Chapter 5

Field Emission Improvement from Pillar Array of Aligned Carbon Nanotubes

Ultra low turn-on field of 1V/μm, ultra low threshold field of 2.9 V/μm and ultra high field emission current density of 692 mA/cm^2 at 7 V/μm are achieved from an pillar array of aligned carbon nanotubes, which grown on a Fe(5nm)/Ti(50nm) coated Si substrate by atmospheric pressure thermal chemical vapor deposition. Adjusting the ratio of distance between neighboring pillars (R) to the pillar height (H) to R/H=1/3 and 2.3, both of their field emission characteristics can be effectively enhanced. The best field emission characteristics listed above can be achieved when R/H is adjusted to 1/3. The obtained turn-on field and threshold field is about 1/3 times lower than the values that have been reported.

5.1 Introduction

Electron field emission from carbon nanotubes (CNTs) have attracted a great deal of intense academic and commercial interest since the first discovery of CNTs by Iijima in 1991[5.1], and is related to the fabrication of field emission displays. It is indispensable to reduce the turn-on field and threshold field to achieve practically applicable field electron emitters that operate at lower power consumption. It has been reported that field emission can effectively enhanced for aligned CNTs as field emitters when the ratio of distance between neighboring nanotubes to the height of each individual CNT is about 2 [5.2]. However, the optimum rule(R/H=2) for CNTs as electron field emitters has not been realized.

In this paper, we have grown pillar array of aligned carbon nanotubes by changing the process parameters and succeeded in fabricating the ratio of inter-pillar distance (R) to pillar height (H) to be 1/3 and 2.3. Each pillar with R/H ratio of 2.3 and 1/3 are composed of CNTs with a high density of approximately 10^9 cm^{-2}. The obtained field emission characteristics with the pillar array of CNTs of different R/H ratios are showed to be effectively enhanced and ultra low threshold field and ultra high field emission current density can be achieved.

5.2 Experimental Procedures

In this study, the fabrication procedures of CNTs are listed as below. A 1 μm-thick photoresist is spin-coated on an n-type Si (100) substrate and patterns of square cells with an emission area 25×10^{-4} cm^2 are fabricated by photolithography. Then Fe (5nm)/Ti (50nm) multilayer catalyst are subsequently deposited on the photoresist patterned Si substrate by electron beam evaporation system. Afterward, the patterned film is formed by the lift-off method. Finally, CNTs are grown selectively on the iron layers by the atmospheric pressure thermal chemical vapor deposition.

Samples are placed horizontal up into the reactor at about 400°C, and then be heated to 700°C at 100°C/min in pure N_2 with the flow rate at 1000 sccm. N_2/H_2 mixture gases are fed into the furnace to pre-treat the catalytic film with the same gas flow rate at 500sccm. For the case of pillar arrays of longer CNTs, the pre-treatment time is 20min and the flow rates of reaction gases are C_2H_4(20)/ N_2(500). For the case of pillar arrays of shorter CNTs, the pre-treatment time is 10min and the flow rates of reaction gases are C_2H_4(20)/ N_2(500)/H_2(500).The gas pressure is held at about 1 atm and the growth time is 10 min. The field emission tests are measured in a parallel plate diode configuration at room temperature in vacuum of ~ 5×10^{-6} Torr. The spacer between the anode and CNTs cathode is approximately 120 μm and the emitting area is $25x10^{-4}$ cm^2. The field emission current is measured as a function of the anode voltage.

5.3 Results and Discussion

Figures5-1(a) and 5-1(b) show low magnification SEM images of pillars of CNTs with R/H ratio of 1/3. Figures5-1(c) and 5-1(d) show cross sectional views of different magnification. The pillar is aligned perpendicular to the substrate surface and consists of CNTs with a number density of 10^9 cm^{-2}. The pillar height (H) is about 30μm and the distance between pillars (R) is 10μm. Each pillar can be regarded as an individual emitter since the electron field emission can be neglected inside the pillar due to the field screening effect. Figures5-2(a) and 5-2(b) show low magnification SEM images of pillars of CNTs with R/H ratio of about 2.3. Figure 5-2(c) shows SEM cross sectional view. The pillar is aligned perpendicular to the substrate surface and consists of CNTs with a number density of 10^9 cm^{-2}. The pillar height (H) was about 4.3μm and the distance between inter-pillars was 10μm.

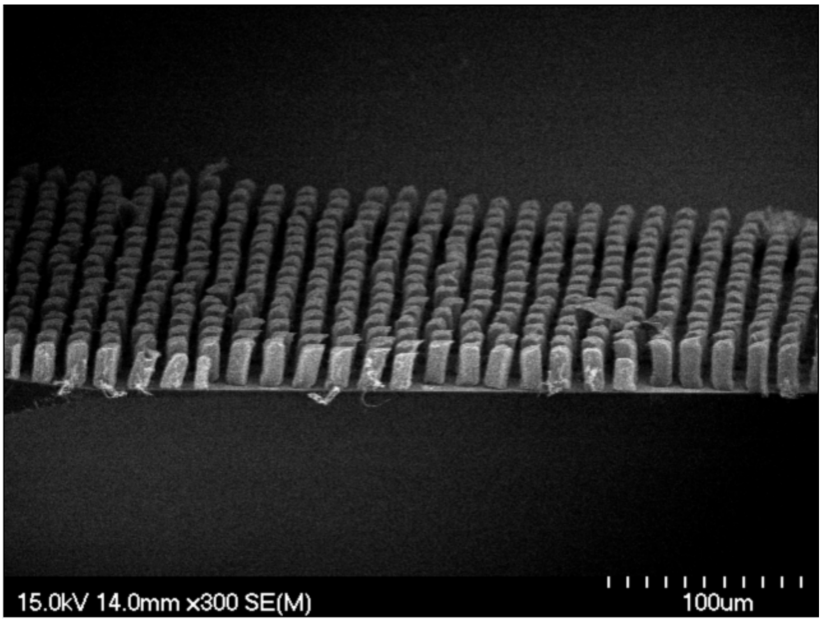
Figure 5.3 shows the field-emission characteristics from pillar arrays of aligned CNTs with R/H ratio of 2.3. The corresponding Fowler-Nordheim plots are shown in Fig. 5-3(b) and the linearity of the F-N plot confirmed the field-emission phenomenon. The turn-on field, which is defined as the field when F-N plot becomes linear, is 1.9V/μm. The threshold field, which is defined as the field when field emission current density reaches 10mA/cm^2, is 3.9 V/μm. The field emission current density achieved 163mA/cm^2 at 6.6 V/μm. The field enhancement factor β of the FN equation was estimated to be approximately 8700 by setting the work function to be 5eV.

Figure 5.4 shows the field-emission characteristics from pillar arrays of aligned CNTs with R/H ratio of 1/3. The corresponding Fowler-Nordheim plots are shown in Fig. 5-4(b) and the linearity of the F-N plot confirmed the field-emission phenomenon. The turn-on field, which is defined as the field when F-N plot becomes linear, is 1V/μm. The threshold field, which is defined as the field when field emission current density reaches 10mA/cm^2, is 2.9 V/μm. The obtained turn-on field and threshold field is about 1/3 times lower than the values that have been reported [5.3-5.7]. Besides, the ultra high field emission current density of 692mA/cm^2 at 7 V/μm is also the best value that has been reported. The field enhancement factor β of the FN equation was estimated to be approximately 25000 by setting the work function to be 5eV. The reason of the very good field emission characteristic of pillar like CNTs arrays is probably due to that we envision the CNTs on the periphery of the pillar effect a dominant electric field concentration on their tops, acting as a major emission sites.

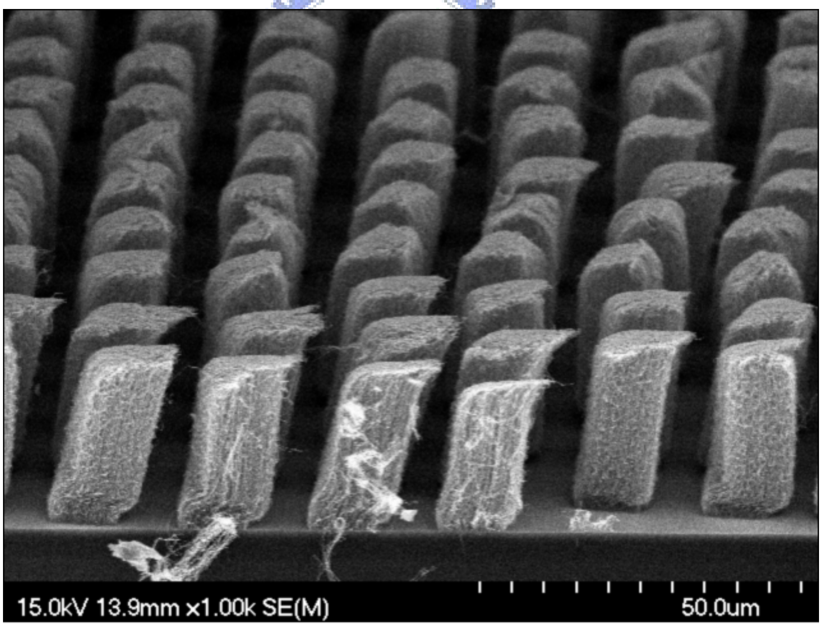
We regarded each pillar of CNTs as individual field emitter and tried to realize the optimal R/H ratio of 2 in order to obtain highly field emission enhancement. In this study, we adjust R/H ratio to be 1/3 and 2.3. However, we achieved better field emission characteristics when R/H ratio was 1/3. Further research on the field emission characteristics of pillar arrays of CNTs is needed.

5.4 Conclusions

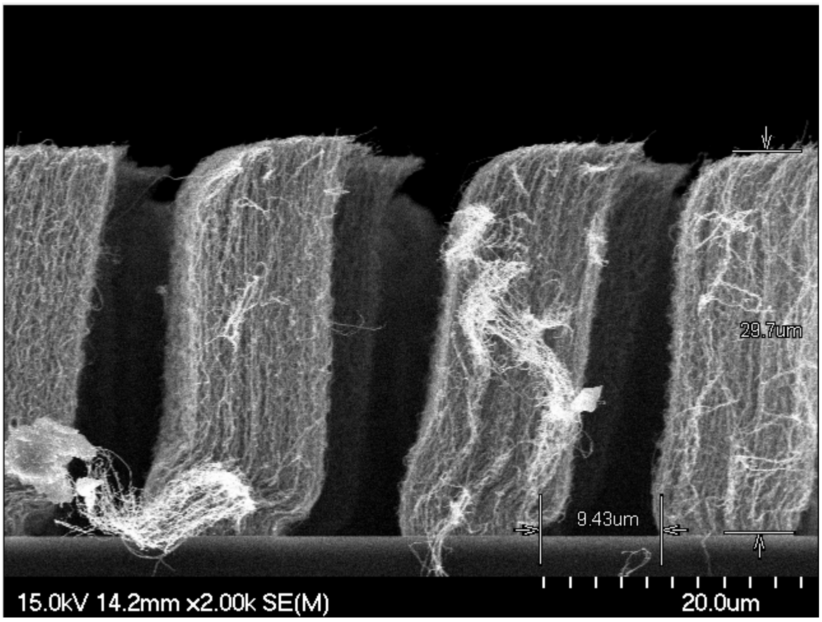
Pillar array of CNTs can be regarded as individual field emitter and adjust the R/H ratios to 2.3 and 1/3 to investigate their field emission characteristics is studied in this paper. Ultra low turn-on field of 1V/μm, ultra low threshold field of 2.9 V/μm and ultra high field emission current density of 692 mA/cm^2 at 7 V/μm are achieved from an array of pillars of aligned carbon nanotubes with R/H ratio of 1/3. The obtained turn-on field and threshold field is about 1/3 times lower than the values that have been reported.



(a)



(b)



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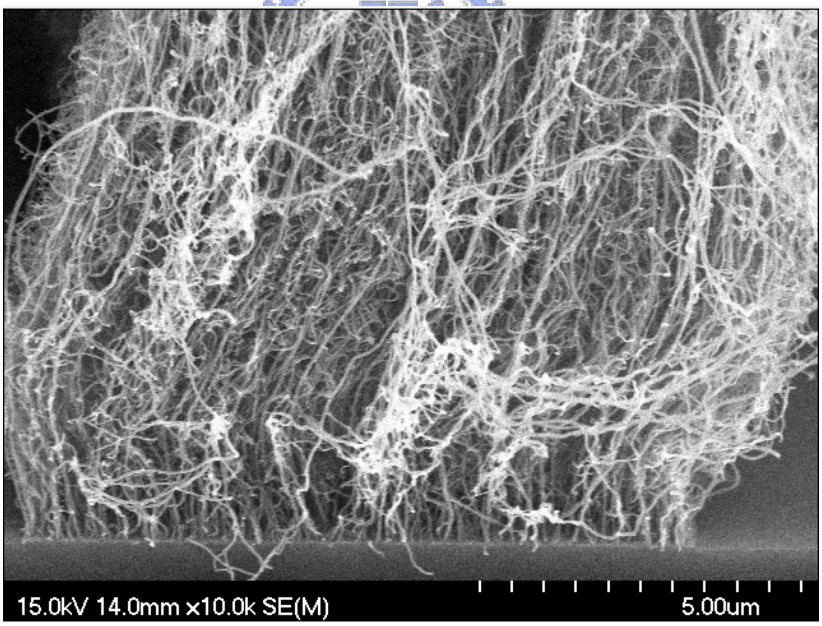
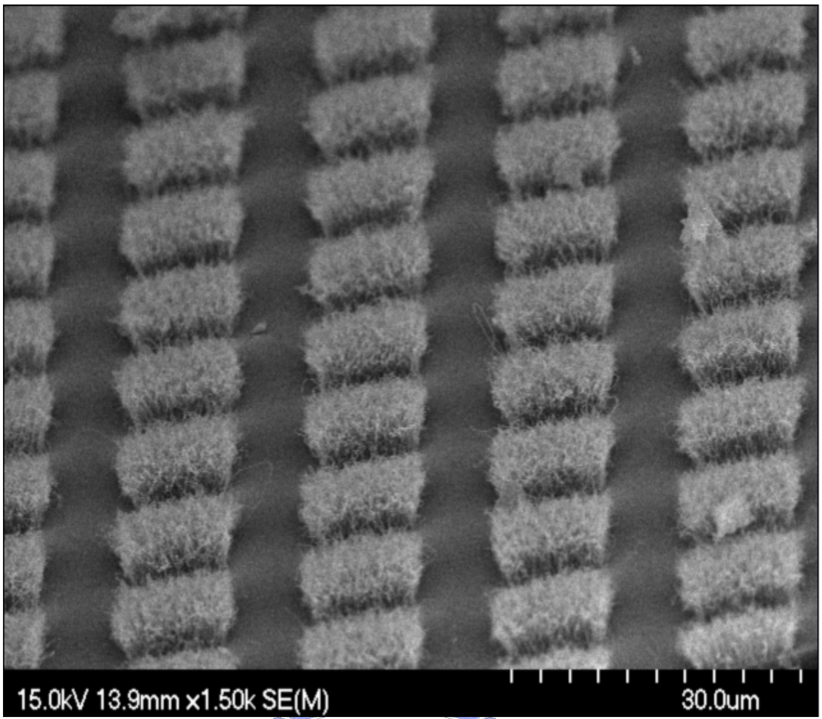
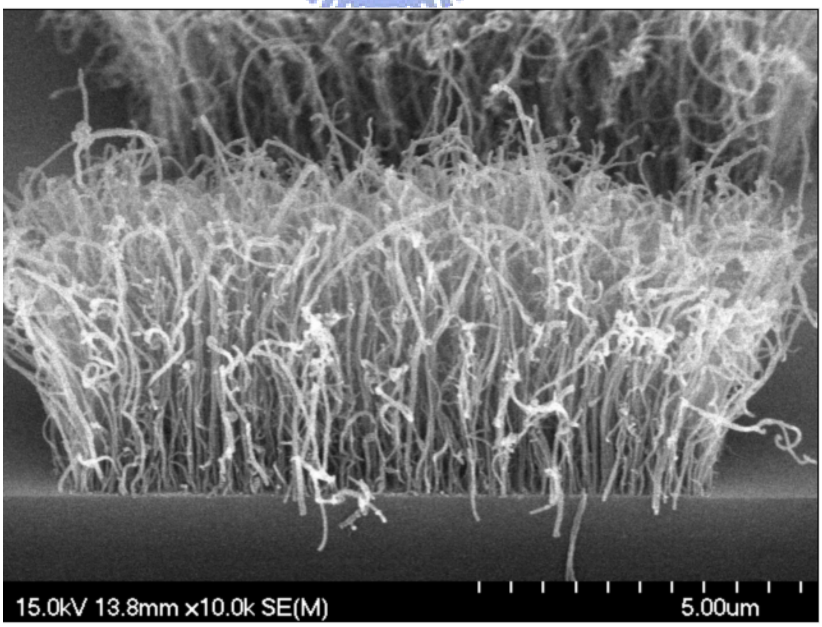


(d)

Figure5-1 SEM images of pillars of CNTs with R/H ratio of 1/3. (a) and (b) show low magnification view, and (c) and (d) cross-sectional views of different magnification.



(a)



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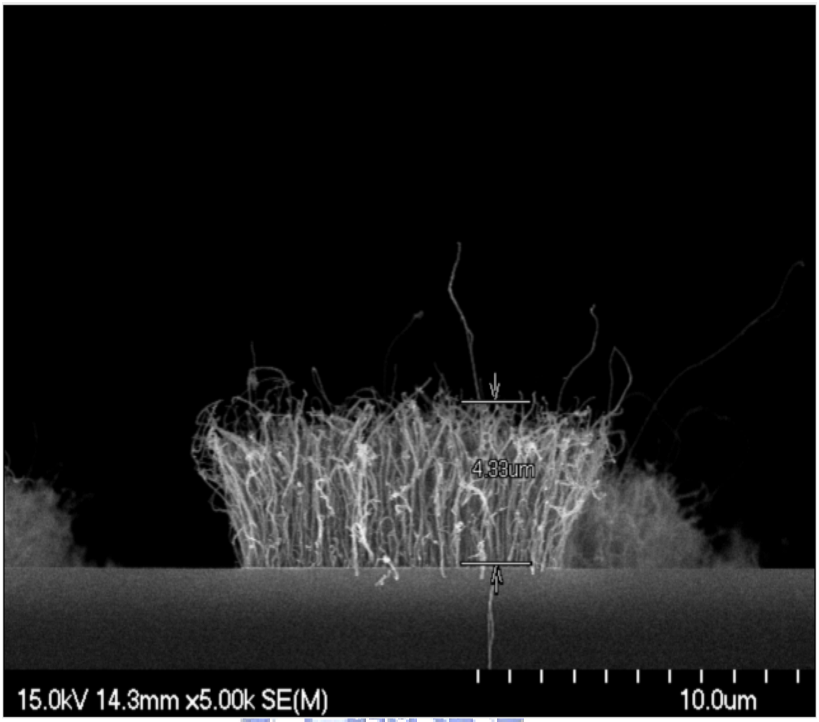
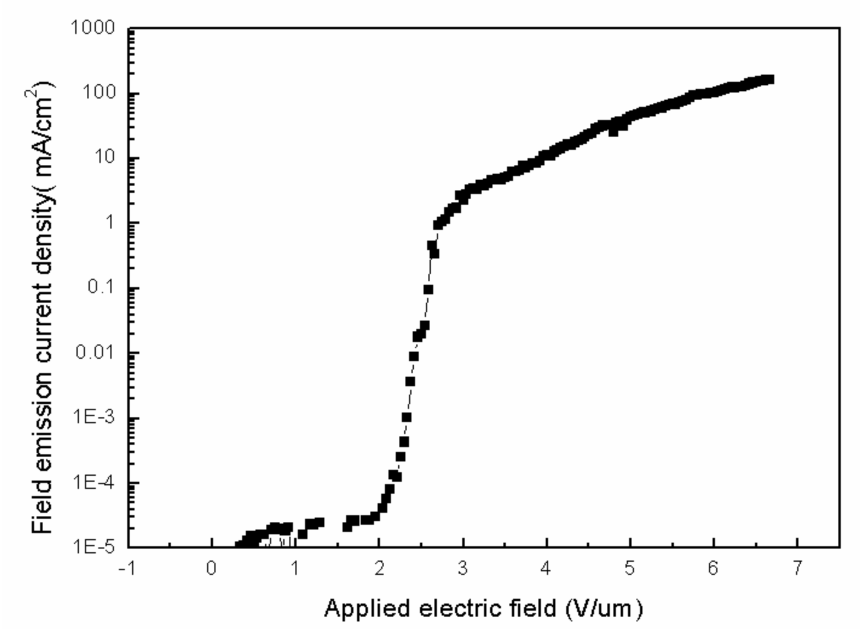
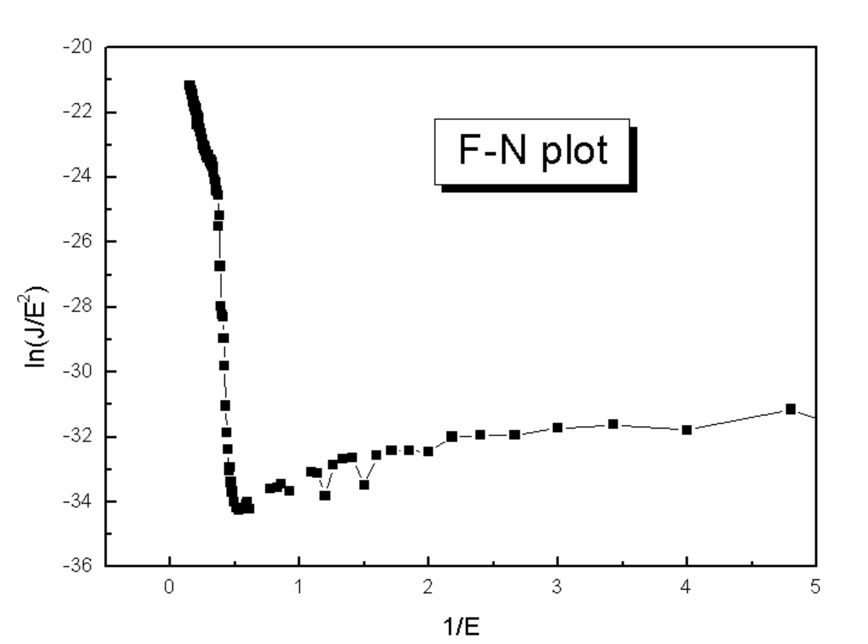


(c)

Figure5-2 SEM images of pillars of CNTs with R/H ratio of 2. (a) and (b) show low magnification views. (c) cross-sectional view



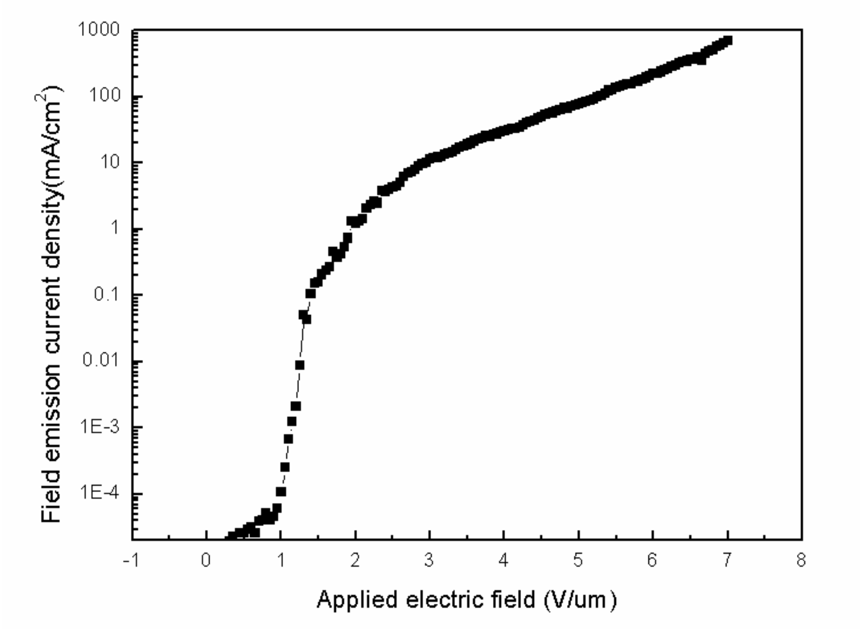
(a)



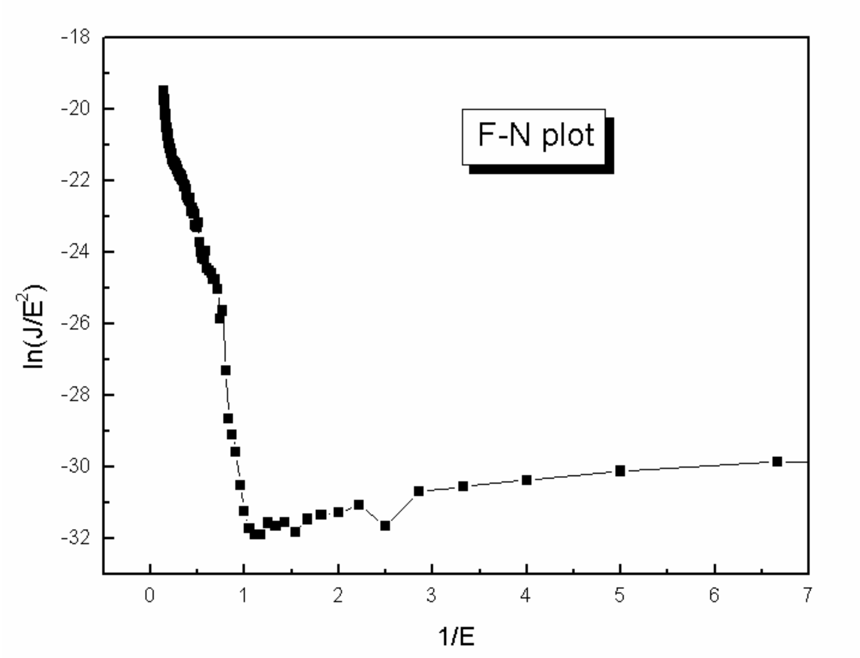
(b)

Figure5-3 Field emission characteristics of pillars of CNTs with R/H ratio of 2.3.

(a) Field-emission current density vs applied field. (b) Corresponding F-N plot.



(a)



(b)

Figure5-4 Field emission properties of pillars of CNTs with R/H ratio of 1/3. (a) Field-emission current density vs applied field. (b) Corresponding F-N plot.