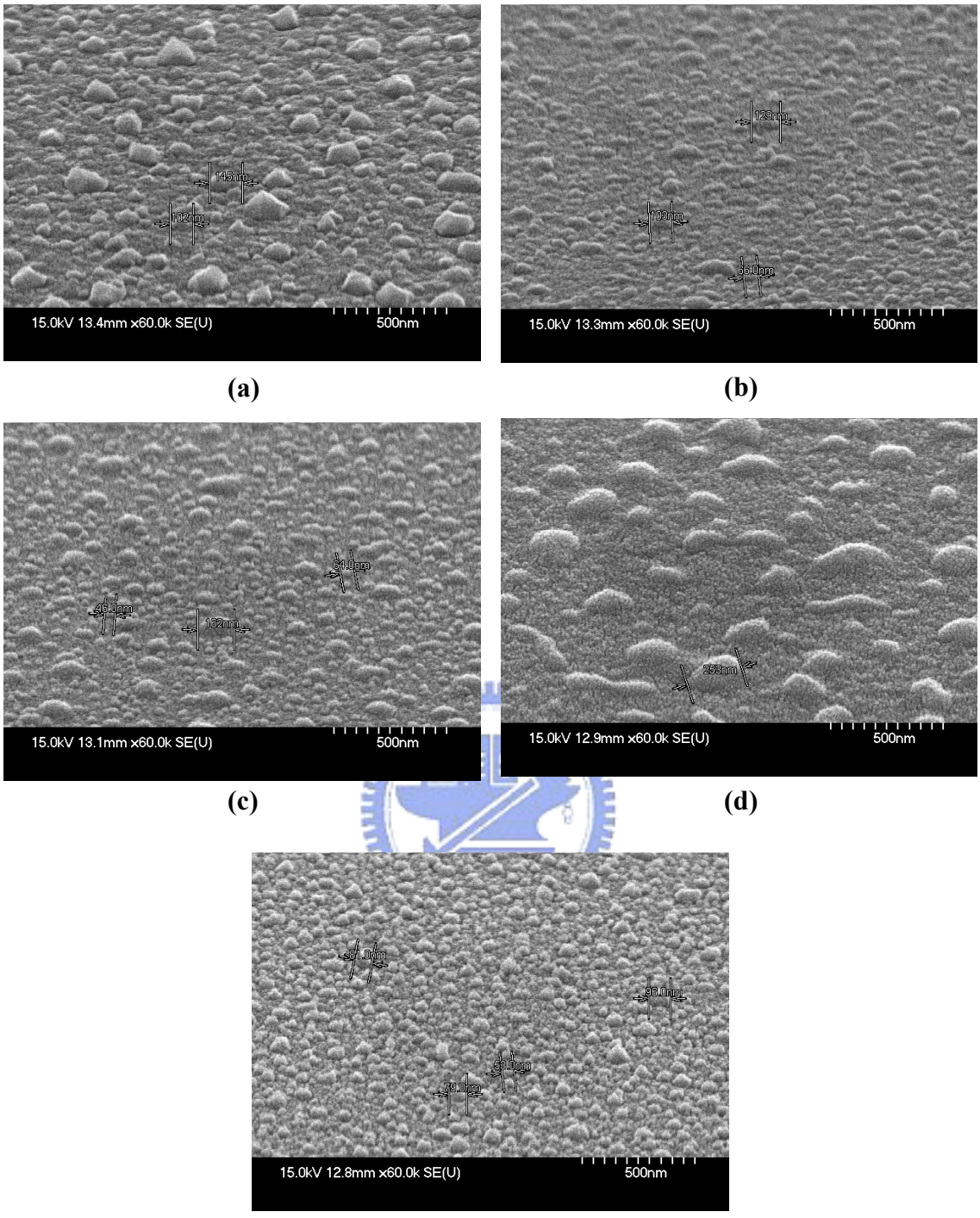


Fig. 4-1 SEM images of (a) Fe (b) Ni (c) FeNi (d) NiPd (e) FeC nanoparticles after pretreatment at 700℃ in Experiment A

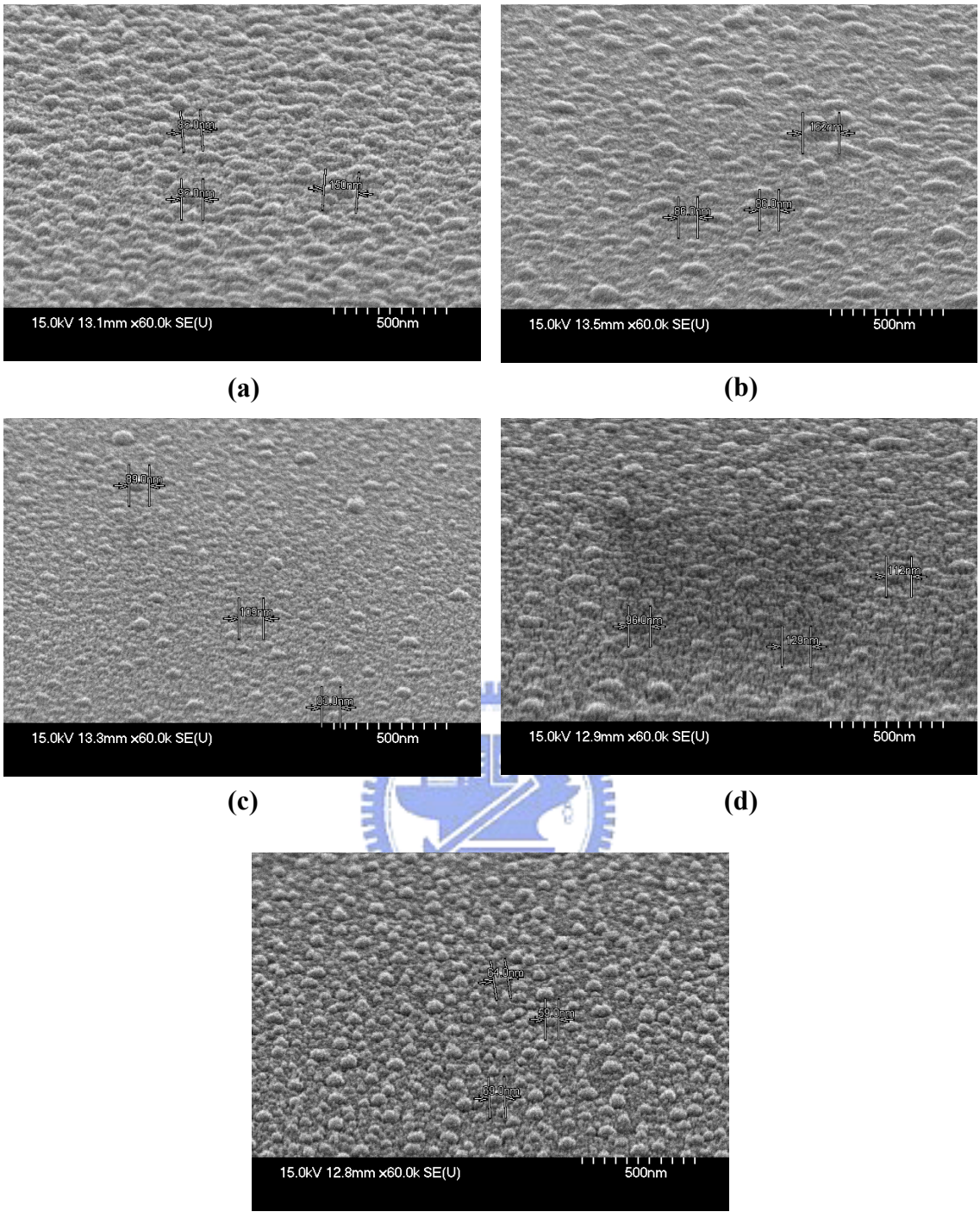


Fig. 4-2 SEM images of (a) Fe (b) Ni (c) FeNi (d) NiPd (e) FeC nanoparticles after pretreatment at 600℃ in Experiment B

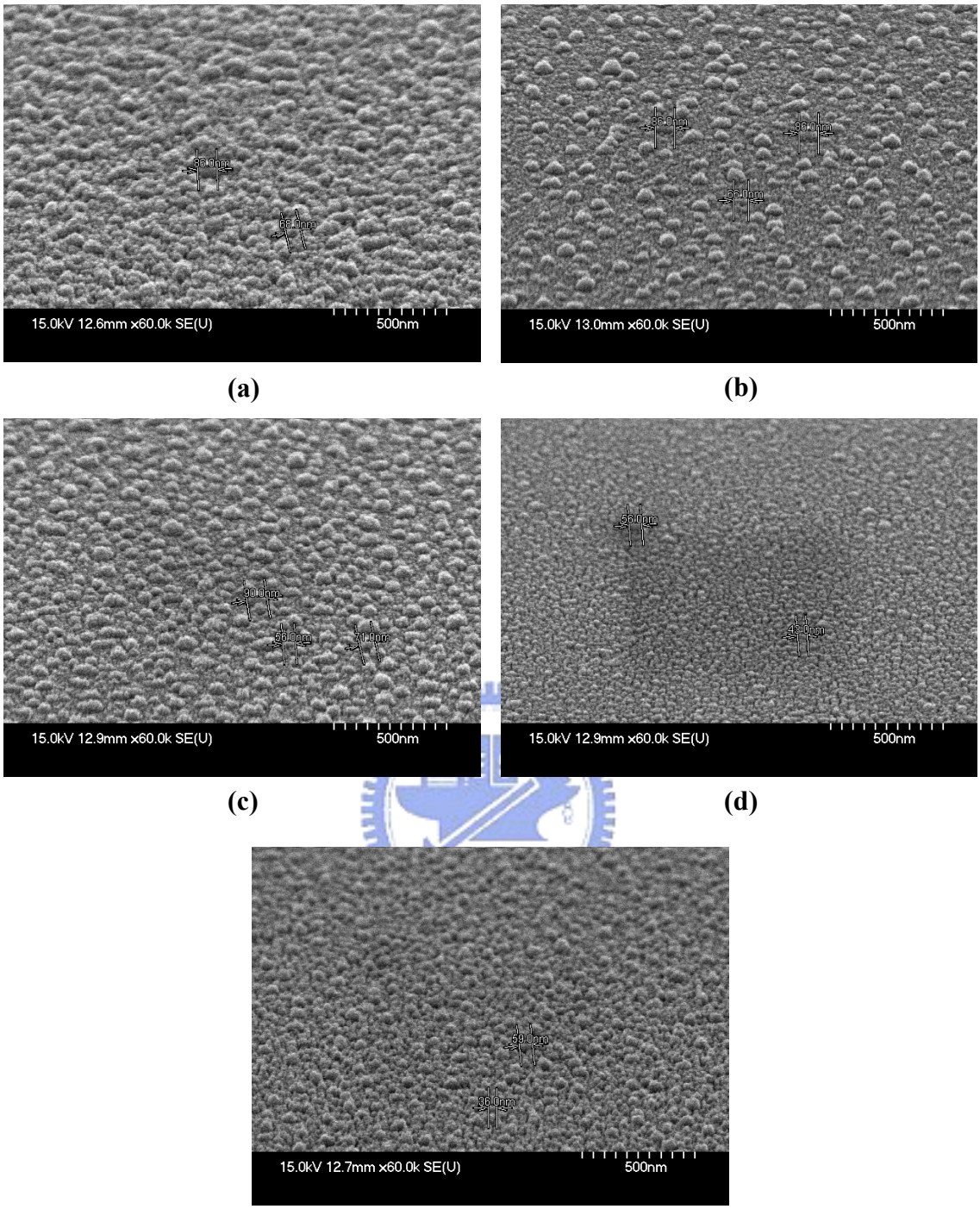
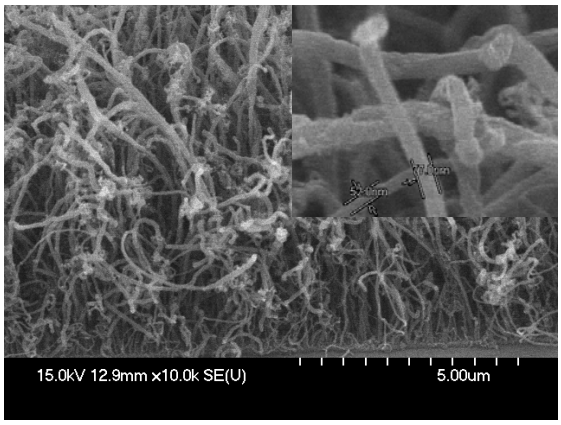
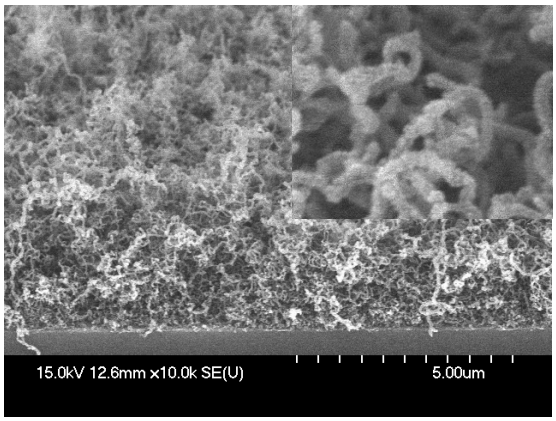


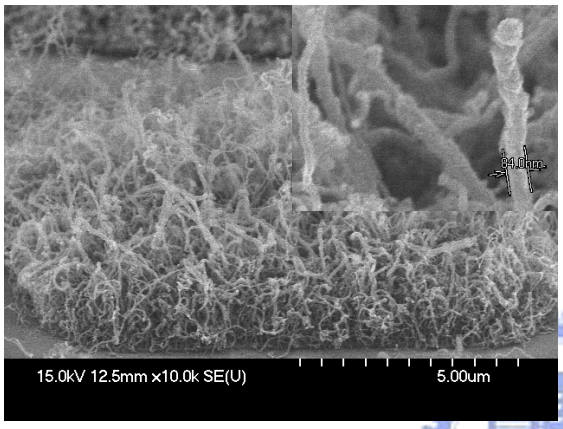
Fig. 4-3 SEM images of (a) Fe (b) Ni (c) FeNi (d) NiPd (e) FeC nanoparticles after pretreatment at 500℃ in Experiment C



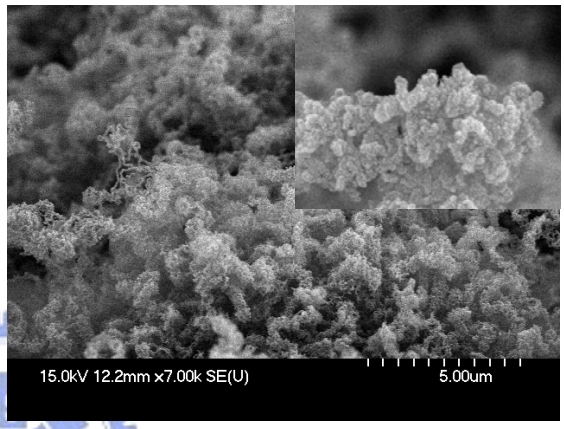
(a)



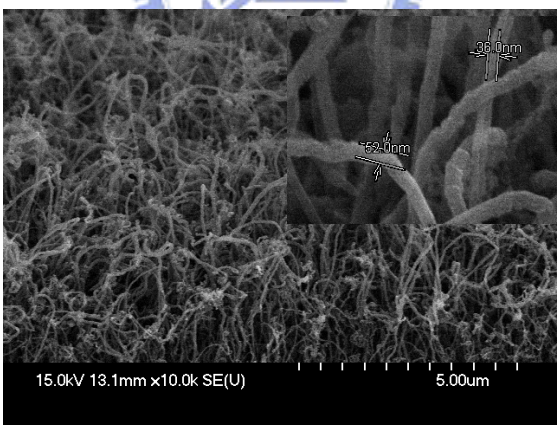
(b)



(c)



(d)



(e)

Fig. 4-4 SEM images of CNTs with (a) Fe (b) Ni (c) FeNi (d) NiPd (e) FeC as catalyst grown at 700℃ in Experiment A, and the inset shows the magnified image

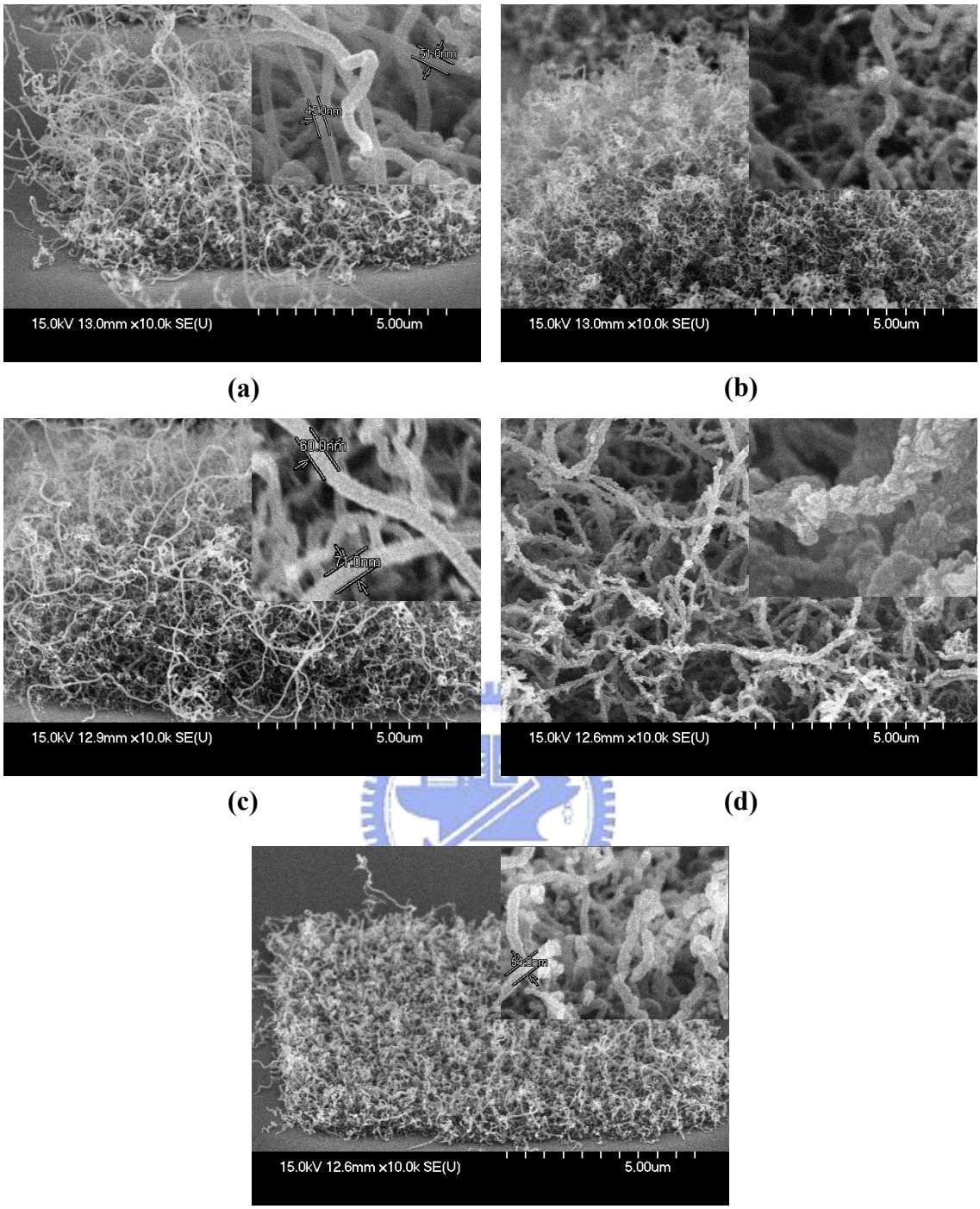


Fig. 4-5 SEM images of CNTs with (a) Fe (b) Ni (c) FeNi (d) NiPd (e) FeC as catalyst grown at 600℃ in Experiment B, and the inset shows the magnified image

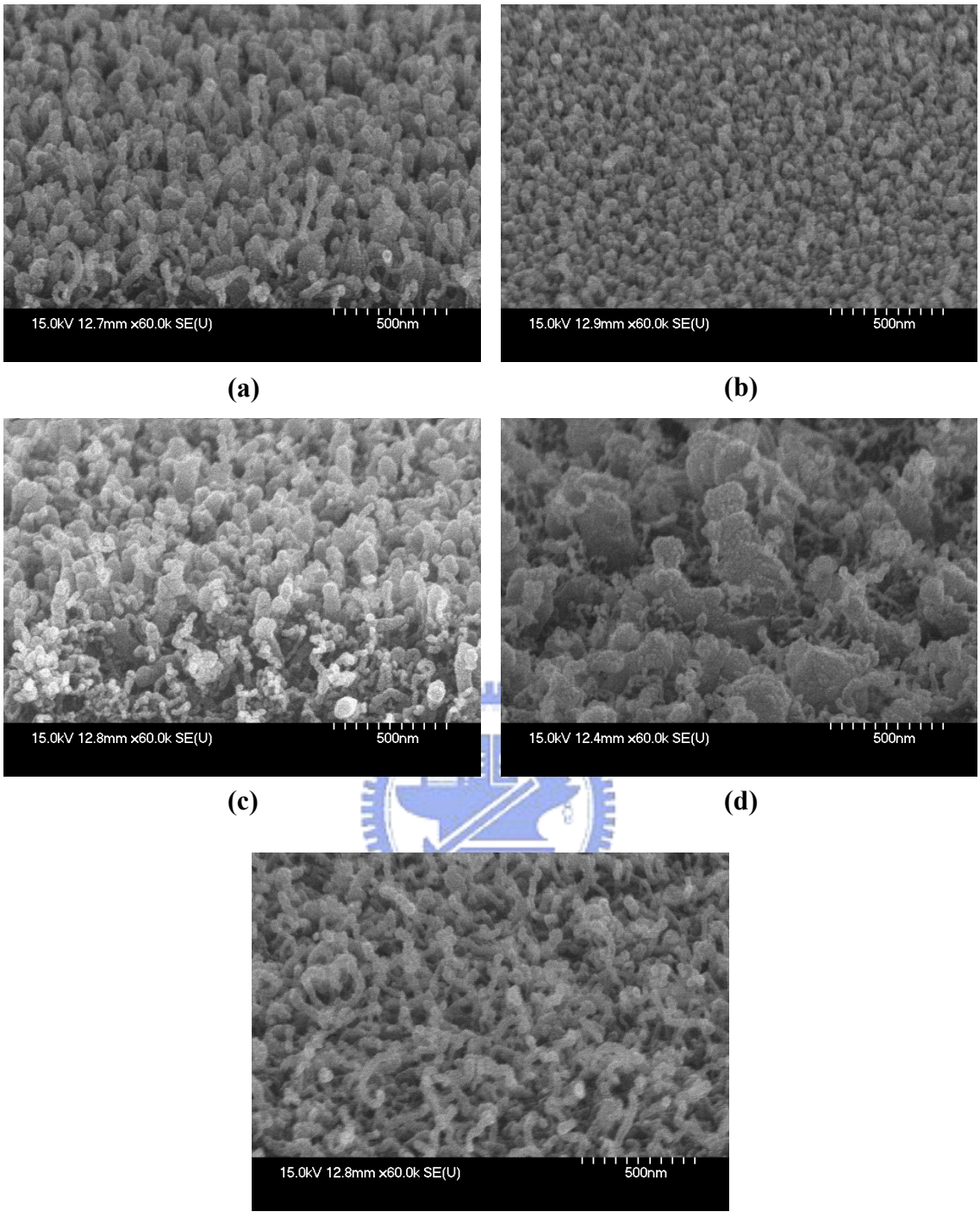


Fig. 4-6 SEM images of CNTs with (a) Fe (b) Ni (c) FeNi (d) NiPd (e) FeC as catalyst grown at 500℃ in Experiment C

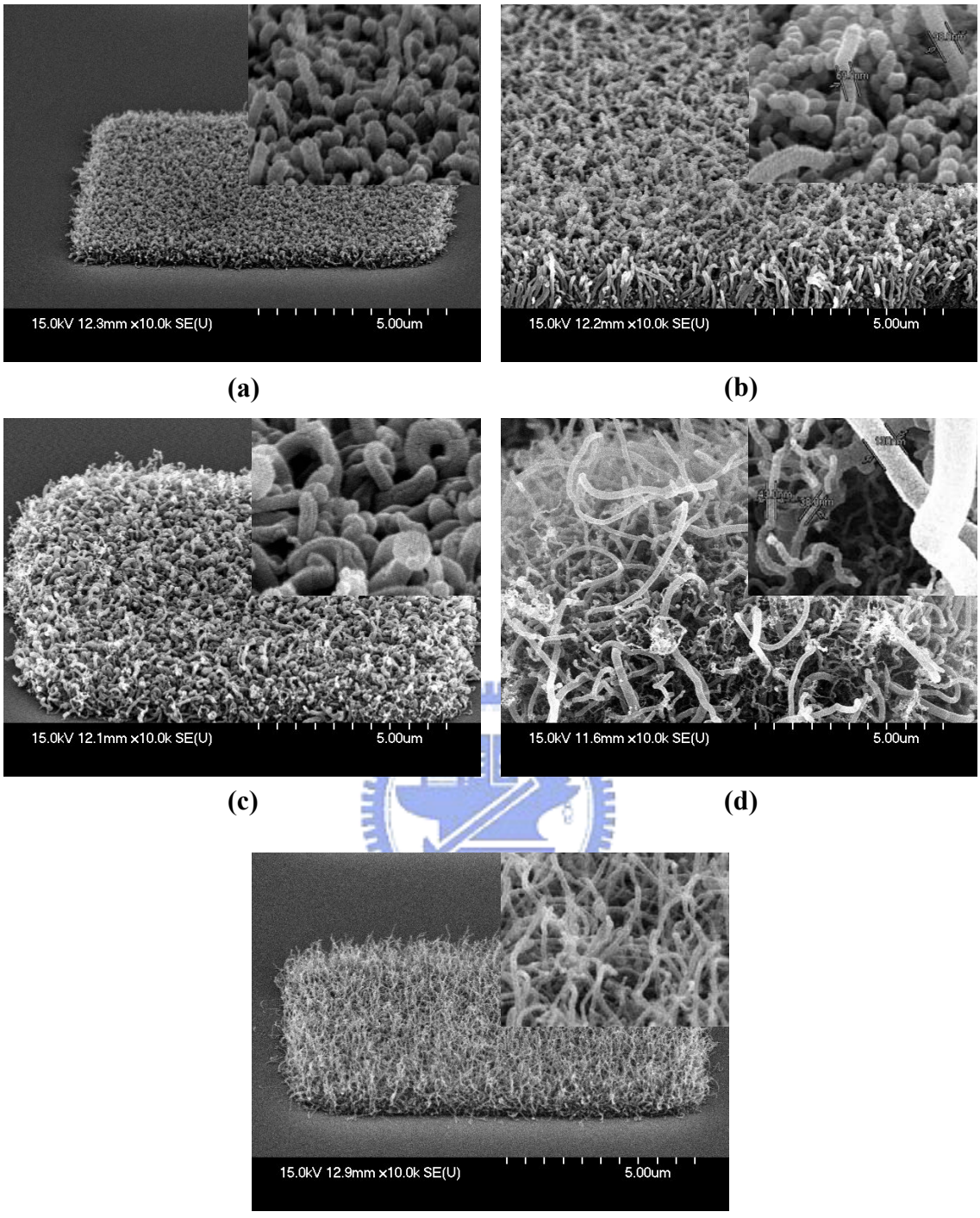


Fig. 4-7 SEM images of CNTs with (a) Fe (b) Ni (c) FeNi (d) NiPd (e) FeC as catalyst grown at 500℃ in Experiment D, and the inset shows the magnified image

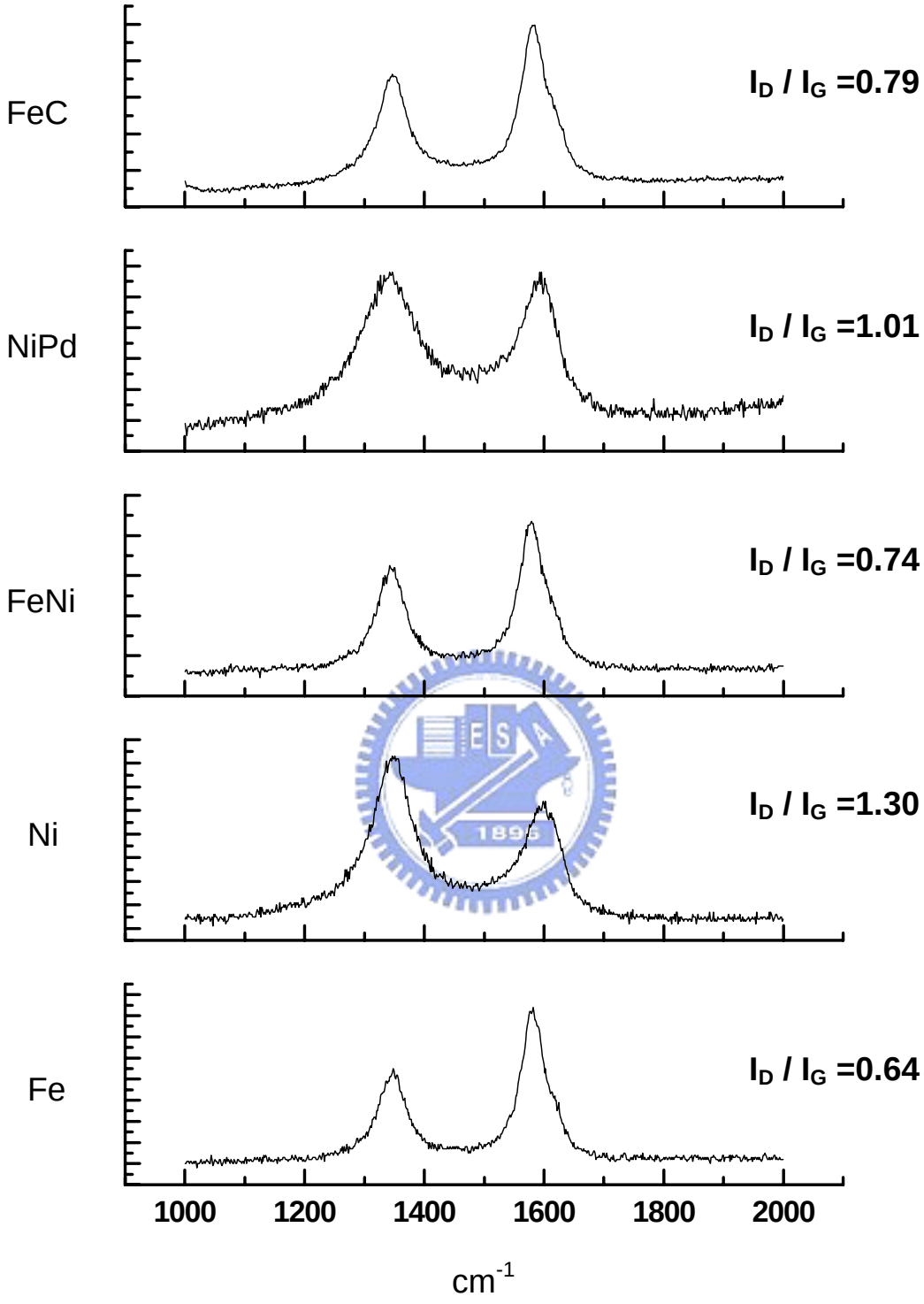


Fig. 4-8 Raman spectrum of CNTs grown at 700℃ in Experiment A

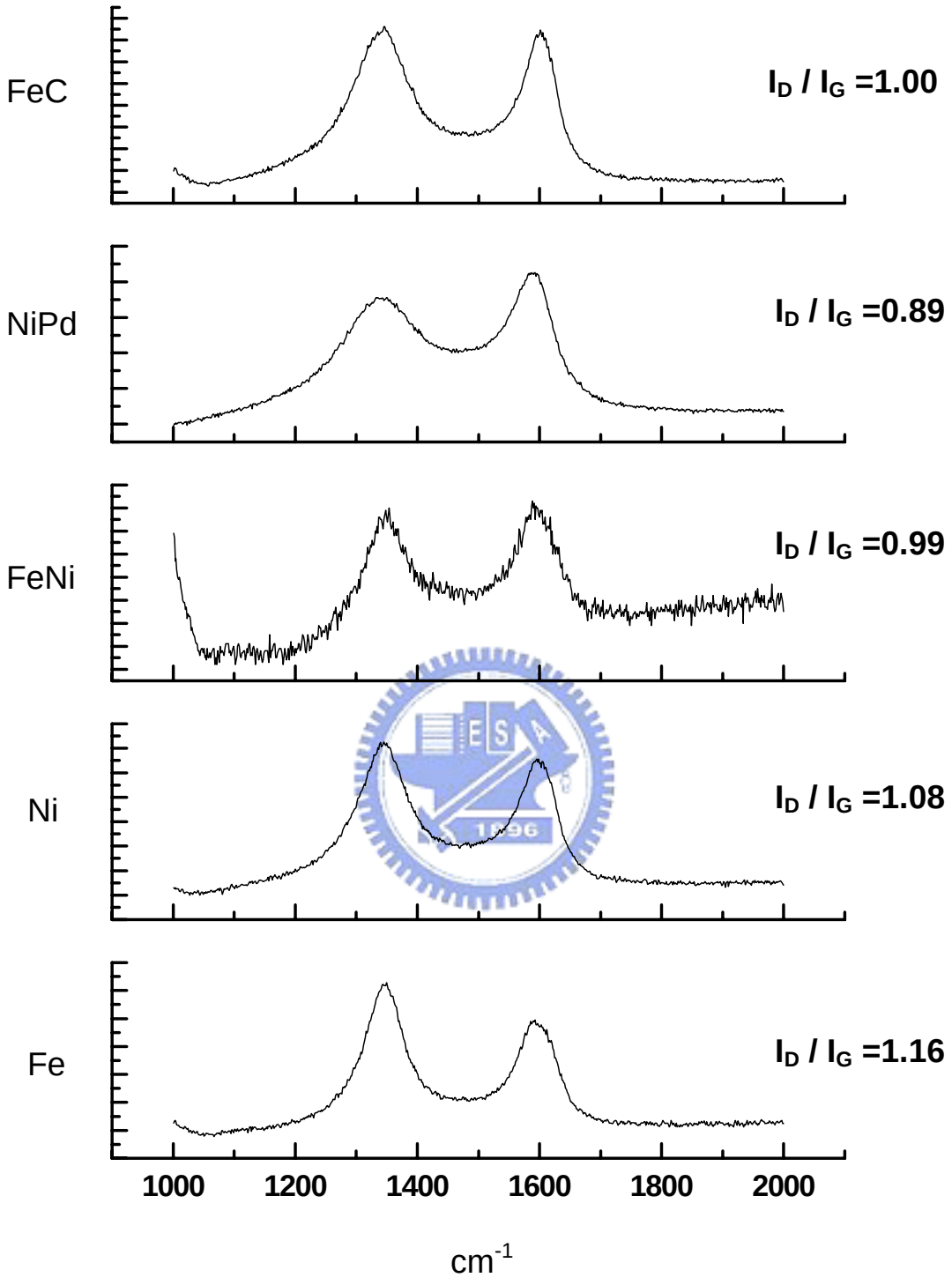


Fig. 4-9 Raman spectrum of CNTs grown at 600℃ in Experiment B

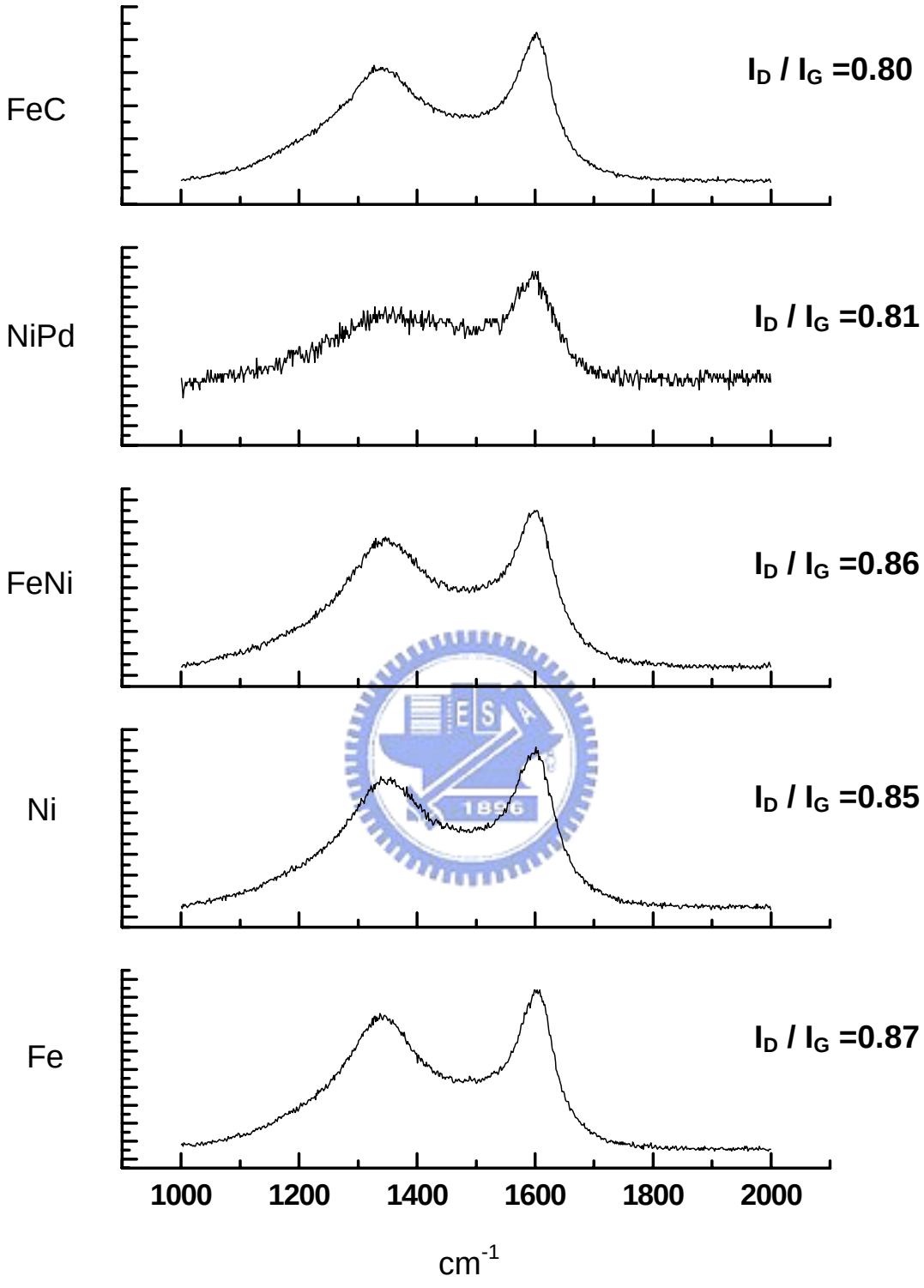
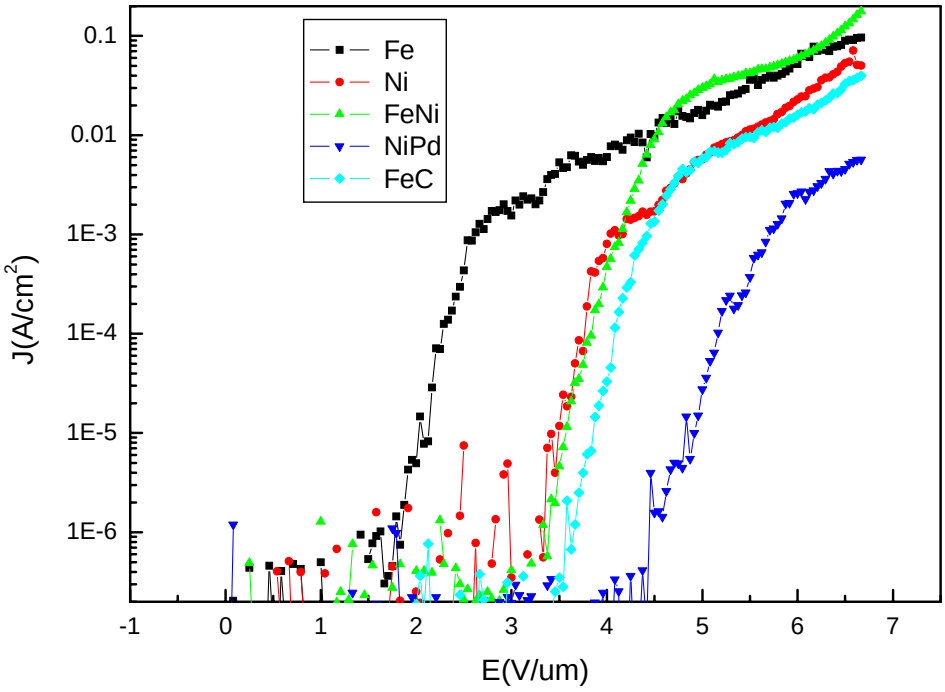
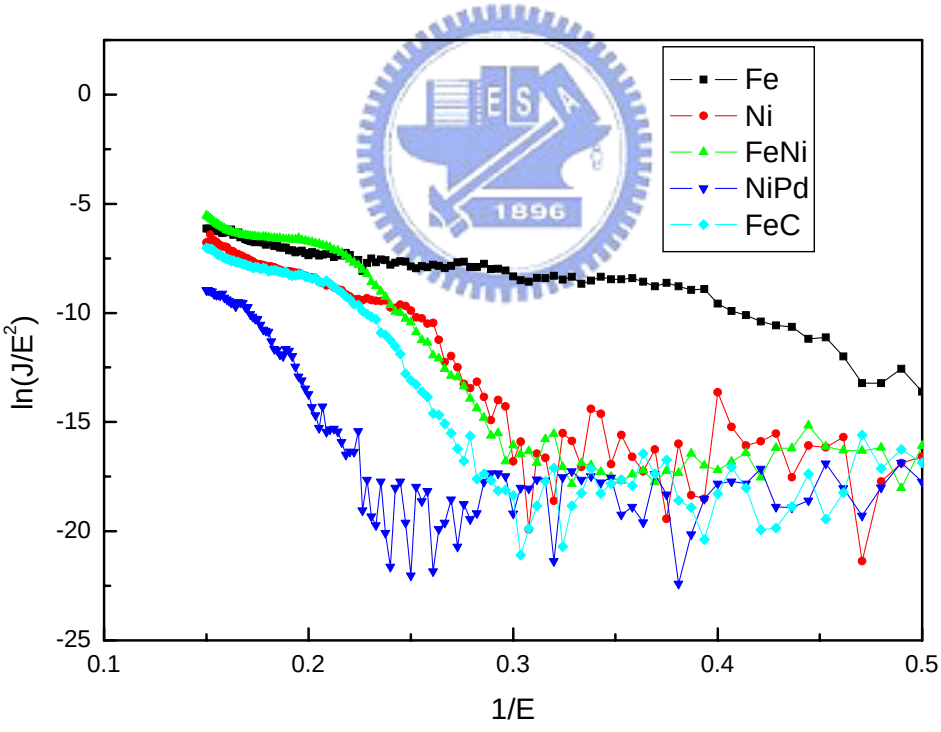


Fig. 4-10 Raman spectrum of CNTs grown at 500℃ in Experiment D

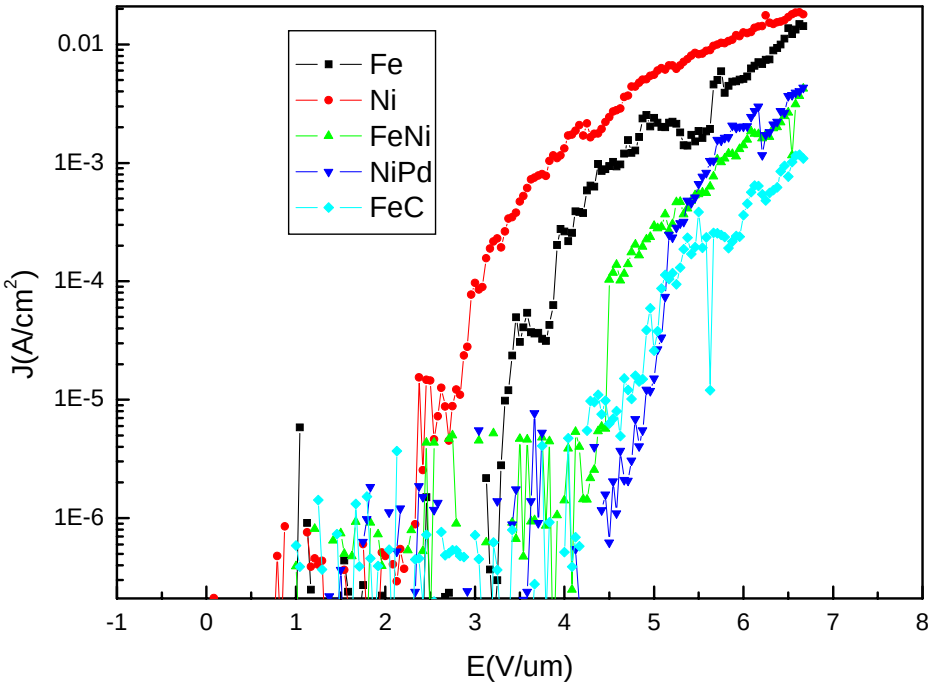


(a)

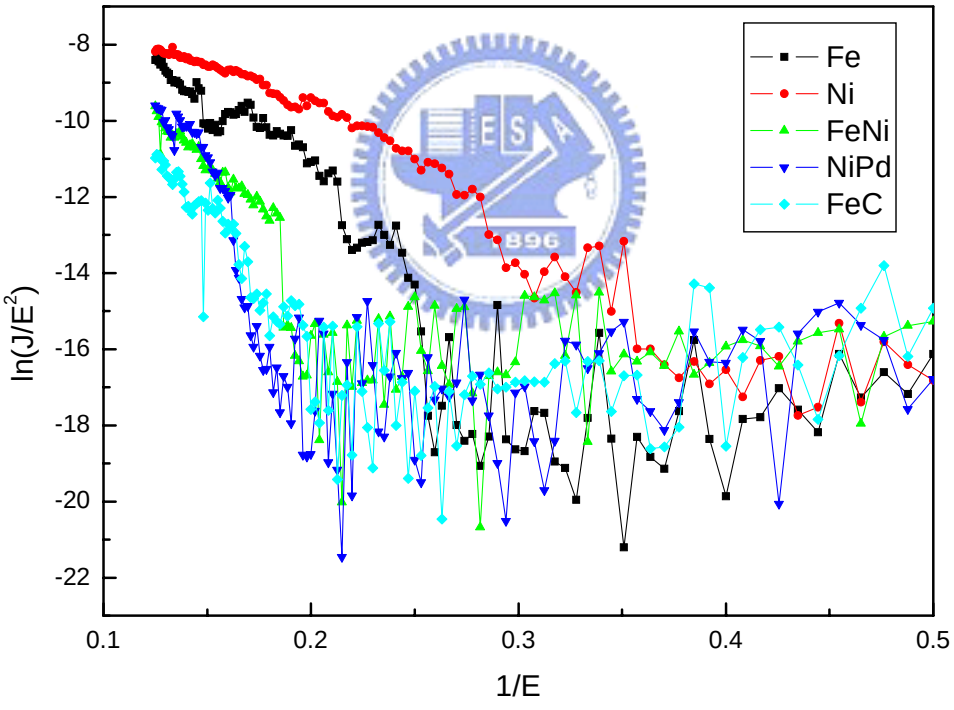


(b)

Fig. 4-11 (a) Field emission characteristics and (b) F-N plot of CNTs grown at 700℃ in Experiment A

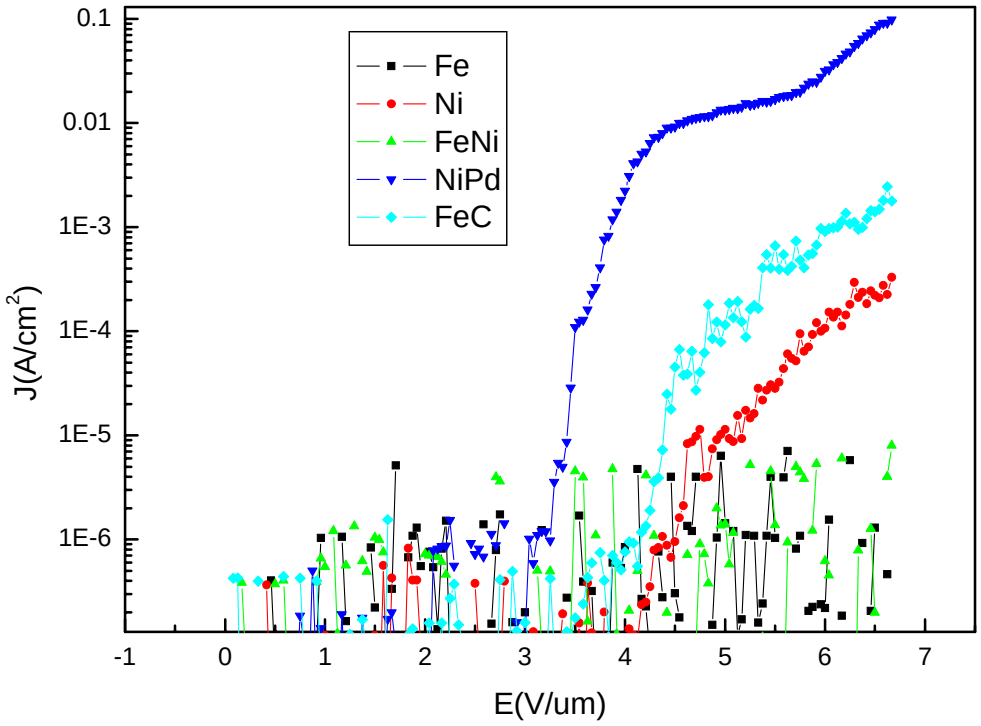


(a)

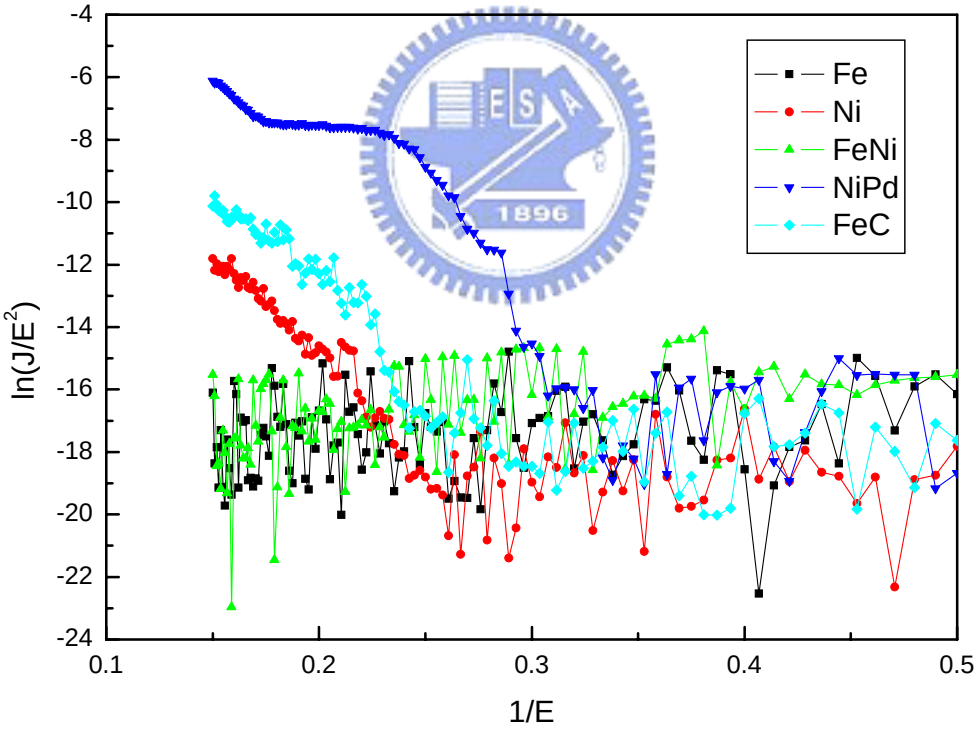


(b)

Fig. 4-12 (a) Field emission characteristics and (b) F-N plot of CNTs grown at 600℃ in Experiment B



(a)



(b)

Fig. 4-13 (a) Field emission characteristics and (b) F-N plot of CNTs grown at 500℃ in Experiment D

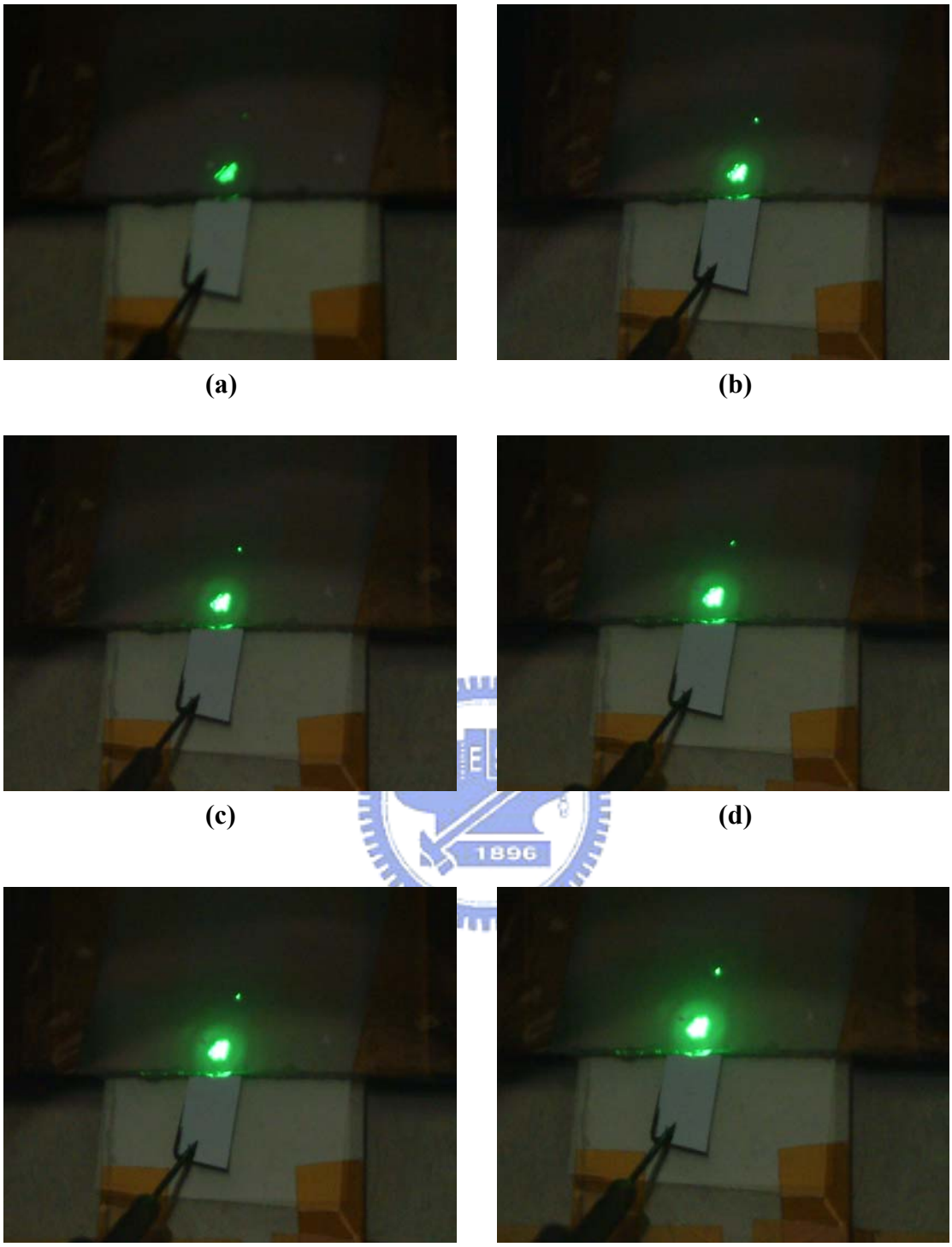


Fig. 4-14 The luminescent images on the ITO anode with phosphor coating on it were observed at applied electric field (a) 4.2, (b) 4.6, (c) 5, (d) 5.4, (e) 5.8, and (f) 6.3 V/um, respectively.

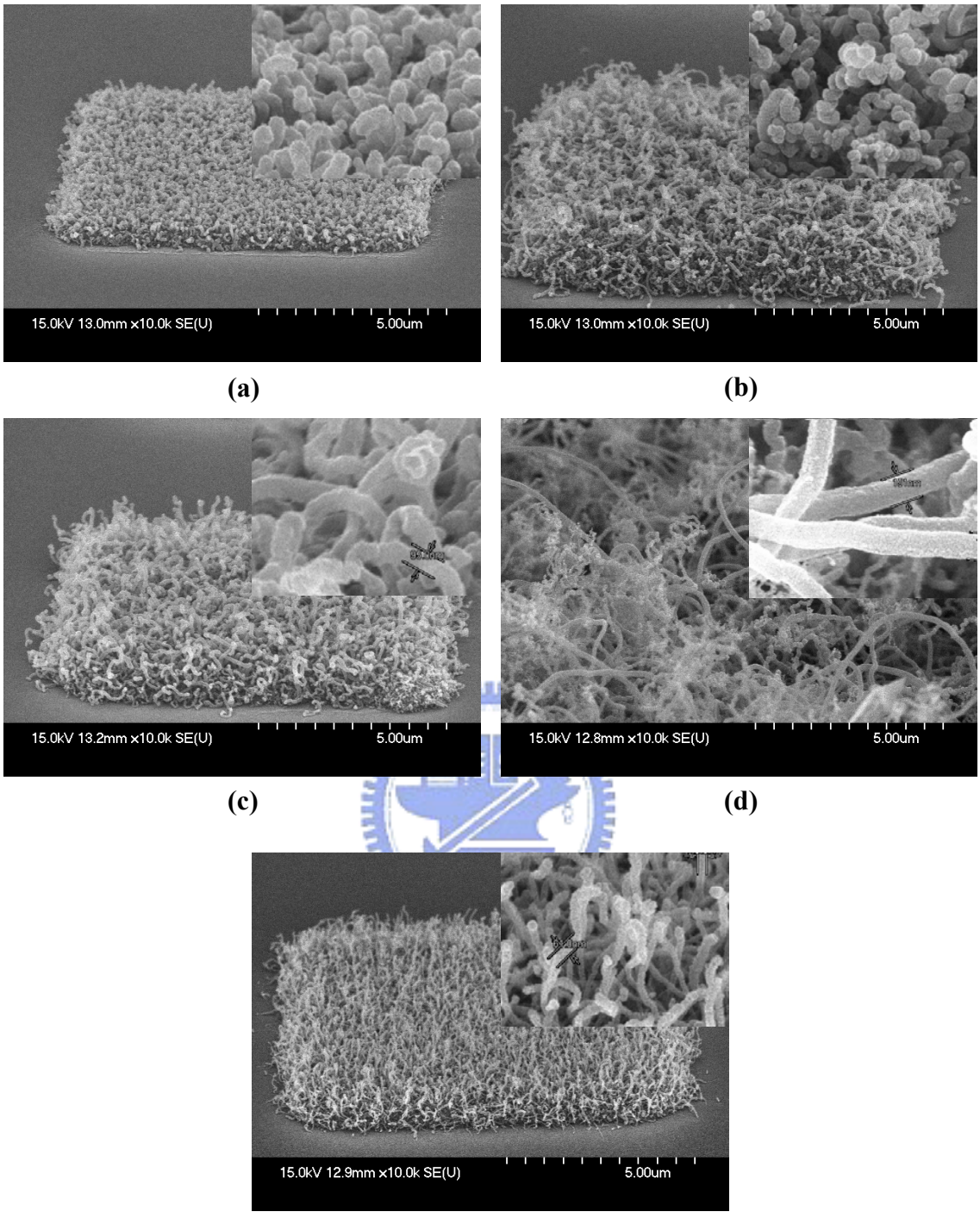
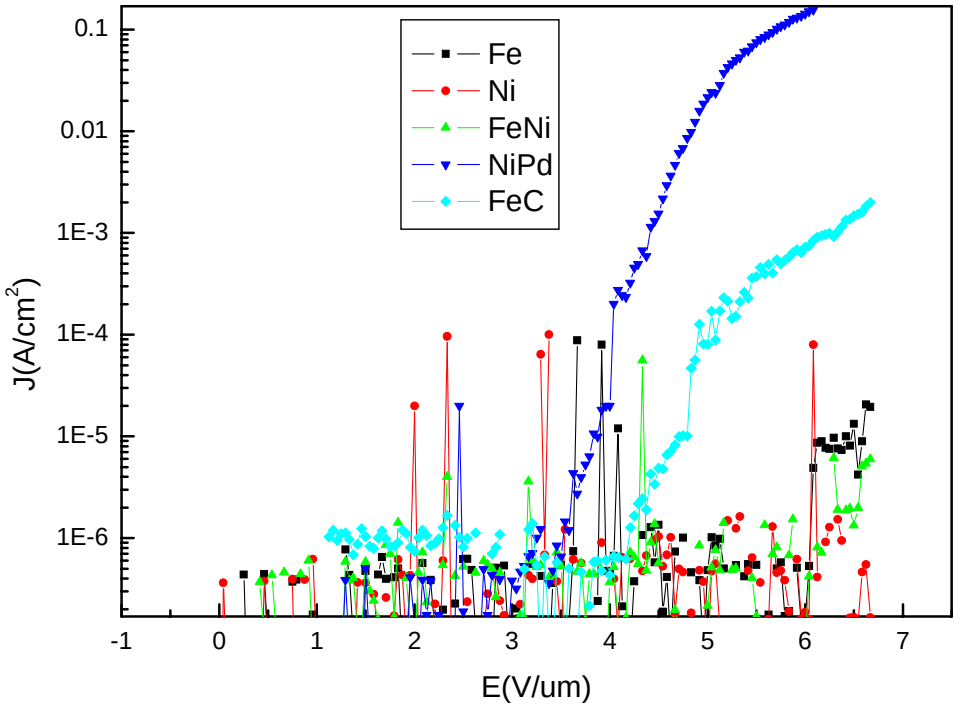


Fig. 4-15 SEM images of CNTs with (a) Fe (b) Ni (c) FeNi (d) NiPd (e) FeC as catalyst grown at 500℃ in Experiment E, and the inset shows the magnified image

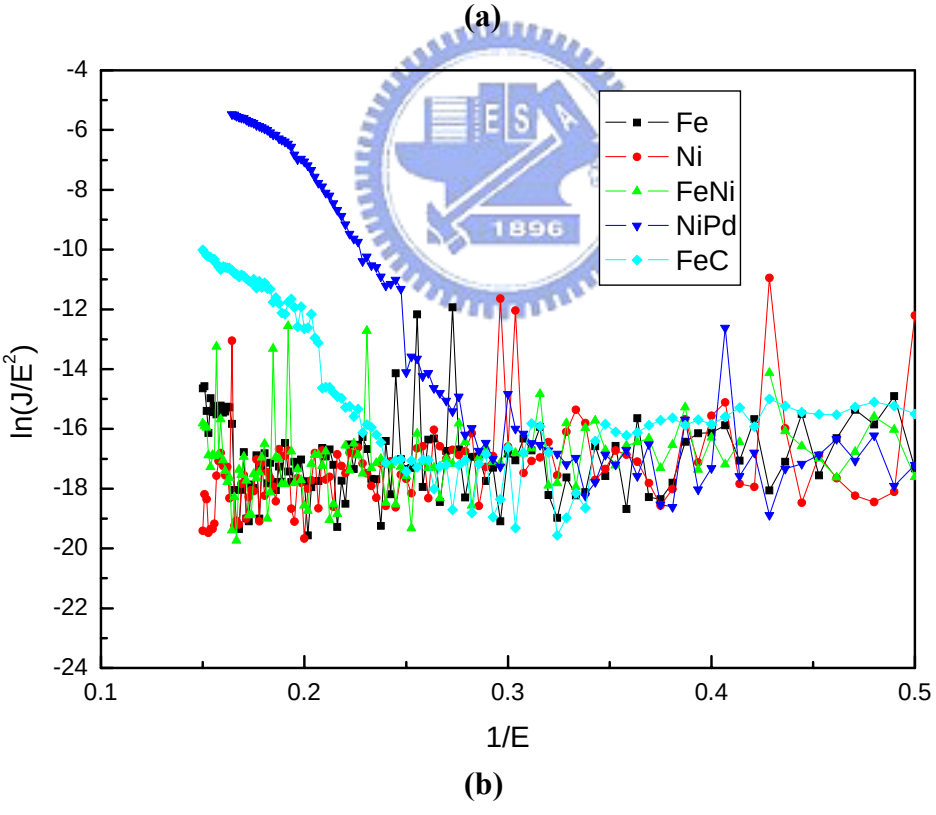
(a)

(b)

Fig. 4-16 TEM images of CNTs grown with (a) NiPd (b) FeC as catalyst at 500℃ in Experiment E



(a)



(b)

Fig. 4-17 (a) Field emission characteristics and (b) F-N plot of CNTs grown at 500℃ in Experiment E

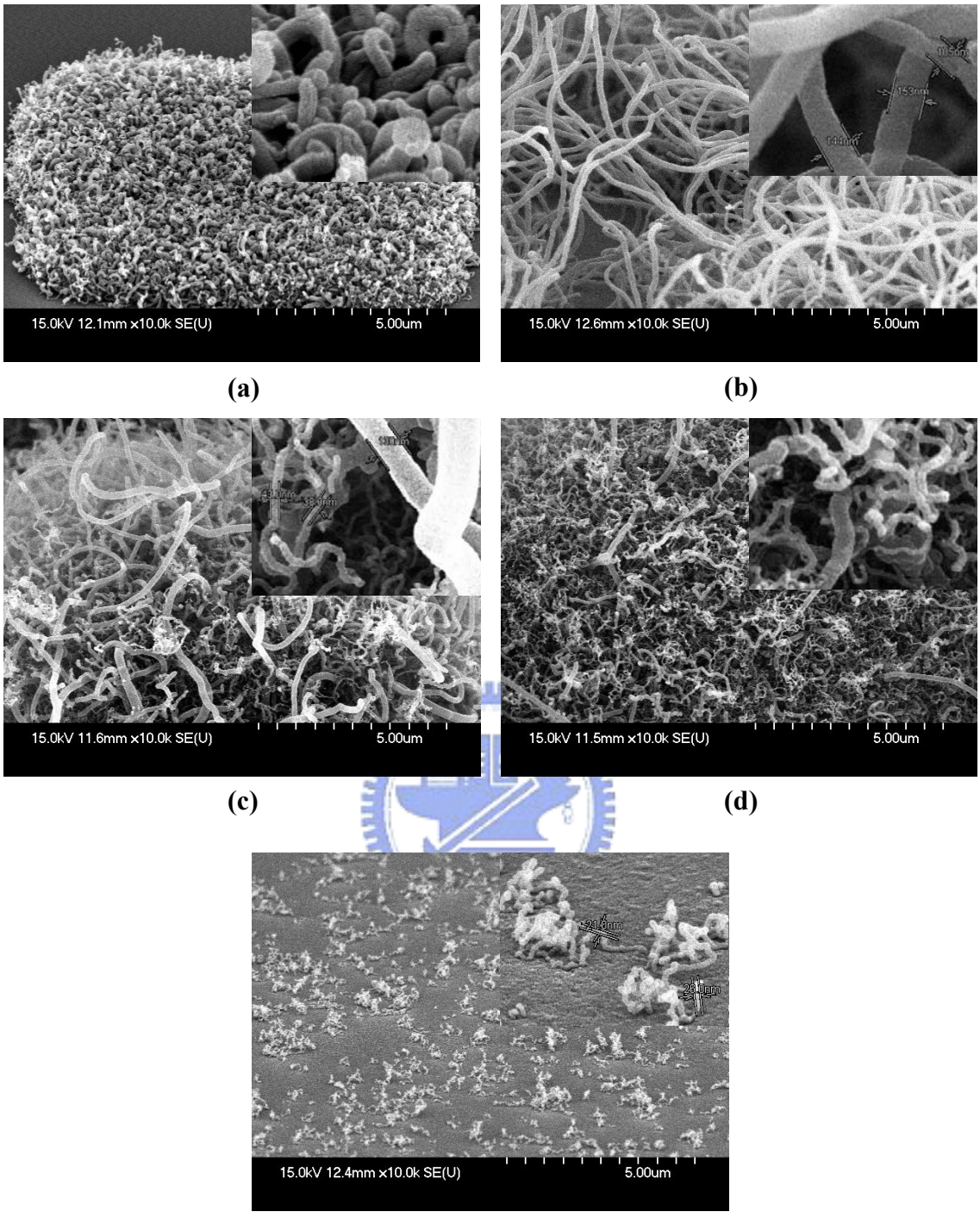


Fig. 4-18 SEM images of CNTs with (a) Ni (b) NiPd (Pd:21%) (c) NiPd (Pd:60%) (d) NiPd (Pd:84%) (e) NiPd (Pd:92%) as catalyst grown at 500℃ in Experiment F, and the inset shows the magnified image

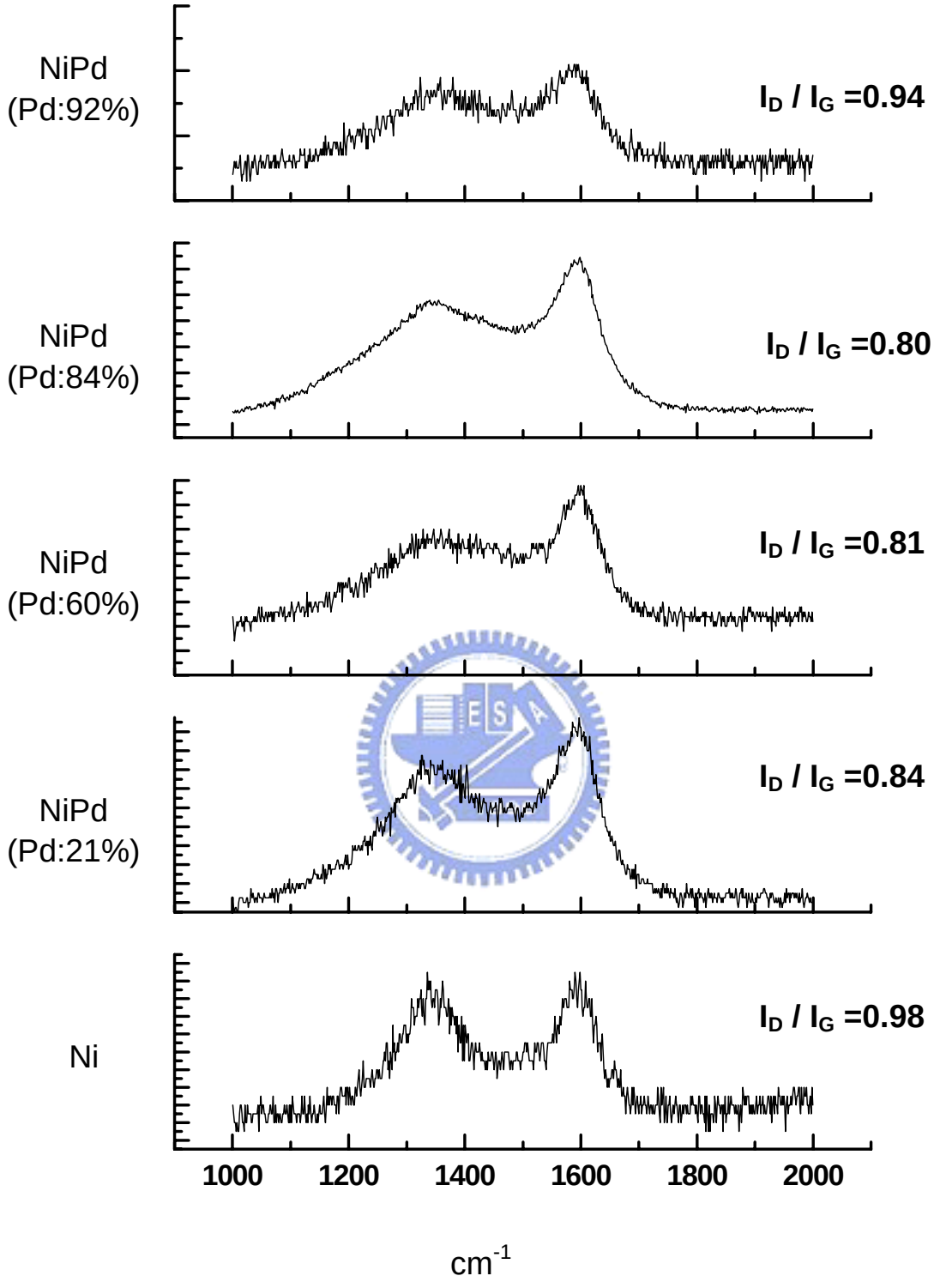
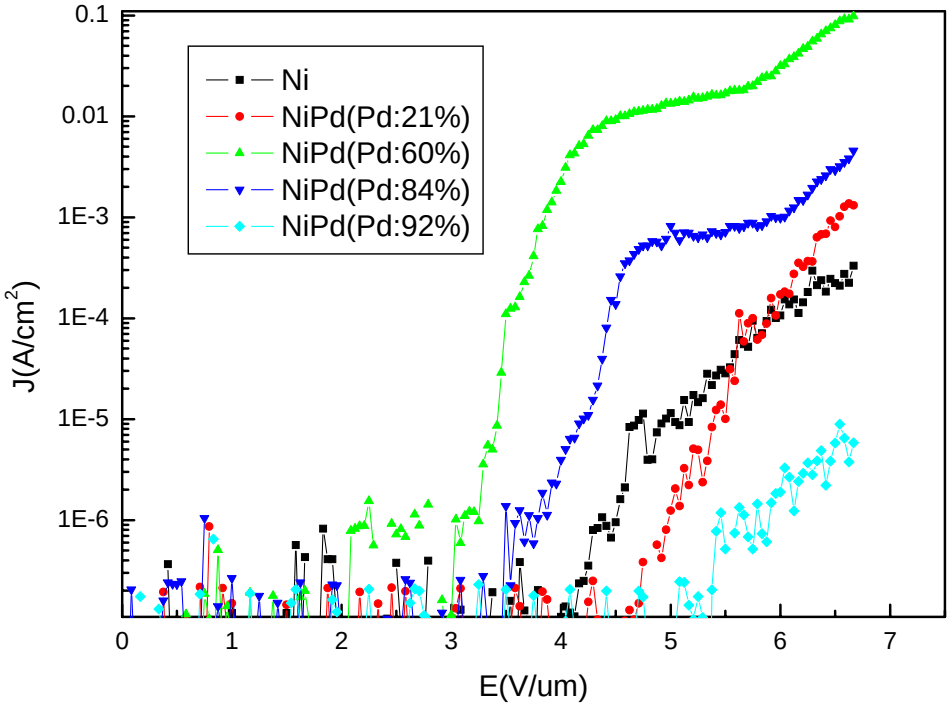
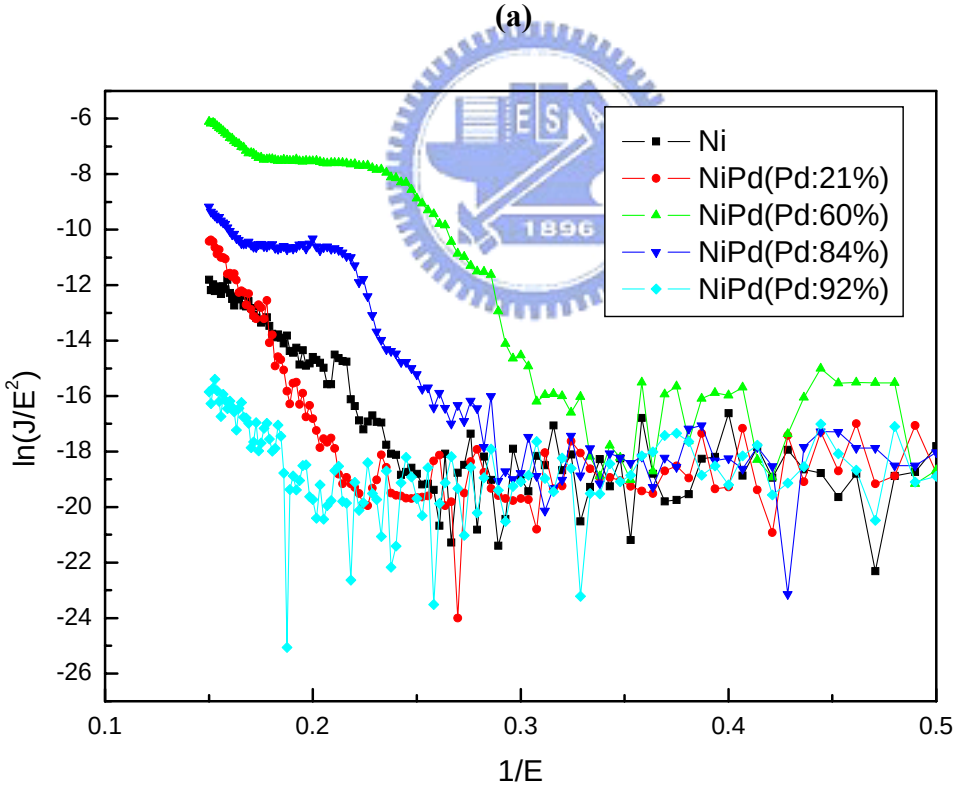


Fig. 4-19 Raman spectrum of CNTs grown at 500℃ in Experiment F

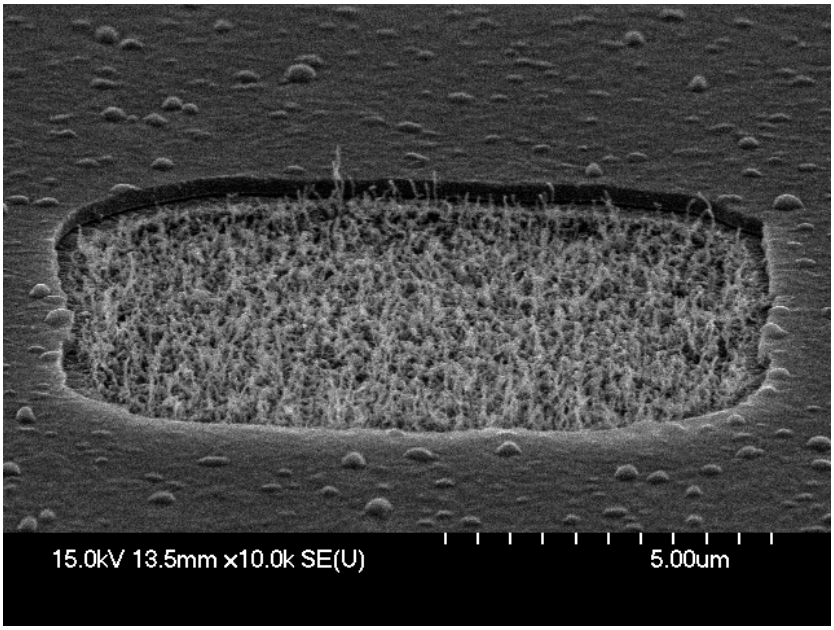


(a)

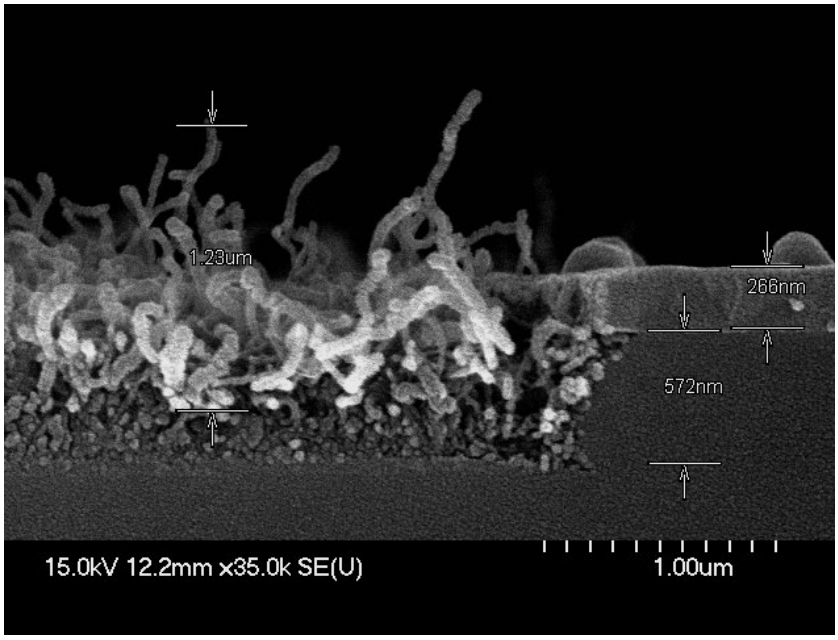


(b)

Fig. 4-20 (a) Field emission characteristics and (b) F-N plot of CNTs grown at 500℃ in Experiment F

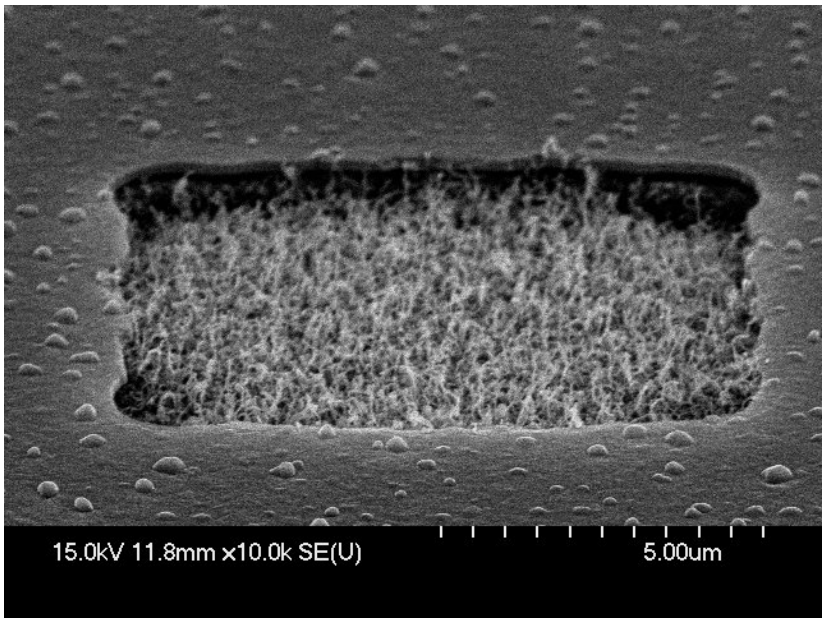


(a)

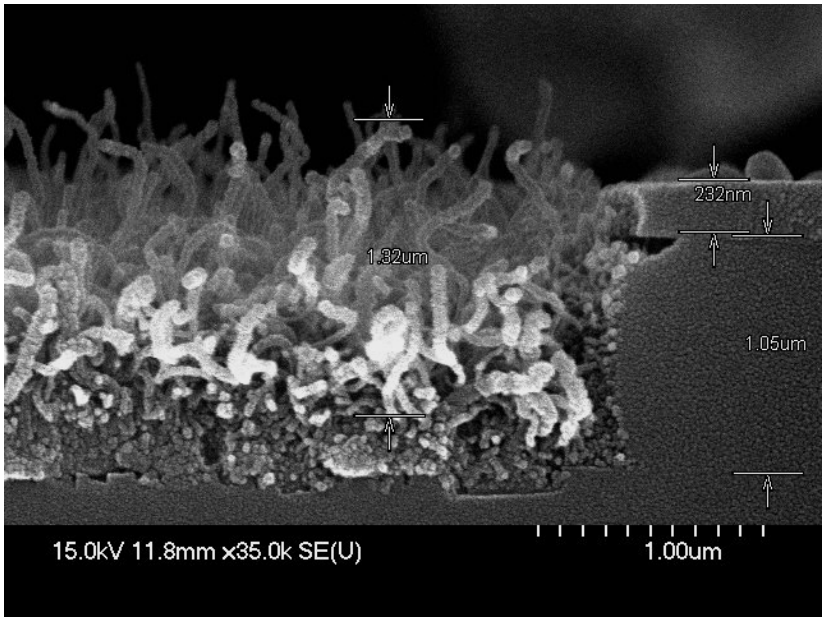


(b)

Fig. 4-21 SEM images of (a) whole pattern (b) cross-section view in under-gate structure

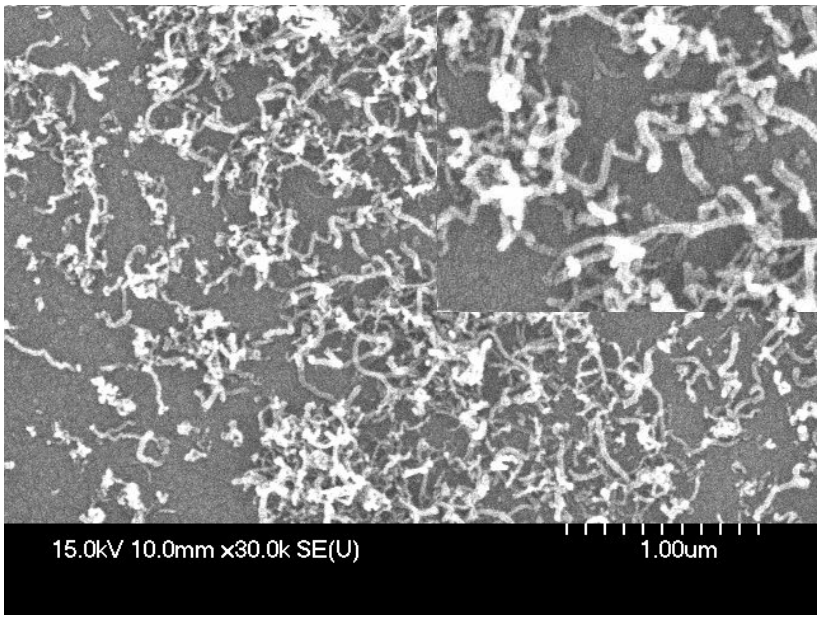


(a)

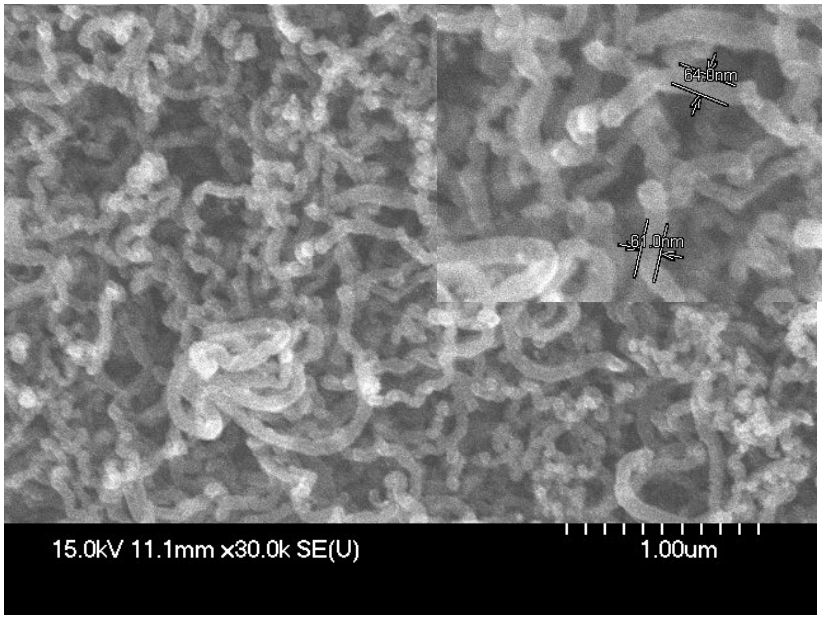


(b)

Fig. 4-22 SEM images of (a) whole pattern (b) cross-section view in planar-gate structure



(a)



(b)

Fig. 4-23 SEM images of CNTs with (a) FeC (b) NiPd as catalyst grown on glass substrate, and the magnified image is shown in the inset

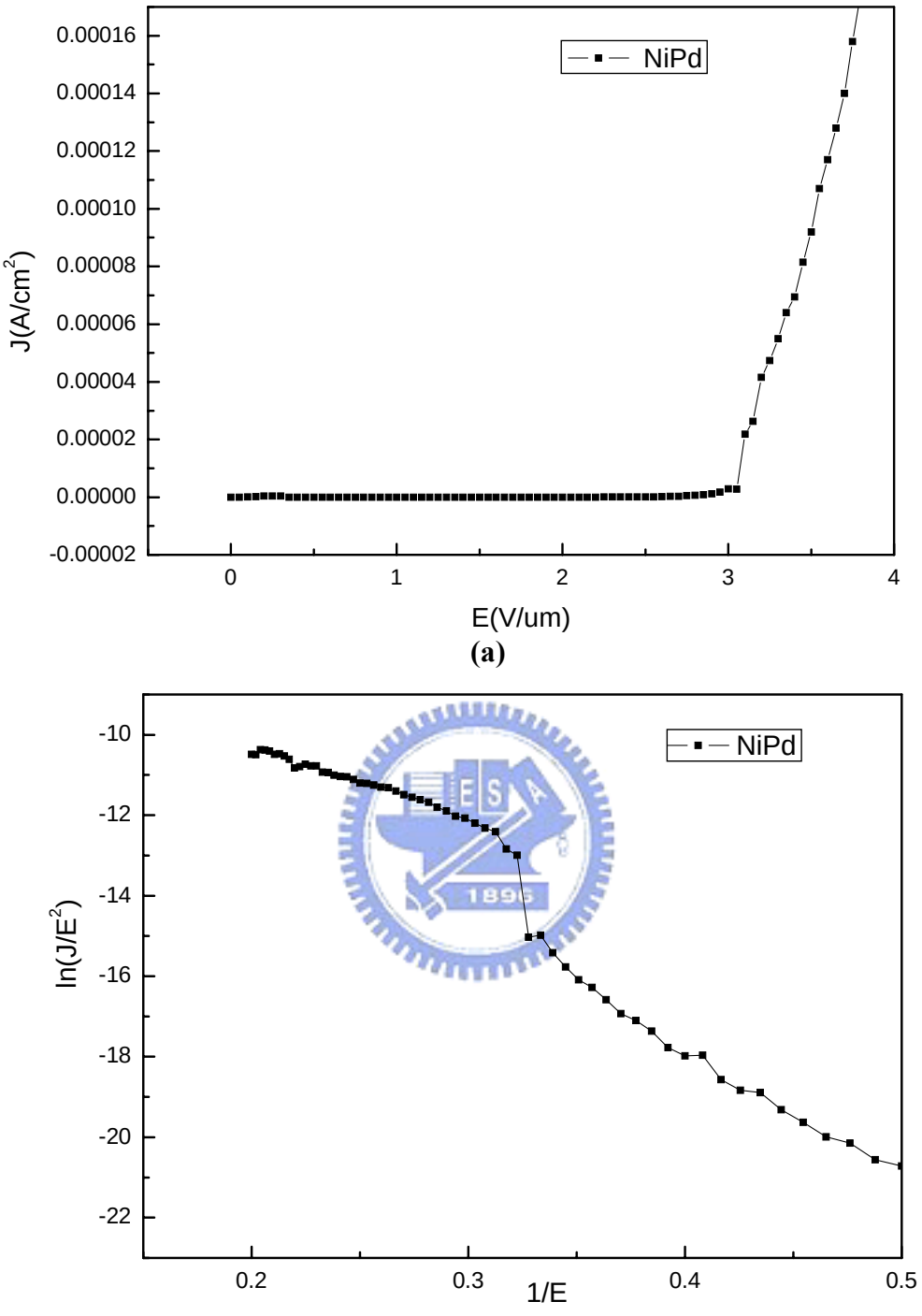
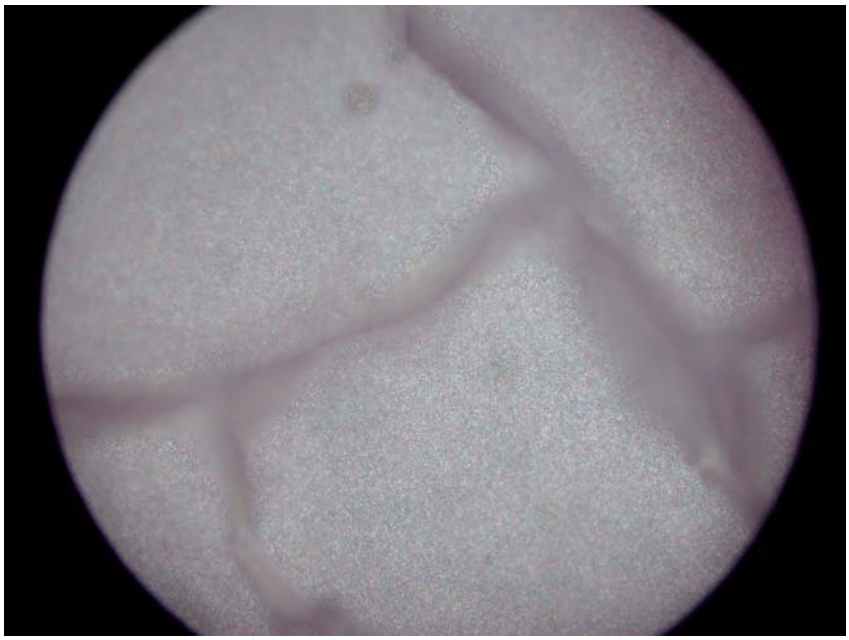
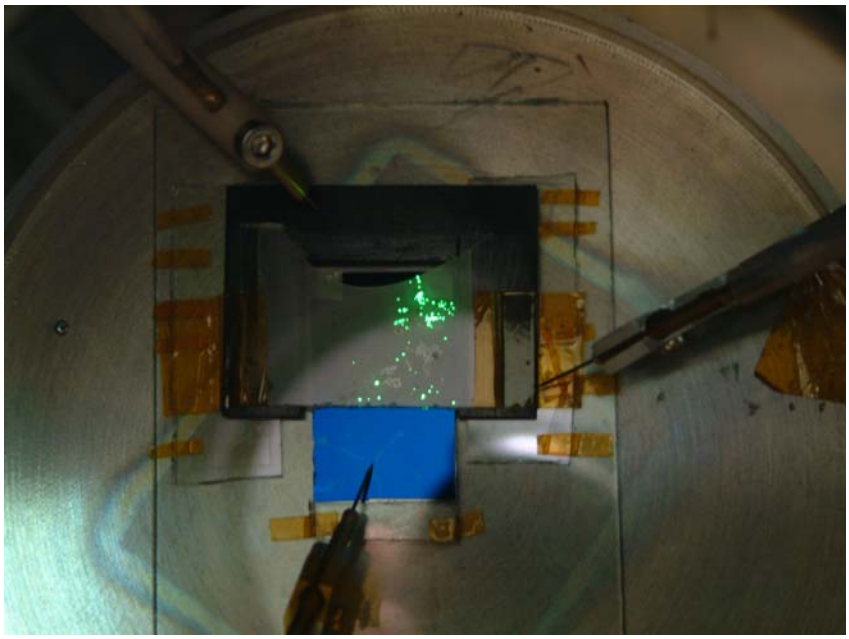


Fig. 4-24 (a) Field emission characteristics and (b) F-N plot of CNTs grown on glass substrate in Experiment I



(a)



(b)

Fig. 4-25 (a) Image of CNT film by OM (b) the luminescent image that corresponded with the electron emission from the CNTs was obtained on the anode phosphor substrate

Table 1-1 Comparison between vacuum microelectronic and semiconductor devices

Items	Solid State Microelectronics	Vacuum Microelectronics
Current Density	$10^4 – 10^5$ (A/cm^2)	similar
Turn-on Voltage	0.1 – 0.7 V	5 – 300 V
Structure	solid/solid interface	solid/vacuum interface
Electron Transport	in solid	in vacuum
Electron Velocity	3×10^7 (cm/sec)	3×10^{10} (cm/sec)
Flicker Noise	due to interface	due to emission
Thermal & Short Noise	comparable	comparable
Electron Energy	< 0.3 eV	a few to 1000 eV
Cut-off Frequency	< 20 GHz (Si) & 100 GHz (GaAs)	< 100 – 1000 GHz
Power	small – medium	medium – large
Radiation Hardness	poor	excellent
Temperature Effect	-30 – 50 °C	< 500 °C
Fabrication & Materials	well established (Si) & fairly well (GaAs)	not well established

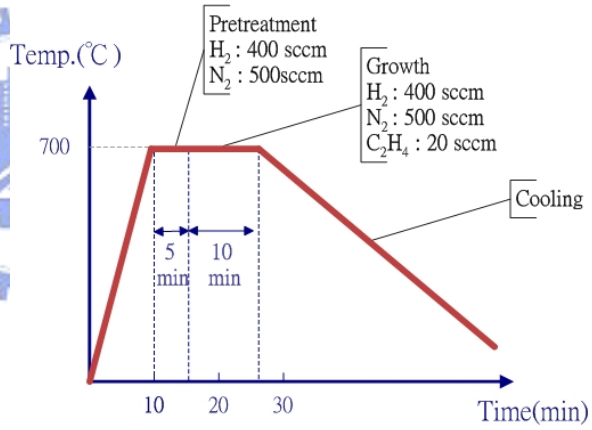
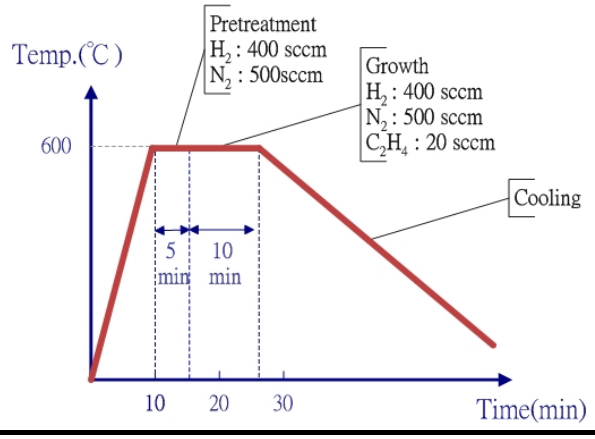
Table 2-1 Physical properties of some common catalysts

Catalyst	Atomic size (Å)	Atomic weight (amu)	Melting point (℃)
Fe	1.26	55.85	1536
Ni	1.24	58.71	1453
Co	1.25	58.93	1495
Pd	1.37	106.4	1552

Table 3-1 Catalyst for CNTs growth

Catalyst	Thickness (Å)	Composition proportion	Depositing system
Fe	50	1	Dual E-gun
Ni	50	1	Dual E-gun
FeNi	50	1 : 1	Dual E-gun
NiPd	50	2 : 3	Dual E-gun
FeC	50	95.7 : 4.3	Sputter

Table 3-2 Process of Experiment A-F

Item	Process Temp.	Catalysts	CNTs Synthesis Diagram
A	700	1. Fe 2. Ni 3. FeNi (1:1) 4. NiPd (2:3) 5. FeC (95.7:4.3)	
B	600	1. Fe 2. Ni 3. FeNi (1:1) 4. NiPd (2:3) 5. FeC (95.7:4.3)	

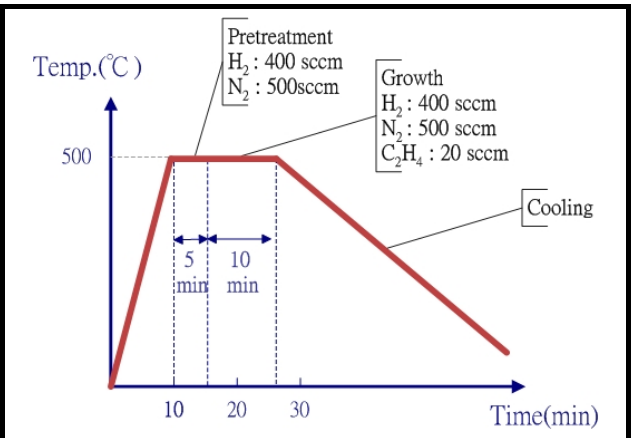
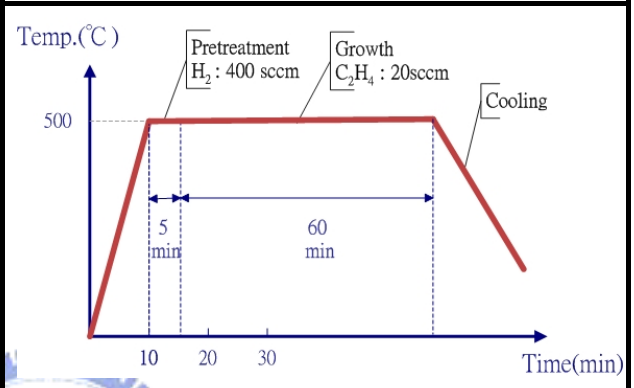
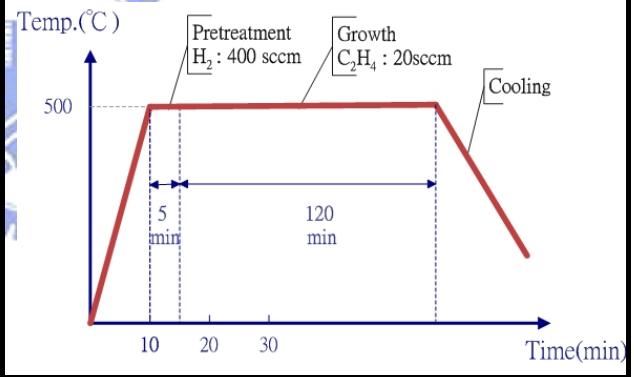
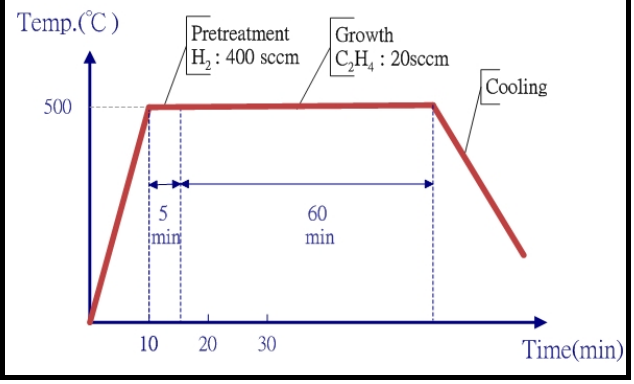
C	**500**	**1. Fe** **2. Ni** **3. FeNi (1:1)** **4. NiPd (2:3)** **5. FeC (95.7:4.3)**	
D	**500**	**1. Fe** **2. Ni** **3. FeNi (1:1)** **4. NiPd (2:3)** **5. FeC (95.7:4.3)**	
E	**500**	**1. Fe** **2. Ni** **3. FeNi (1:1)** **4. NiPd (2:3)** **5. FeC (95.7:4.3)**	
F	**500**	**1. Ni** **2. NiPd** (Pd:21%) **3. NiPd** (Pd:60%) **4. NiPd** (Pd:84%) **5. NiPd** (Pd:92%)	

Table 3-3 Process of Experiment G-H

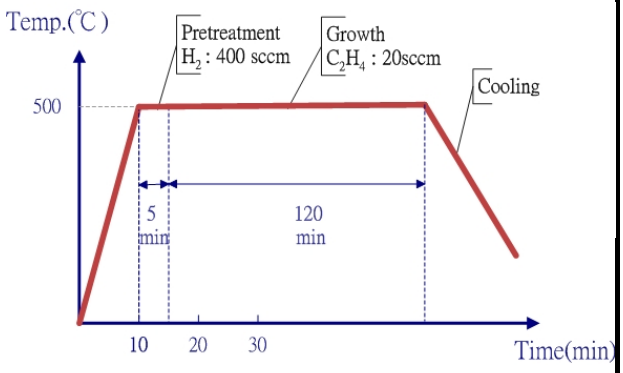
Item	Process Temp.	Catalysts	CNTs Synthesis Diagram
G	500	SiO_2 1 um	
		FeC 50 Å (95.7:4.3)	
H	500	SiO_2 5000 Å	
		FeC 50 Å (95.7:4.3)	

Table 3-4 Characteristics of PD200 and soda-lime glass

Characteristics of PD200/AS			
Item		PD200	AS Soda-lime glass
Thermal Properties	Thermal Expansion Coefficient (10^{-7}/℃)	83	87
	Strain Point (℃)	570	511
	Softening Point (℃)	830	735
	Annealing Point (℃)	620	564
Mechanical Properties	Density (g/cm^3)	2.77	2.49
	Young's Module (Kg/mm^2)	7800	7300
	Shear Module (Kg/mm^2)	3200	3000
	Poisson's Ratio	0.21	0.21
Electrical Properties	Bulk Resistivity at 150 ℃ logρ(Ω・cm)	12	8.5
	Dielectric Constant at 1 MHz	7.8	7.6
Optical Properties	Refractive Index N_D	1.55	1.52

Table 3-5 Process of Experiment I

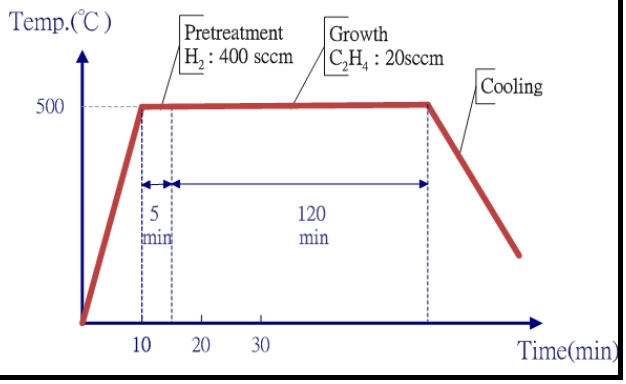
Item	Process Temp.	Catalysts	CNTs Synthesis Diagram
I	500	NiPd 50 Å (2:3)	

Table 4-1 Turn-on field (V/um) of CNT emitters

Catalyst / Item	Fe	Ni	FeNi	NiPd	FeC
A	2.05	3.4	3.56	4.84	3.85
B	3.32	2.83	4.47	4.9	4.69
D	NA	5.2	NA	3.4	4.37
E	NA	NA	NA	3.7	4.7
I				3.07	
F	Ni	NiPd(21)	NiPd(60)	NiPd(84)	NiPd(92)
	5.2	5.38	3.4	4.2	6.6

Table 4-2 Current density (mA/cm^2) of CNT emitters at 6V/um (Experiment A, B, D, E, F) and 3.75 V/um (Experiment I)

Catalyst / Item	Fe	Ni	FeNi	NiPd	FeC
A	58.8	23.3	62.1	26	16.2
B	5	12.1	1.37	2.1	0.39
D	NA	0.12	NA	34.3	1.02
E	NA	NA	NA	152.3	0.99
I				0.16	
F	Ni	NiPd(21)	NiPd(60)	NiPd(84)	NiPd(92)
	0.12	0.17	34.3	1	0.002