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# Nanotube Encoders

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**Abstract.** Linear encoders for nanoscale position sensing based on vertical arrays of single multi-walled carbon nanotubes (MWNTs) are investigated from experimental, theoretical, and design perspectives. Vertically aligned single MWNTs are realized using a combination of e-beam lithography and plasma-enhanced chemical vapor deposition (PECVD) growth. Field emission properties of the array are investigated inside a scanning electron microscope (SEM) equipped with a 3-DOF nanorobotic manipulator with nanometer resolution functioning as a scanning anode. Lateral position of the scanning anode is sensed from the emission distribution. High resolution (best: 12.9 nm; practical: 38.0 nm) for lateral position sensing around an emitter has been realized.

## Introduction

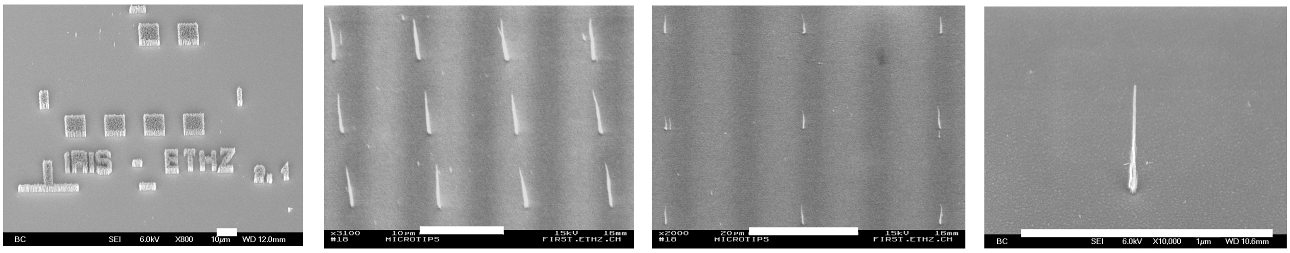
In electric servomotors, encoders play a significant role by providing precision angular or linear position sensing feedback. Similarly, with the development of nano machines [1, 2] nanometer-scale position sensing with nanometer-sized devices is required for their successful application.

To shrink the sizes of conventional optical encoders, different measurement principles must be considered. Although tunneling current and laser-deflection techniques can provide extremely high resolution, the effective distance of the former is less than 1 nm and the latter generally involves a complex laser apparatus. Another possible feedback mechanism is to use the interlayer resistance of a telescoping multi-walled carbon nanotube (MWNT) for position sensing. The potential for quantized interlayer conductance can result in resolutions at atomic lattice-levels [3]. On the other hand, the dependence of field emission currents on inter-electrode distance has shown promise for non-contact position sensing [4, 5]. Recent results with individual nanotube emitters and telescoping nanotubes have shown the feasibility of this method [2]. Moreover, the energy distribution around a field emitter [6, 7] is a potential technique for lateral position sensing.

Plasma-enhanced chemical vapor deposition (PECVD) has been successfully used for the growth of individual MWNTs from nickel catalyst nanodots defined by e-beam lithography [7]. In this paper, we present a nano encoder based on vertically aligned single MWNT emitters grown with this technique. Vertical and lateral position sensing are investigated from experimental, theoretical, and design perspectives.

## Directed Growth of Arrays of Single MWNTs

Vertically aligned MWNTs were realized using a combination of e-beam lithography and PECVD growth of MWNTs. Electron beam lithography was used to define 50-150 nm nickel catalyst dots at precise locations on a silicon chip. Next, vertically aligned nanotubes were grown by PECVD at Nanolab Inc, USA. Precise control of the position, density and alignment of the tubes has been achieved. Aligned nanotube arrays with spacing varying from 250 nm to 25 µm were realized. Fig. 1 shows vertically aligned MWNTs grown by this technique.

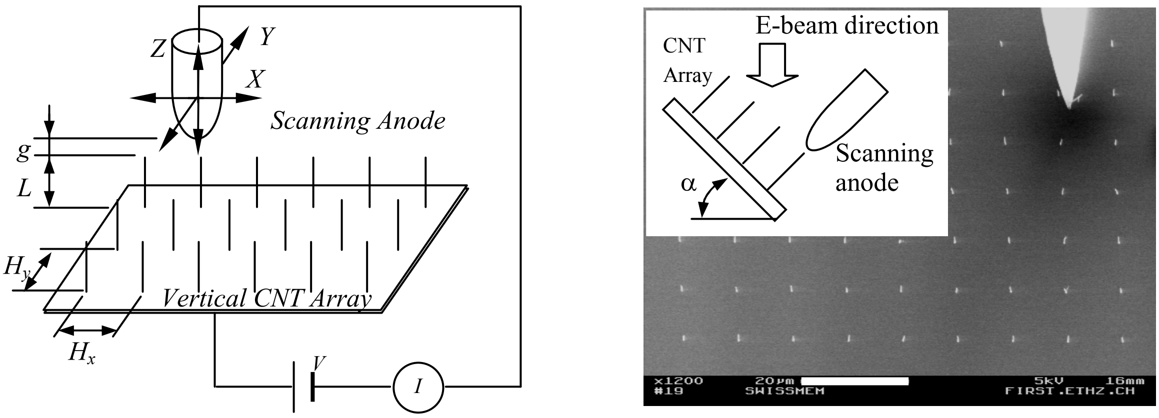



(a) (b) (c) (d)

Fig. 1. Single MWNT arrays. (a) 250 nm to 1 μm spacing (Insets show logos “IRIS” and “ETHZ” observed at a 45° tilt angle). (b) 10 μm spacing 3×4 array of single MWNTs. (c) 25 μm spacing 3×3 array of single MWNTs. (d) An individual tube in the array. (Scale bars: 10μm)

## Principle and Implementation of Nano Encoders

**Structure.** A single CNT array based nano encoder is designed as shown in Fig. 2. A scanning anode is placed on a moving body, and its position detected by monitoring the field emission current from the CNT emitter array.




(a) (b)

Fig. 2. Nano encoder consisting of a scanning anode field emission probe and a single nanotube array. (a) Structure. $L$ is the length of the tubes, $H_x$ and $H_y$ the spacing between tubes in $X$ and $Y$ direction, and $g$ the inter-electrode (anode probe-tube tip) distance. (b) SEM image of nano encoder (tilt angle for observation α=45° as shown in the inset).

**Vertical Position Setting.** Experimental research on CNT field emission demonstrated that nanotubes obey the Fowler-Nordheim (F-N) theory [8]. According to this theory, the emission current can be expressed as:

$$I = 1.54 \times 10^{-6} \frac{AL^2V^2}{G^2 r^2 \Phi} \exp\left( -6.79 \times 10^7 \frac{\Phi^{3/2} Gr}{VL} \right) \quad (1)$$

where, $I$ is the emission current [A], $V$ the applied voltage [V], $\Phi$ the work function of nanotube tip [eV], $r$ the tip radius of curvature [cm], $L$ the protruding length of emitter [cm], $G$ ($G$=$L$+$g$, $g$ the tip-anode distance) the inter-electrode distance [cm], $A$ the emission area [cm$^2$].

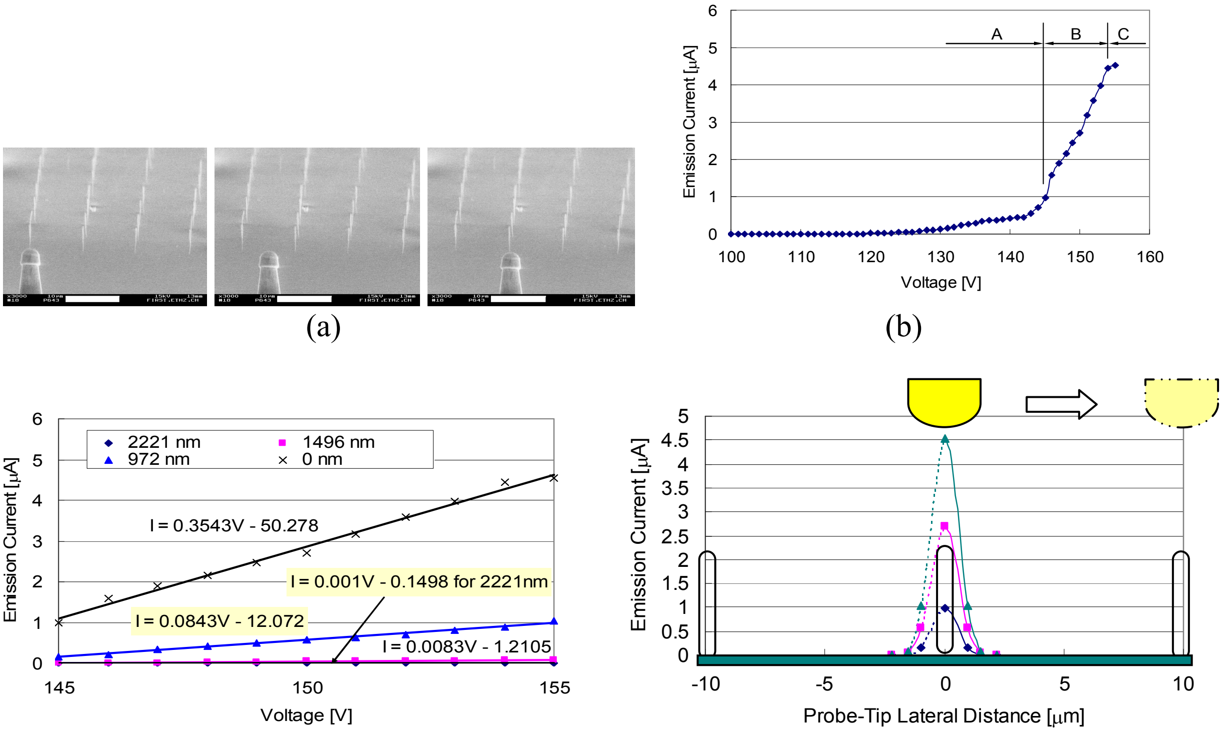
For lateral position sensing, the vertical position of the anode can be set to a value to obtain a lower working voltage while keeping a high signal/noise (S/N) ratio. Experiments in have shown that it is possible to sense the vertical position of the anode relative to the tip of nanotube emitter. A resolution of 100 nm has been demonstrated at room temperature inside $10^{-4}$Pa vacuum. The possibility of combining this technique with lateral position sensing exists.

**Lateral Position Sensing.** Simulation has shown that the field enhancement factor changes with emitter density, and current density is a function of the distance between nanotube emitters [9]. This suggests the possibility of detecting the lateral position of a scanning anode by monitoring the emission current.

However, the best lateral sensing resolution of the nano encoder cannot be realized by shortening the spacing between nanotubes, because it has been recognized that arrays of closely spaced nanotubes have lower field enhancement factors than sparse arrays due to field shielding [6]. The nanotube spacing distance $H$ and the nanotube height $L$ are critical to the field enhancement factor. When nanotubes are far apart, the field enhancement is strong, but the total number of emitters per unit area is low which reduces the emitted current. When nanotubes are close together they shield each other reducing the field enhancement factor. At $H/L \sim 2$, an optimal spacing is reached where the field is only minimally reduced by the neighboring nanotubes, and their numbers per unit area remain high. Therefore, to produce the most effective field emission cathodes we must create aligned, patterned arrays of nanotubes at controlled spacing.

**Scanning Anode Field Emission Probe.** A nanomanipulator (MM3A$^{TM}$ from Kleindiek) installed inside a scanning electron microscope (SEM) (Carl Zeiss DSM962) is used for the experiments. The manipulator has three degrees of freedom, and 5 nm, 3.5 nm, and 0.25 nm resolution in $X$, $Y$, and $Z$ directions at the tip (see Fig. 2 (a)), respectively. The manipulator is used to control the relevant position and orientation of a scanning anode to the emitter array fixed on the sample holder of the SEM. In the experiments, the manipulator and the Si substrate with nanotube array is configured as shown in Fig. 2 (b).

## Experiments and Discussions on Lateral Position Sensing




(a) (b) (c) (d)

Fig. 3. Lateral position sensing. (a) Configuration (Scale bars: 10 μm, tilt angle for observation α=75°). (b) I-V curve. (c) I-V curve at different probe-tip lateral distance. (d) Relationship between emission current and lateral distance under different bias with nearby tubes shown.

Lateral position sensing has been calibrated by the scanning anode actuated in the *X* direction of the manipulator (as shown in Fig. 3 (a)), which has a 5nm resolution. The anode probe is first aligned to the tube, and then moves towards the tube tip until a contact occurs. Resistance is measured to monitor the conductance. The probe is then moved away from the tube, and pulses are counted to determine the distance between the tip and the probe at higher resolutions than SEM micrographs provide. The manipulator is stopped at certain positions, and the emission current is measured by sweeping the voltage with a Keithly 6487 Picoammeter/Voltage Source (Resolution: 15 fA, Voltage output: 0-500 V). A typical I-V curve (probe-tip vertical distance: 330nm) is shown in Fig. 3 (b). The curve can be divided into three regions indicated as "*A*" (low current), "*B*" (high current), and "*C*" (saturated current). In general, the S/N ratio is small in "*A*", whereas saturated current will damage the emitter if working in region "*C*". Hence, a point around the middle of region "*B*" is a reasonable choice as operating point, which is about 150 V in Fig. 3 (b). I-V curves for the lateral distances being 0 nm, 972 nm, 1496 nm, and 2221 nm around this voltage are shown in Fig. 3 (c). The measurement was performed at room temperature in an SEM vacuum chamber (vacuum approximably $10^{-6}$ hPa). It can be found from Fig. 3 (d) that the current is a function of the lateral distance under a constant voltage. The resolution is mainly limited by thermal drift, external electric field and other factors. At 150 V resolution can be 38.0 nm by taking the current drift to be 1 nA, which is evaluated according to the measured current; much worse than the measurement system resolution (15 fA). Higher voltage brings about a higher resolution (e.g., the best resolution of 12.9 nm under 155V is achieved but risks damage due to saturation).

**Summary**

Single MWNT array based linear nano encoders have been investigated from experimental, theoretical, and design perspectives. Vertically aligned single MWNTs have been realized using a combination of e-beam lithography and PECVD growth. Electron beam lithography is used to define 50-150 nm nickel catalyst dots at precise locations on a silicon chip. Precise control of the position, density and alignment of the tubes has been achieved. Aligned nanotube arrays with spacing varying from 250 nm to 25 μm are realized. Field emission properties of the array are investigated using a scanning anode actuated with a 3-DOF nanorobotic manipulator with nanometer resolution inside an SEM. Lateral positions have been detected by monitoring the emission current change. High resolution (best: 12.9 nm; practical: 38.0 nm) for lateral position sensing around an emitter has been realized.

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