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# Electron Field Emission with Carbon Nanotube on a Si Tip

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## 1. Introduction

Carbon nanotubes (CNTs) were recognized as an excellent material for electron emission and would be a good candidate for applications in flat panel displays, electron guns, etc. because of their low threshold voltage, long term stability, nanometer scales size, high mechanical stiffness, chemical inertness as well as electrical conductivity. Especially, in many applications where a focused electron beam is needed, the utilizing of an individual CNT is very useful because the individual CNT can emit electrons as a pointed source with small size, small energy spread, high current density. Since electrons can be emitted from a point source, it is possible to focus the beam into a small spot that is very essential for applications in such as electron beam lithography. Beside studying of other potential applications, recently, many researches have been carrying out to explore the electron emission application potential of the CNTs [eg. 1-2]. To our knowledge, utilizing and batch-production of the individual CNT on a tip is still a critical problem that should be sold. In this letter we present the results of synthesis and emission characterization of a single CNT on a sharp Si tip for emission application that is based on the microfabrication and hot-filament chemical vapor deposition (HF-CVD).

## 2. Fabrication of Si tip and synthesis of individual CNT at the apex of the tip

We have fabricated Si tips with a very sharp apex and a high aspect ratio for growing of single CNT at the tip end. The fabrication process is shown in Fig. 1. We used (100)-oriented, phosphor doped Si wafer with resistivity of 1-10 Ωcm as a starting material (step a). Firstly, Si columns with 5 μm diameter and 4 μm height are formed by an anisotropic etching in a $SF_6$ plasma (step b). Using $SiO_2$ caps as masks, Si tips are formed by isotropic etching the Si in a tetramethyl ammonium hydroxide (TMAH) (step c). The etching process in the TMAH was controlled so that there are still $SiO_2$ caps at the top of the tips. Using these $SiO_2$ caps as masks, a second anisotropic etching in the $SF_6$ plasma was done again to increase the height of the Si columns (step d). The substrate is consecutively etched in the TMAH until forming Si sharp tips with Si column with high aspec ratio (step e). To growth the CNT at the apex of the tip, an approximately 4-5 nm catalytic Fe film is entirely deposited by sputtering on the substrate and the CNT growing is done in a hot-filament chemical vapor deposition (HF-CVD) (step f). The conditions for the growing were

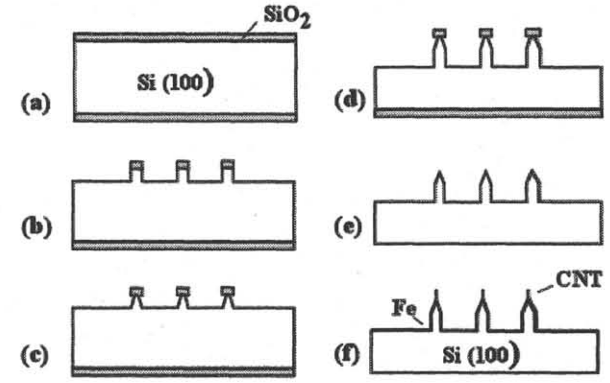


Fig. 1 Fabrication procedure

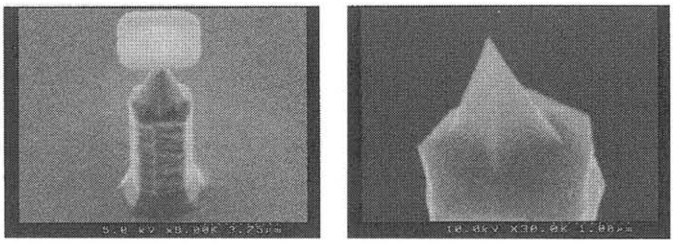

Fig. 2 (a) SEM image of the fabricated Si tip before removing the $SiO_2$ cap; (b) Close up of the Si tip.

identical to that of the Ref. 3. Briefly, the temperature of a Tungsten filament was 1900°C, which is measured by a Pyrometer. The sample is set under the filament with a distance of about 7 mm. The chamber is evacuated to a back pressure of $10^{-3}$ Pa with a turbo molecular pump. $C_2H_2$ and $H_2$ gases are introduced into the chamber with partial pressures of 3 Pa and 30 Pa, respectively. A negative voltage of 300 V was applied to the substrate and the filament is connected to the ground that corresponds to an electric field of $5x10^4$V/m. The growing was done for 10 mins.

Figure 2 shows the SEM images of the fabricated Si-tip before and after removing the $SiO_2$ cap. Diameter at the apex of the tip of about 20 nm and the tip height including Si column of 5 μm was estimated from the SEM images. With the described conditions of HF-CVD, an individual CNT was successfully grown at the apex of the Si tip. An array of 10x10 Si tips was used for the CNT growing and more than 15% of the Si tips were successfully grown with the single CNT. Mostly, the CNT was well aligned in the vertical direction of the wafer according to the applied

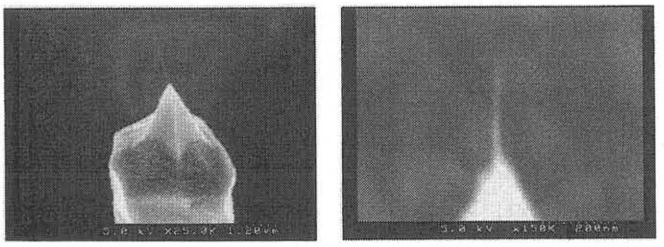

Fig. 3 (a) Typical SEM image of the fabricated Si tip with single carbon nanotube at the apex of the tip. (b) Close up of the well-aligned CNT at the Si tip.

electric field between the filament and the substrate. Some bent CNTs were grown at the apex of the tip. Figure 3a shows typical SEM image of the bent single CNT on the Si tip. A close up of a well-aligned CNT at the Si tip is shown in Fig. 3b. The length and the diameter of the CNT were about 300-400 nm and 15-20 nm, respectively. The exact explanation for the bending of the CNT may be quite complicated and that is not fully discussed in this paper.

## 3. Field emission characterization of individual CNT at the apex of the Si tip

The emission characteristics of the fabricated Si tips with and without CNT on the same substrate were measured in a vacuum chamber with a pressure of $1.7 \times 10^{-4}$ Pa. The substrate is placed on a Cu cathode using a thin Ag paste as a conductively adhesive layer. A moveable micro probe with about 20 μm diameter at the apex was used as an anode electrode. The position of the anode is adjusted using an X, Y, Z positioner from the outside of the chamber under a charge-couple device (CCD) camera. The resolution of the micrometer positioner is less than 5 μm. A Hewlett Packard HP-4155A unit was used to supply a biasing and to monitor the emission current. Firstly, the initial position of the probe is defined by approaching the probe to the flat Si floor of the substrate until appearing a current. The probe is next moved up by 15 μm-distance in z-direction from the ground floor. The probe is next moved to the nearest single Si tip without CNT by adjusting the micrometer in X, Y directions. Since the height of the Si tip was 5 μm, the probe-Si tip distance of 10 μm was addressed. A plot of the emission current versus the applied voltage of the single Si and single CNT/Si tips at 10 μm probe-tip distance is shown in Fig. 4. It can be seen that the emission current of the single Si tip without CNT was started at a voltage of around 200 V. The probe is next moved to the single CNT/Si tip by adjusting the micrometer in X, Y directions without touching the micrometer in Z direction under the CCD observation. Obviously, there was a slight difference between the probe-tip distance of the Si and the CNT/Si tips because of the length of the CNT. However, this difference could be considered as an error of the micrometer and was negligible. The emission current of the CNT/Si tip was appeared at a very low voltage (about 40 V). With the probe-tip distance of 10 μm, the threshold voltage of 4 V/μm and 20 V/μm was evaluated for the CNT/Si and Si tips, respectively.

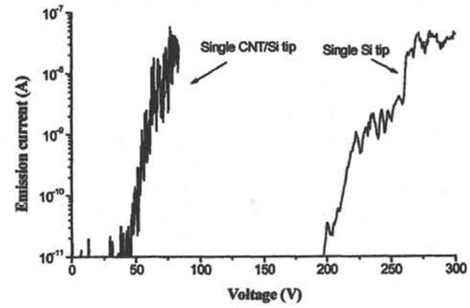


Fig. 4 Electron field emission as a function of applied voltage of individual Si and CNT/Si tips.

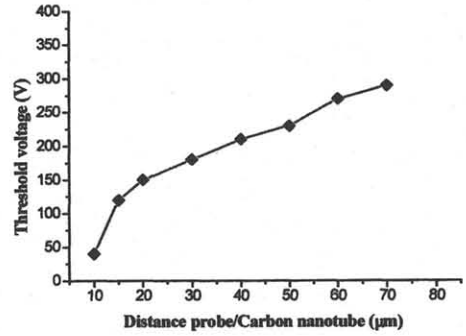


Fig. 5 Threshold voltage as a function of probe-tip distance of the single CNT/Si tip.

By adjusting the probe-tip distance, the threshold voltage of the single CNT/Si tip is increased as shown in Fig. 5.

What we want to mention in this paper is that individual CNT can be selectively grown at the apex of a sharp Si tip by utilizing an electrical field enhancement. The structure and its array could be batch-fabricated with the Si microfabrication and the HF-CVD growing processes. The single CNT on the Si tip exhibited a threshold voltage of 4 V/μm that is 5 times lower than that of the single Si tip without the CNT. This structure is very promising for multi electron beam lithography applications.

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