# Nanoelectronic Devices Constructed Using Individual Vertically Aligned Carbon Nanofibers

Xiaojing Yang[1,2], Derek Austin[1,3], Michael A. Guillorn[1,2], Vladimir I. Merkulov[1], Anatoli V. Melechko[1,3], Douglas H. Lowndes[4], and Michael L. Simpson [1-3]

[1]Molecular-Scale Engineering and Nanoscale Technologies Research Group, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831;
[2] Materials Science and Engineering Department, The University of Tennessee;
[3] Electrical and Computer Engineering Department, The University of Tennessee;
[4] Nanostructured and Thin-Film Materials Physics Group, Oak Ridge National Laboratory

## ABSTRACT

We have fabricated active nanoscale electronic devices based on Vertically Aligned Carbon Nanofiber (VACNF) in a way that will be practical for large-scale manufacturing using conventional fabrication technology. The VACNFs are synthesized in a high-density Plasma-Enhanced Chemical Vapor Deposition (PECVD) process that provides a high degree of control of the growth conditions and consequently, the resultant electronic properties. Rectifying devices containing metal-semiconductor (Schottky) junctions will be presented in this paper and we calculate the barrier height of about 300mV from the temperature sweep measurements. The VACNF devices can operate at current levels of ~ 100uA current without any sign of damage.

***Keywords***: Nanodevice, Vertically Aligned Carbon Nanofiber, Schottky junction, PECVD

## 1. SAMPLE PREPARATION

The development of nanoscale electronic (nanoelectronic) devices has recently become one of the most active fields of research in the physical sciences [1]. Numerous research groups have developed techniques that utilize carbon nanotubes and/or semiconductor nanowires to form logic devices from these nanoscale electronic components [2-4]. While these results are impressive, there is a large disconnect between these techniques and the practical implementation of nanoelectronics on a large scale. Essentially all approaches currently used for making electronic devices with carbon nanotubes and semiconductor nanowires either involves dispersing the ex-situ grown nanotubes or wires onto the electrode arrays or growing the nanotubes horizontally between electrodes. It is difficult to control those processes, thus losing good control of the resultant electrical properties of the devices.

In this paper we employ a method that allows us to fabricate devices on predetermined locations using standard large-scale fabrication techniques: lithography and plasma-enhanced CVD (PECVD). Controls of the location, length, tip diameter, shape and chemical composition of VACNF during the synthesis process have been demonstrated [5,6]. The integration of individual carbon nanofibers into field emission devices and active electrochemical probes has been demonstrated [11,12,13].

The fabrication process is illustrated in fig1.(a)-1(f).In fig1(a). We perform electron-beam lithography (EBL) to pattern catalyst sites for individual fiber growth and also the alignment marks for subsequent lithographic patterning. Following metallization of these patterns, PECVD growth of the VACNFs is performed. The details

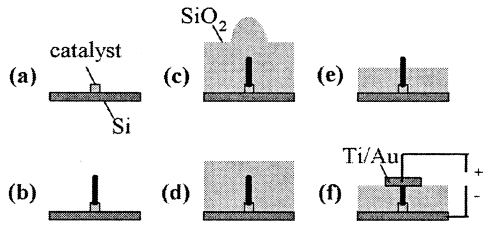
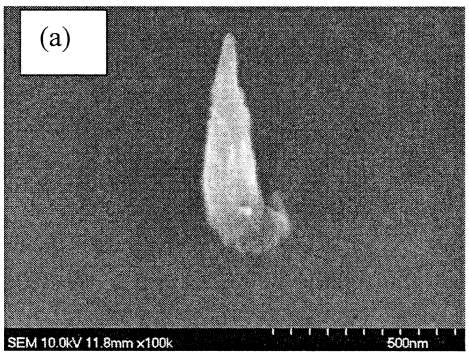
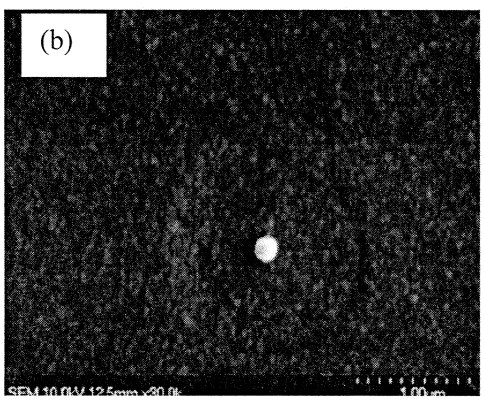



FIG.1 Sketched description of the fabrication process: (a) definition of fiber growth sites; (b) fiber growth; (c)deposition of conformal SiO2 layer; (d) Planarization by CMP; (e) RIE to uncover the nanofiber tips; (f) metallization with Ti/Au.

To whom correspondence should be addressed, email: simpsonML1@ornl.gov



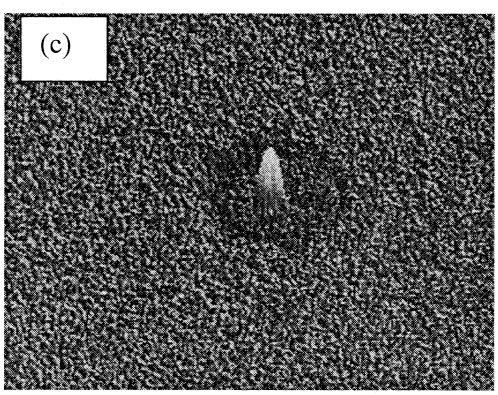




Fig.2: (a) SEM image of the nanofiber before further processing; (b) SEM image of the finished device; (c) AFM image of the finished device.

of the growth process have been described elsewhere [7]. On average, the fiber height is about 1μm, the base diameter is 200-300nm, and the tip diameter is 40-70nm. A Scanning Electron Microscopy(SEM) picture of the nanofibers before further processing is shown in fig 2(a), which is taken at 30-degree angle. After inspecting the fibers in a scanning electron microscope (SEM) and collecting the chemical composition information, the substrates are coated in a conformal layer of $SiO_2$ deposited in a silane based RF PECVD process (Fig 1-c). Chemical mechanical polishing (CMP) is performed to planarize the surface (Fig 1-d). It has been shown that substrates containing VACNF material are compatible with the CMP process [11, 12]. The tips of the fibers are then uncovered by reactive ion etching (RIE) using halocarbon-based plasma (Fig 1-e). We have shown that these processes do not damage the VACNFs in any observable manner [10-12]. Photolithography is performed to pattern the upper interconnect structures such that each fiber may be individually contacted. This pattern is metallized with a layer of Ti followed by a layer of Au (Fig 1-f), as Ti thin films adhere to graphitic carbon better than many other materials. The relatively inert Au layer was chosen to protect the electrode from contamination.

An SEM image of the upper electrode of a completed measurement structure is shown in Fig 2. (b), which is taken at normal incidence to the sample. A tapping mode Atomic Force Image (AFM) is also shown in Fig.2 (c).the images clearly show the VACNF tips encased in the metal. The crater surrounding the tip is due to the CMP process. Note, however, I-V characteristics of Schottky behavior are observed also on some devices which we can not identify VACNF tips as shown in the fig.2. (b) and 2.(c).

## 2. I-V BEHAVIOR AND DISCUSSION

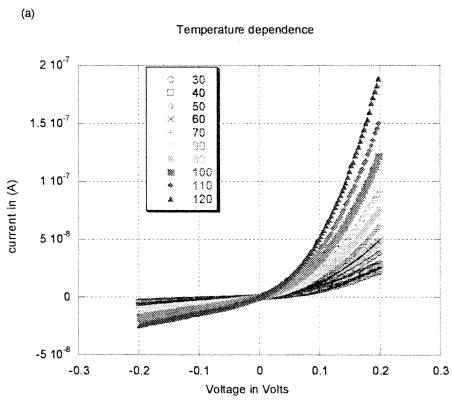
In the Thermionic model, a Schottky-Barrier Junction (SBJ) is said to be ideal if its I-V characteristics fits well to the diode equation:

$$I = I_{sat}\left[\exp(eV/kT) - 1\right] \quad (1)$$

Where $I_{sat}$ is the reverse bias saturation current given by

$$I_{sat} = SAT^2 \exp(-q\phi_e / kT) \quad (2)$$

Where $S$ is the diode area, $A$ is the Richardson constant and $\phi_e$ is the effective barrier height.



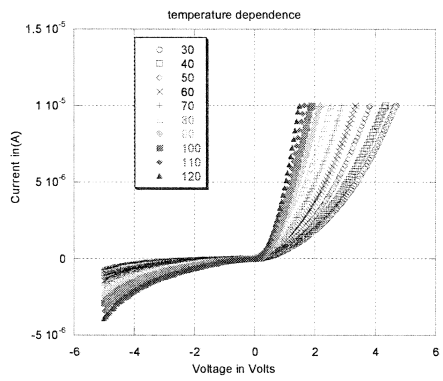




Fig.3: I-V curves obtained on our sample.

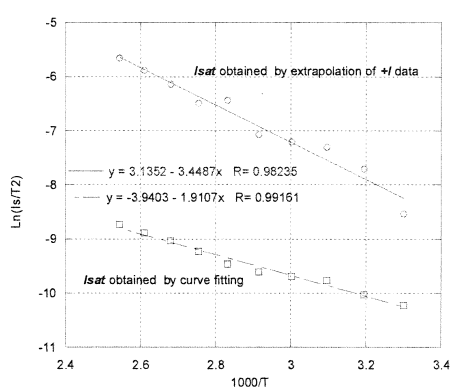



Fig.4 .Temperature dependence of the fitting parameter , $I_{sat}/T^2$.

For many reasons, the I-V characteristics often deviate from ideal SBJ behavior. So we fitted SBJ device to the generalized diode equation,

$$I = I_{sat}[\exp(eV/nkT) - 1]. \quad (3)$$

N is the ideality factor, which is round 1~2 ( which is 1 in the case of ideal SBJ) . *Isat* and $n$ can be determined by fitting I-V data according to (3).

In our device the silicon substrate serves as the bottom contact and the patterned Ti/Au electrode for individual nanofiber top contact. We reproducibly find a rectifying Schottky behavior in these devices. The nanofibers are quite robust and can sustain 100uA current without any damage. The data was taken using HP 4156A parameter analyzer. The sample was placed at a Signatone Hot chuck in air without light. The temperature was controlled by Signatone MODEL S-1060R. Fig.3. (a) and (b) shows the I-V behavior with applied high and low voltages respectively.

Since *Isat* is usually a small value,we did the following: (1)we only fit the data obtained with small applied voltages:-100mV~100mV;(2) Instead of just fitting that equation , we plot the I-V curve in semi-log scale and try to extrapolate the *Isat* value.

Once we get the *Isat* value, we can use equation (2) and plot $\ln(Isat/T^2)$ versus $1/T$ and calculate the slope to get the barrier height $\phi_e$ ,as shown in Fig.4. The barrier height extrapolated is about 200~300mV.In the literature a barrier height of 124.2mV was reported [8] .

To improve the curve fitting, we also propose a model in which a resistor is in parallel with the diode to account for the leakage current pass. The resistance turns out to be 0.5Gohms and the curve fitting is not affected much. This in turns proves that our simple diode equation is a good approximation.

The nanofiber within the finished device contains 0% nitrogen. We also checked the other device with ~30% N2 .It appears that the rectifying behavior is improved .But we still need further evidence. The doping effect has been discussed by other authors [9]

A lot of questions still remain about the SBJ: where is this junction? We speculate the junction to be at the bottom of the nanofiber at the interface with the silicon substrate. We are carrying further measurement to find out.

## 3. CONCLUSION

In conclusion, we've found another practical and deterministic way to fabricate nanodevice .The SBJ device we made displays a reproducible rectifying behavior. The barrier height is determined to be 200~300mV.

It is very possible that adding Nitrogen will improve the Schottky rectifying behavior.

## 4. ACKNOWLEDGEMENT

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