Vacuum Field Emission Devices with Integrated CNTs

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Abstract*—This research looks at the design and fabrication of sub 100-nm carbon nanotube-based vacuum field emission devices. The devices in this project are based in the Fowler-Nordheim emission of electrons, which allow the devices to hold radiation hardened capabilities due the absence of a semiconductor channel. On top of the radiation hardened capabilities of the Vacuum FETS, the emitter material, SWCNT (Single-Wall Carbon Nanotubes) themselves hold radiation hardened capabilities. SWCNT could also be the nanomaterial that replaces silicon in CMOS FETs (Field-Effect- Transistors). Through extensive preparation and testing, a field emission device based on carbon nanotube emitters with an effectiv anode-to-cathode distance of 100 nm was designed, fabricated, and tested.

Index Terms – Carbon Nanotubes, Vacuum FETs, SWCNT

I. INTORDUCTION

The goal of this project is to design, fabricate, and test a vacuum field emission device that is based on the electron emission of carbon naonotubes. The proposed design of this vacuum field emission device will integrate CNT (Carbon Nanotube) sources as the emitter in a lateral orientation and a vacuum channel in the vertical orientation. This deisgn will allow the device to have and control a short channel length that can compete with the complex and state-of-the-art FETs. The project was the focus of a start of a multi-year project where we focused on designing a device and fabricating a device that reaches Fowler-Northeim emission when the device is tested.

A. Vacuum Field Emission Device

In the 1990s, after CNTs were discovered, it was predicted that single-walled carbon nanotubes (SWCNT) would be the nanomaterial that could outperform silicon and create a post-CMOS world where Moore's law could continue. At this stage, CNTs are currently being used as a transistor and starting to outperofrm Silicon CMOS.

Carbon Nanotubes are also unique in the case that they can be used as either a metallic or semiconducting material, which is dependent on the tubular axis.

	SOA CMOS* 10 nm FinFET	Vacuum FETS** Silicon vacuum tube	Proposed CLVFET Lateral SWCNT emitter
Channel gate length	**10 nm** (immersion lithography))	**50 nm** (180nm-lithography and oxidation trimming)	**1 – 50 nm** (vertically defined by thin film deposition/ALD)
Source-to-gate distance	**0.8 nm** (high-k dielectric HfO_2 - equivalent oxide thick.)	**10 nm** (air gap)	**1 – 10 nm** (high-k dielectric equivalent thickness)
V_{DD}	**0.7 V**	**3 V**	**≤ 1.8 V**
I_{OFF}	**10 nA/µm** NMOS (VDS=0.7V)	**< nA** (~ nm tip) (VDS=2V)	**< nA/µm**
I_{ON}	**1.7 mA/µm** NMOS (VDS=0.7V)	**3 µA (~ nm tip)** (VG=3V)	**TBD/µm** or **/SWNCT**

*Etienne Sicard. Introducing 10-nm FinFET technology in Microwind. This paper describes the implementation of a high performance FinFET-based 10-nm CMOS Technology .. 2017.
**Jim-Woo Han, Dong-Il Moon, and M. Meyyappan, "Nanoscale Vacuum Channel Tansistor," Nano Lett. 2017, 17, 2146-2151

B. Carbon Nanotubes

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B. THEORY

A. Vacuum Field Emission Device

i. Design

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For the device to perform as a Vacuum Field Emission Device, the deisgn must have at least three layers: Anode, Trench, and Cathode. The trench refers to the channel length and will be the thickness that we control, while the Anode will be a layer of metal, and the Cathode will refer to the emitter source, or the Carbon Nanotubes in our case. The designs will all vary by shape, size, anode size, and their overlay with the trench.

ii. Fowler-Nordheim Emission

Fowler-Nordheim emission, also referred to as Field Emission, is the process whereby electrons tunnel through a barrier in the presence of a high electric field. In our case, we will be visually testing for Fowler-Norheim Emission by creating an anode-to-cathode distance and then grounding the cathode layer while putting a positive voltage on the anode layer. This should cause the electrons to move, and for Fowler-Nordheim emission to be achieved. This theorized emission can be seen in the figure below:

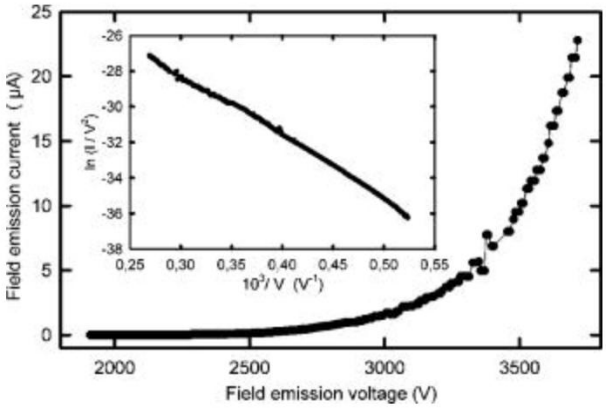

Figure 1. Fowler-Nordheim Emission

Mouton, R & semet, vincent & Kilgour, David & Brookes, M.D. & Binh, Vu. (2007). Polymer embedded C nanopearls field emission cathodes for time of flight mass spectrometers. Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures. 26. 127-128. 10.1109/IVNC.2007.4480962.

This Fowler-Nordheim emission of electrons is described in terms of current density, **J** (as seen in the equation below), where the current density is based mostly on the strength of the Electric Field, **E**. This is due to the fact that the rest of the equation is constants.

$$J = k_1 \frac{\beta^2 E^2}{\Phi} \exp\left[-k_2 \frac{\Phi^{1.5}}{\beta E}\right]$$

B. Carbon Nanotubes

A carbon nanotube is a tube-shaped material, made of carbon, have a diameter measuring on the nanometer scale. This diameter can actually directly effect the electrical properties and work function of the carbon nanotubes. Therefore, depending on what we are trying to achieve with the device, we could actually choose carbon nanotubes with different diameters and/or different dopants. These work fucntions can be seen on the figure below.

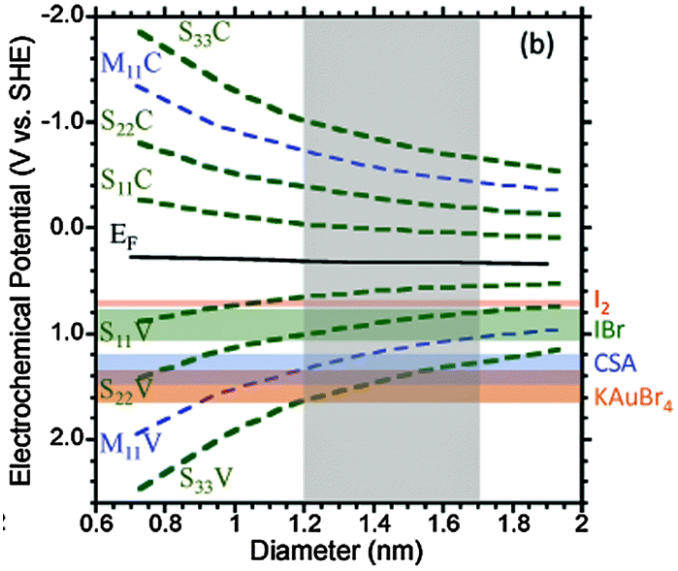

Figure 2. Characteristics of SWCNTs

C – Radiation Hardness

Radiation Hardness refers to the qualification given to electrical components after testing that proves these components and systems are resistant to damage or malfunctions caused by ionizing radiation. Radiation Hardened, or RADHARD, products are typically used in outer space, high-altitute flight, around nuclear reactors, and particle accelerators. The designed device carries both radiation hardened capabilities for both vacuum field emission and the carbon nanotubes themselves also carry radiation hardness capabilities.

For this exact project, we focused on the design and fabricating a device that followed Fowler-Nordheim emission. This project will be continued for multiple years, and will move onto radiation hardened testing in later years.

C. FABRICATION PROCEDURE

i. Mask Design

The first step in this project was to design a simple mask that had an array of different designs rangin in feature size, shape, trnech size, and more. These different designs were used to investigate what is the best method for making a device work in Fowler-Nordheim emission. By testing the different designs, we were able to find which design will work best and then focus on bringing down the feature size for future designs.

ii. Proposed Process Procedure

The proposed experimental procedure to achieve sub-100nm vacuum field emission devices are shown as follows:

(1) RCA clean all of the process wafers prior to the silicon dioxide growth

(2) A layer of 800nm wet SiO2 is thermally grown.

(3) 500nm of aluminum is sputtered on top of the SiO2 to serve as the anode layer

(4) The wafer is coated with I-CON 7 ARC on the aluminum followed by coating the wafer with diluted 1:1 OiR620 photoresist.

(5) Using an ASML Stepper, a clear mask is exposed on the Aluminum layer to serve as the Anode layer.

(6) The aluminum layer is then etched back by dipping the lot of wafers in a solvent strip for 1 min 30 seconds

(7) Using Low Pressure Chemical Vapor Deposition (LPCVD), 100 nm of thin oxide is deposited onto the substrate. This thickness will directly correlate to the channel length.

(8) The wafer is coated with I-CON 7 ARC on the aluminum followed by coating the wafer with diluted 1:1 OiR620 photoresist.

(9) Using an ASML Stepper, a dark mask is exposed on the Aluminum layer to serve as the trench layer.

(10) Using a DryTek, the thin oxide is etched back

(11) A thin film of CNT is transferred onto the substrate in a method that can be shown later in this section

(12) The wafer is coated with I-CON 7 ARC on the aluminum followed by coating the wafer with diluted 1:1 OiR620 photoresist.

(13) Using an ASML Stepper, a clear mask is exposed on the CNT layer to serve as the cathode laye

(14) Using the LAM 490, the CNT film is etched back

SEM images are required after the final step and the devices are tested

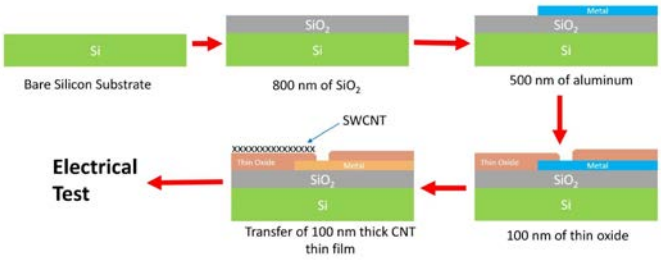

Figure 1. Projected Process Flow

iii. SWCNT Thin Film Process

In order to use carbon nanotubes in this project, a thin film of carbon nanotubes had to bcreated. This thin film process allowed us to select the desired properties of the SWCNTs, as in we chose the diameter of the SWCNTS, which in return gave us a desired work function.

In order to make the SWCNT thin film, high purity laser vaporized SWCNTs (mixed chirality, 1.2 – 1.7 nm diameter, and electrochemical potential of 0.5 – 2.0 V of SHE) were dispersed in chloroslufonic acid and further individualized with the aid of ultrasonic agitation. This gave us an aqueous solution of the SWCNTs.

Next, the disperson of SWCNTs were transferred onto a ceramic filter by vacuum filtration while the acid was rinsed with acetone. The film was left to dry for a minuimum of 30 minutes with the vacuum on, and then was ready to be transferred onto the subtrate.

iv. SWCNT Thin Film Transfer

In order for the SWCNT transfer to occur, the substrate with the completed aluminum and LTO layers was completely dispersed into DI water.

From this point, the ceramic filter with the SWCNT thin film was slowly dispensed into the DI water where the film slowly separated from the filtered and floated on the surface of the DI water. The substrate was then slowly lifted from out of the DI water where the SWCNT thin film stuck to the top of the substrate. The substrate was then left to dry overnight, and ready to move on for patterning and etching of the SWCNT film the next day.

D. RESULTS AND DISSCUTIONS

i. Microscope Images

From the microscope images after SWCNT lithography occurred, we saw that reside of the transfer process resulted in visible defects, which can be seen in the figure below.

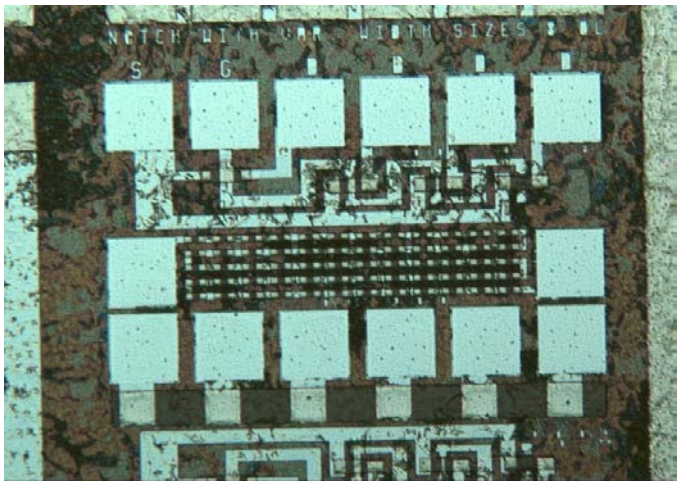

Figure 4. SWCNT Lithography Before Etch

On top of residue from the transfer process, issues in aluminum reflectivity also left visible defects on the substrate, which is shown on the figure below. All of these defects were visible before the oxygen plasma etch.

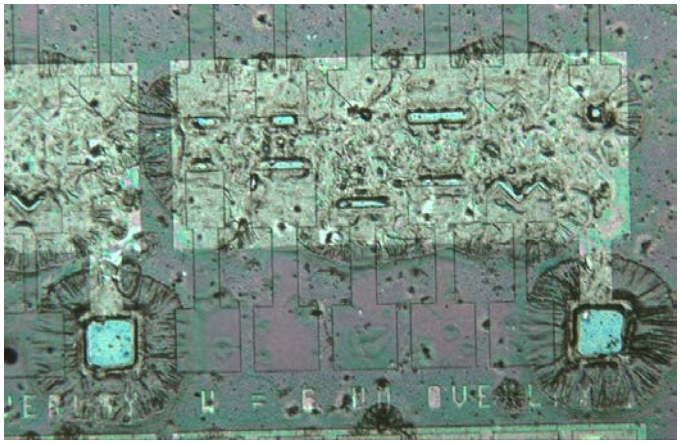

Figure 5. Aluminum Reflectivity Before Etch

After the SWCNT was etched, the lithography defects resulted in damaged SWCNT cathode structures. Not all structures were damaged though, and there were enough to do our electrical testing and continue the process.

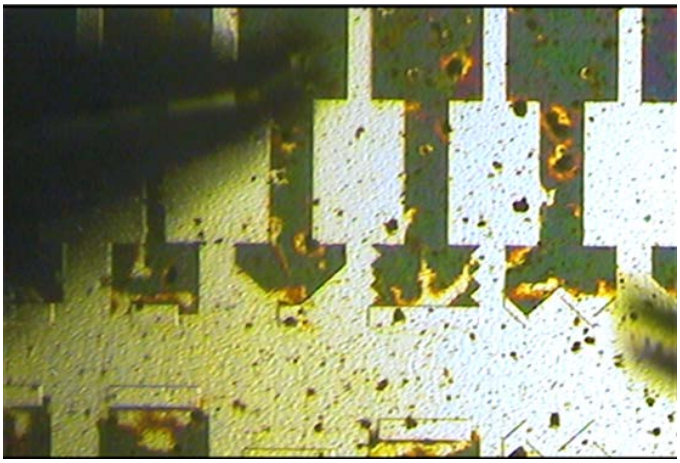

Figure 6. Microscope Image of Finished Device

ii. SEM Images

After microscope image were complete, a Scanning Electron Microscope was used to distincly show where the SWCNTs existed and where they were etched down. This can be seen in the figure below where the SWCNTs exist only around the edge of the devices.

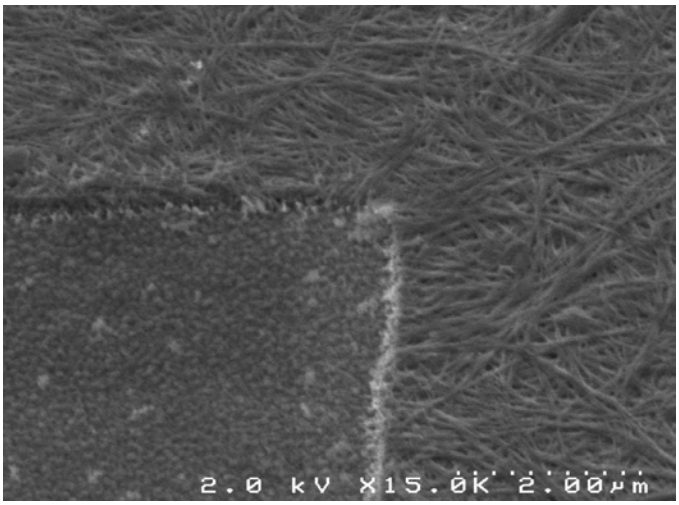

Figure 7. SEM Images of Finished Device

The contrast difference near the edge of the pattern may have indicted that the etch resulted in damaged or modified carbon nanotubes.

iii. Electrical Testing

Electrical Testing focused mainly around the test of two different devices. The first device being a completed device with a design where the cathode does not overlap the trench,

and the second being a completed design where the cathode does overlap the trench.

The first device tested followed the design below.

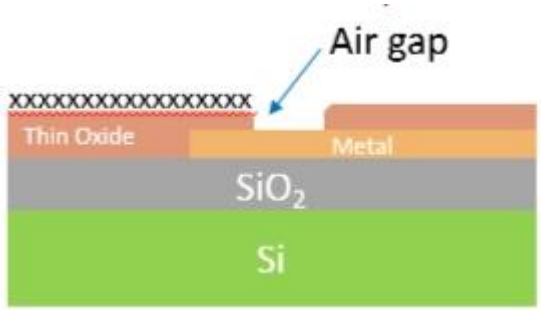

Figure 8. Cross Section of Device with no Trench Overlap

By grounding the cathode layer and placing a positive voltage on the anode layer, we were able to electrically test this structure and plot the following results.

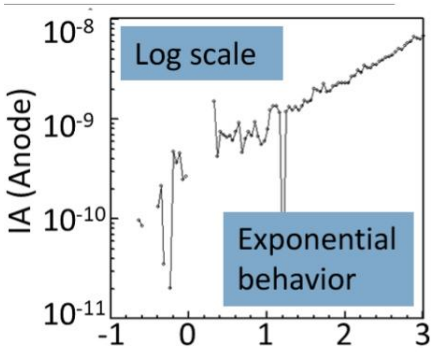

Figure 9. I-V Curve of Device with no Trench Overlap

Due to the air gap in the design, the electrical testing of this structure showed that Fowler-Nordheim emission had been achieved, according to the structures shown in the theory section.

The rest of the electrical testing then focused on testing the design below.

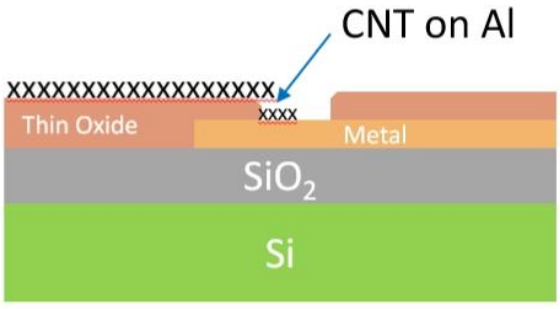

Figure 10. Cross Section of Device with Trench Overlap

Again, by grounding the cathode layer and placing a postive voltae on the anode layer, we were able to electrically test the structure and plot the following results.

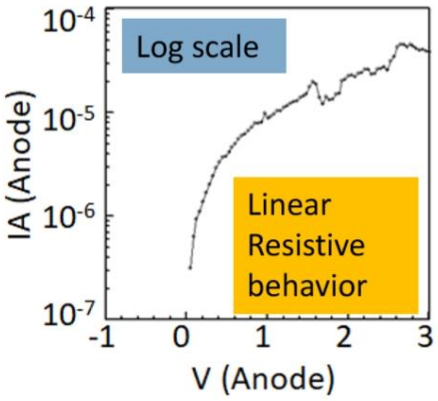

Figure 11. I-V Curve of Device with Trench Overlap

In this design, the CNTs moved onto the aluminum layer, causing the anode and cathode to have the same material and for the structure to act as resistor. This gave us an asswer to how to correctly use the trench in the deisgn of the structures for these devices.

E. CONCLUSION

After fabrication, experimentation, and testing was complete, it was safe to say that proof of concept of a field emission device was achieved. Our device succesfuly used carbon nanotubes as the emitter, and showed fowler-northeim emission while havin gan effective anode-to-cathode distance of 100 nm.

To continue on with this project, certain changes should be made in the figure to prevent damage to the SWCNT. The SWCNT thin film transfer and patterning process needs improvement to reduce defects, protect SWCNTs and improve resolution. Further processing will need to factor in the particle buildup from over night drying of the substrate after SWCNT transfer, and for the oxide plasma etch damaging SWCNT.

Although the devices were operational and showed Fowler-Northeim Emission, further testing needs to be done so to

APPENDIX

Process	Tool/Recipe
Oxide Growth (800nm)	Tool: Bruce Furnace Tube 1.

	Recipe: 357 Full wet 8000A Ox.
Aluminum Sputter	Tool: CVC 601 Sputter 5 mins @ 2000W to Burn off Oxide 20 mins @ 2000W to Sputter on Aluminum
I-CON ARC 7 Coating	Tool: CEE Spin Coat Station. HMDS: Yes Dehydration: 145 C, 60 sec. Cool: 60 sec. Spin Speed: 2000RPM. Soft Bake: 90 C, 60sec Cool: 60 sec
Diluted OiR 620 Coating	Tool: SSI wafer track. HMDS: No Dehydration: No Cool: No Spin Speed: 1000RPM. Soft Bake: 95, 60sec Cool : 15 sec.
Exposure	Tool: ASML PAS 5500 i-line Stepper. Dose: 250 mj/cm2 Focus: -0.4 NA = 0.6 σi = 0.535 σo = 0.9
OiR 620 Develop	Tool: SVG wafer track. PEB: 110, 60 sec. Cool: 15 sec. Develop: 45 sec. Hard Bake: 145, 60sec Cool: 15 sec.
Aluminum Etch	Tool: Chemical Aluminum Etch
Oxide Etch	Tool: Drytek
Low Thermal Oxide	Tool: LPCVD Furnace Recipe: LTO 425 Base Pressure: 40 mT Dep. Pressure: 2225 mT. SiH4: 50sccm.
	Time: 6 min.

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