Electron field emission characteristics of carbon nanotube on tungsten tip

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Abstract. Electron field emission characteristic of carbon nanotubes on tungsten tip was investigated in 2x10⁻⁶ Torr vacuum. The measurement results showed that the CNTs/W tip could emit electron at 0.7 V/µm (nearly 10 times lower than that of the W tip itself) and reach up to 26 µA at the electric field of 1 V/µm. The emission characteristic follows the Fowler-Nordheim mechanism. Analysis of the emission characteristic showed that the CNTs/W tip has a very high value of field enhancement factor ($\beta = 4.1 \times 10^4 cm^{-1}$) that is much higher than that of the tungsten tip itself. The results confirmed the excellent field emission behavior of the CNTs materials and the CNTs/W tip is a prospective candidate for advanced electron field emitter.

Keywords: Field emission, Schottky emission, CNT, electron sources.

1. Introduction
Carbon nanotubes (CNTs) have attracted much attention as an electron source because of their ultra-small radius, high aspect ratio and remarkably high electrical conductivity [1, 2]. They can be applied to the cathodes of a flat-panel display, cathode-ray-tube lighting elements, and as field-emission sources in modern electron microscopies [3-5]. In high-resolution electron microscopy applications, CNTs offer several advantages such as enhanced current stability, low threshold voltage and long lifetime. Continuous progress in the semiconductor industry, nanotechnology requires significant enhancement in the resolution and progressing speed of currently available electron sources [6, 7]. These needs can be met by improving the performance of cold electron emitters with the aid of CNTs.

Furthermore, because of high mechanical strength and chemical characteristic, CNT is considered to be the ideal tip for scanning probe microscopy (SPM) application such as atomic force microscopy (AFM) and scanning tunneling microscopy (STM) [8]. A CNT tip for SPM offers important advantages over the conventional metal tips by virtue of high-lateral-resolution imaging, tracing of rough surfaces with steep and deep feature, preventing the multi-tip effect and reducing damage to delicate samples. Moreover, in electrical resistance measurements, the CNT tips are expected to measure electrical resistance of nanostructure materials. Conventionally metal tips such as W or Pt/Ir are not suitable for measuring electrical resistance of nanostructure materials of sizes below 100 nm.
This is because a radius of curvature of electrochemically etched metal tip is usually larger than 50 nm. In case of the AFM application, the CNT tip has already proven above-mentioned advantages [9, 10]. The CNT for AFM is well established and is now commercially available.

Various techniques to fabricate CNT tips for atomic force microscopy have developed recently. For example, CNT tips prepared by mechanical assembly under optical microscopy or scanning electron microscopy (SEM) were shown to enhance the spatial resolution of the AFM [11, 12]. Recently, Konishi et al. [13] have announced that they could synthesize conductive CNT tips in high-yield in the following way: a) attaching a CNT at the apex of a supporting W tip by a dielectrophoresis method, b) deposition of amorphous hydrocarbon around the junction portion between the CNT and the W tip by electron beam deposition (EBD), c) annealing of the tip at 500°C, and d) coating the surface of the tip with a Pt/Ir layer by pulsed laser deposition (PLD). This method not only reduces the contact resistance at the junction between the CNT and the supporting W tip but also enhances the sticky ability of the CNT on the W tip. However, this method is expensive and requires a complex experimental setup.

For fabricating CNT in high production yield, high density and low cost, CVD is the most suitable method [14]. CNT fabricated by CVD using support catalyst is ideal for field emission, sensors, and other applications requiring the growth on patterned substrate. In this work, we use CVD method to fabricate CNTs/W tip by directly growing the CNT on the apex of the sharpened tungsten tip. Detailed process of fabrication of the CNTs/W tip was presented in Ref. [15]. In this paper we present the result of electron field emission characteristics of the fabricated CNTs/W tip.

2. Experimental

CNTs were directly grown on a sharp tungsten tip using CVD method. At first, tungsten tip of sub-50 nm in diameter was formed by electrochemically etching in a KOH 5 wt.% solution. In order to grow CNT on the sharp tungsten tip, Fe nanograins were created at the apex of the W tip by using electroplating in one circle of 20 Hz pulse mode in FeCl3 0.01 wt.%. solution. CNT was then grown from the Fe nanograins on the sharp W tip using hot-filament CVD apparatus. During the growing process, the temperature in CVD chamber was 750°C, feedstock gas was a mixture of (C2H2 : H2, 50 sccm : 600 sccm) gases and CVD process took place in 30 minutes. In order to enhance the alignment and support the individual CNT formation, a DC electric field was applied between the W tip and the electrode with an electric field of approximately 8.10^4 V/m. To measure the electron field emission characteristic of the CNTs/W tip we used the emission measurement system as shown in figure 1. The set-up consists of a vacuum chamber having cathode to hold emitter tip in vertical position. Anode was used to collect the electron emission and connected to the computerized Keithley-248 source and Keithley-2001 measurement units. The gap between anode and cathode can be manually controlled. The measurement was carried out at pressures of 2x10^-6 Torr at room temperature.

3. Results and discussion

Figure 2 shows SEM image of the sharp tungsten tip after electrochemical etching from a commercial W wire of 0.3 mm diameter. The diameter at the apex of the tip was approximately 50 nm. We found that the diameter of the tip played a critical role for growing the CNTs. If the W tip is too sharp (less than 20 nm) it is not easy to create individual Fe nanograin catalyst by electroplating method. Therefore, probability of growth of CNT is difficult. Inversely, if the W tip is too obtuse (more than 1 µm) many Fe nanograin catalysts are created. Consequently, several CNTs will be grown at the top of the tip. Besides, to evaluate the quality of the electrochemically etched W tip, we estimated the diameter of the commercial STM tip by observing SEM image. Figure 3 shows SEM image of the Pt/Ir STM tip of Agilent Technology Company. From figures 2 and 3, it is clearly seen that the diameter at the apex of our W tip is nearly 10 times smaller than the diameter at the apex of the commercial Pt/Ir STM tip.
By CVD method, CNTs were grown successfully on the apex of tungsten tip as shown in figures 4 and 5. Using measurement system as shown in figure 1, the electron field emission characteristics of the W and CNTs/W tips were characterized. This measurement system enables us to investigate the $I-V$ characteristic of mentioned emitters. Figure 6 is the total electron emission current from the bundle CNTs/W tip and W tip when applying voltage to the anode. As shows in figure 6, the CNTs/W tip started emitting electron at 0.7 V/µm and rising up to 26 µA at the electric field of 1 V/µm. Whereas the W tip could emit electron at 5.8 V/µm and only reach to 13 µA at the electric field 6.3 V/µm. Thus, the CNTs/W tip could emit electron at threshold voltage nearly 10 times lower than that of the W tip itself. The threshold voltage is defined as the voltage at which the emission current starts increasing.
from the baseline. These results indicate that the CNTs/W tip shows a better performance as electron field emitter. From Fowler-Nordheim theory, the emission current $I$ can be expressed in a simplified form [16, 17]

$$I = 1.54 \times 10^{-6} \frac{S \beta^2}{\phi} V^2 \exp(-6.83 \times 10^7 \frac{\phi^{3/2}}{\beta V}) . \quad (1)$$

Here, the emission current $I$ and the applied voltage $V$ are expressed in A and V, respectively. The work function $\phi$ is expressed in eV and the emitting area $S$ is expressed in cm$^2$. The field enhancement factor $\beta$ corresponds to the geometry shape of the emitter, and is inversely proportional to the diameter of the emitting tip. By rearranging equation (1), we obtain:

$$\ln(I/V^2) = A(1/V) + B , \quad (2)$$

where $A = -6.83 \times 10^7 \phi^{1.5} / \beta$ and $B = \ln(1.54 \times 10^{-6} S \beta^2 / \phi)$.

![Figure 6. Electron emission current as a function of anode voltage from CNTs/W tip and W tip.](image)

![Figure 7. Fowler-Nordheim plots of I-V curves in figure 6.](image)

The corresponding Fowler-Nordheim plots and the values of field enhancement factor $\beta$ are shown in figure 7. By adopting work functions of tungsten and CNTs of 4.55 and 5.0 eV, respectively, the field enhancement factor were determined to be $0.89 \times 10^4$ cm$^{-1}$ and $4.1 \times 10^4$ cm$^{-1}$ for W tip and CNT/W tip, respectively. The field enhancement factor for CNT/W tip was 5-times larger than that of
the W tip.

The results confirmed the excellent field emission behavior of the CNTs materials and the CNTs/W tip is a prospective candidate for the advanced electron field emitter. Although the electron emission characteristic of individual CNT/W tip was not done in this time, according to recent papers, individual CNT tip had lower threshold voltage, the field enhancement factor higher than the bundle CNT tip [18]. The emission on individual CNT/W tip will be done the next time for our further work. The CNTs/W tip was also successfully applied as an advanced STM tip. The result will be presented elsewhere.

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