Introduction

This report introduces the application of carbon nanotubes (CNTs) and nanotechnology to the wireless realm. Use of carbon nanotubes in high-frequency electronic devices has several advantages. Specifically, such components result in favorable characteristics, such as high transconductance and long mean-free paths.[1] Transconductance is the ratio of a change in output current to the change in input voltage that caused it. A high transconductance means a more efficient production of charge carriers. Mean-free path is the mean distance traveled by charge carriers before a scattering-based collision. A long mean-free path results in more efficient charge carrier transport.

CNTs are popularly applied as high-frequency field-effect transistors. Semiconducting behavior in CNTs was first reported by Tans *et al.* in 1998: "By applying a voltage to a gate electrode, the nanotube can be switched from a conducting to an insulating state."[2] The tube conducts at a negative applied voltage, and it turns off at a positive applied voltage. The difference between these two states is multiple orders of magnitude (approximately 10^6). This type of behavior is similar to that of a p-type MOSFET, wherein the nanotube replaces silicon as the semiconductor.[3] A diagrammatic representation of such a setup, and a graph of conductance at varying applied voltages, is shown below in Figure 1.

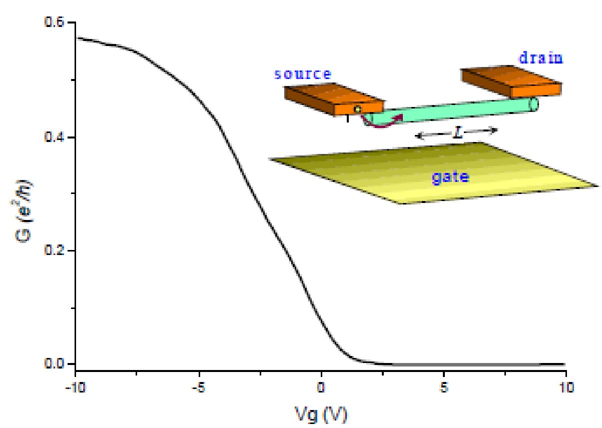

Figure 1: Conductance *G* vs. gate voltage V_g of a p-type semiconducting single-wall nanotube field effect transistor, with device geometry shown diagrammatically in the inset.[4]

Further, it was shown that single-wall nanotubes (SWNTs) have a unique characteristic of a nonlinear current-voltage curve, increasingly emphasized as the gate voltage decreases from 0 V. A plot representing a few different current-voltage curves, and a schematic of the measurement geometry, are shown below in Figure 2.

[1] Rutherglen *et al.*, 2007
[2] Tans *et al.*, 1998
[3] McEuen *et al.*, 2002
[4] McEuen *et al.*, 2002

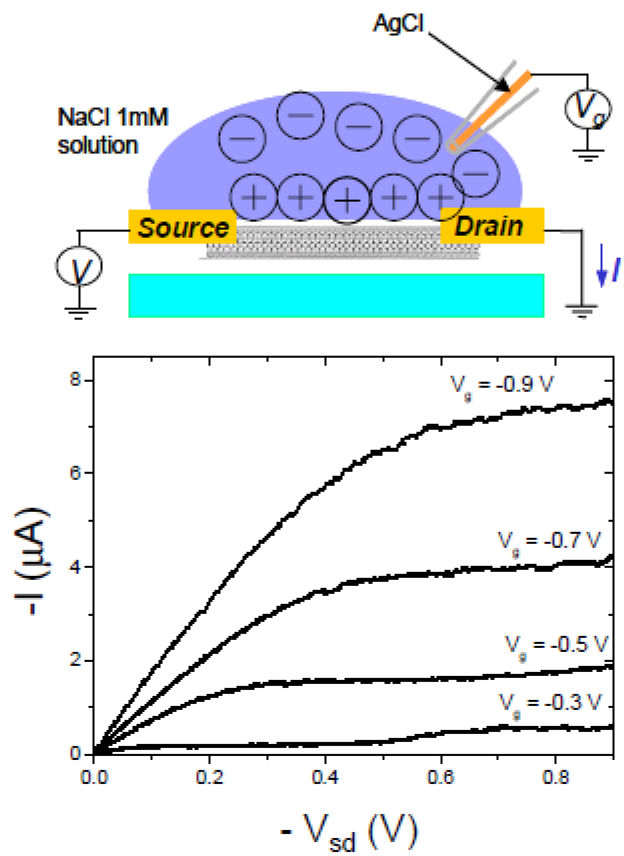

Figure 2: I-V characteristics at different V_gs for a p-type SWNT FET utilizing an electrolyte gate. The measurement geometry is shown above.[5]

Building on this technology, Rutherglen *et al.* created a CNT-based amplitude-modulated (AM) demodulator for modulation frequencies up to 100 kHz. To demonstrate practical application, this group went a step further and successfully demonstrated such a demodulator in an actual AM radio receiver operating at a carrier frequency of 1 GHz, transmitting high-fidelity audio. This demodulation relies on the nonlinear I-V characteristic of the CNT as shown in Figure 2 above. Biasing the CNT such that the operating point is centered on the maximum nonlinear portion of the I-V curve, the demodulation effect is ideally maximized.[6] Figure 3 below shows a schematic of a test setup relying on CNT properties.

[5] McEuen *et al.*, 2002
[6] Rutherglen *et al.*, 2007

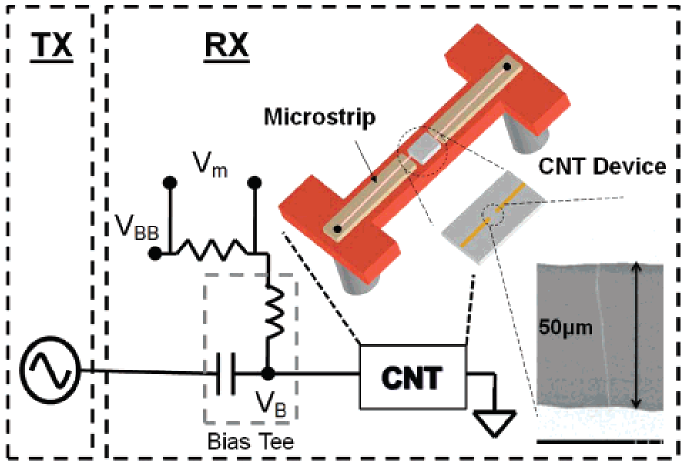

Figure 3: Schematic of the test-setup for the CNT-based AM demodulator. SEM image of a CNT (right).[7]

Description of the Process

CNT applications as an RF mixer (which convert RF power at one frequency into power at another frequency to assist in the simplification of digital signal processing) have been demonstrated by multiple groups. Kocabas *et al.* have "fabricated nanotube transistor radios, in which SWNT devices provide all key functions, including resonant antennas, fixed RF amplifiers, RF mixers, and audio amplifiers."[8] Rosenblatt *et al.* "have probed the electrical properties of top-gated single-walled carbon nanotube transistors at frequencies up to 50 GHz by using the device as a microwave mixer."[9] All of these groups use the CNT's nonlinearity of the drain current with respect to the gate source current. Another group, Rodriguez *et al.*, used a slightly different technique, taking advantage of the nonlinearity of the source-drain current relationship created by the zero-bias anomaly that manifests at low temperatures, in the case of this group, at $T = 77$ K.[10]

Rutherglen *et al*. use the traditional room-temperature nonlinearities in the I-V curve to generate experimental results for the CNT-based amplitude modulated demodulator, focused on modulation frequencies up to 100 kHz. As such, the device this group created represents a two-terminal nonlinear device, which is simpler than prior three-terminal mixers/detectors of the groups above.

To construct a CNT-based amplitude modulated demodulator, CNTs were synthesized on high-resistivity silicon wafers, > 8000 Ω cm, in order to reduce the effect of parasitic capacitance (undesirable capacitance resulting from components in close proximity to each other[11]) at high frequencies. Next, optical lithography was used to pattern catalyst regions onto the wafer. Following sonication for one hour, 100 mM $FeCl_3$ catalyst was applied for 10 s, then rinsed with DI water. The chemical vapor deposition process to grow nanotubes was then used on these prepared wafers. Following CNT growth,

[7] Rutherglen *et al.*, 2007
[8] Kocabas *et al.*, 2007
[9] Rosenblatt *et al.*, 2005
[10] Rodriguez *et al.*, 2006
[11] Alley *et al.*, 1973

20 nm palladium and 80 nm gold electrodes were evaporated onto the nanotubes with a width of 300 µm and a gap-spacing of 50 µm. Samples with a single CNT bridging the gap were selected for use in the experiment. As shown in Figure 3 above, the sample device was placed on a microwave mount with two SMA connectors and a microstrip line connecting the device. Of the four such devices tested, all four successfully demodulated AM signals.[12] Representative plots of conductance vs. gate voltage, (a), and current vs. voltage, (b), are shown below in Figure 4.

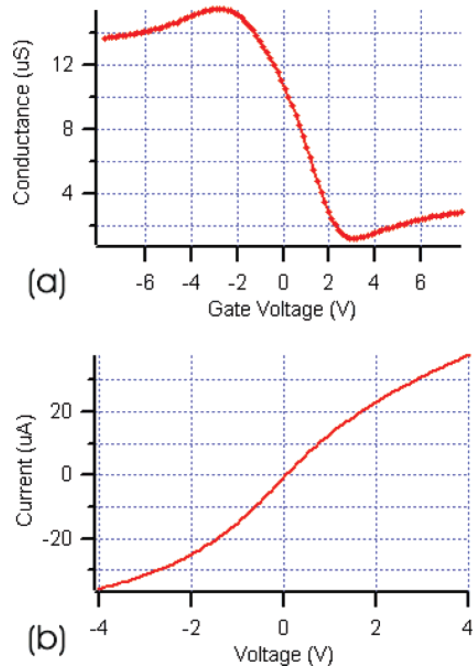

Figure 4: (a) Plot of the source-drain differential conductance vs. gate (substrate) voltage of the semiconducting CNT. (b) Current-voltage curve.[13]

To analyze the use of a CNT as a demodulator, a test setup was constructed as in Figure 3 above. An Agilent E4428C signal generator including amplitude modulation was used as the RF source transmitter (TX in Figure 3). This signal was transmitted through a MiniCircuits 0.1-6000 MHz bias tee, then into the constructed device. Amplitude modulation of the RF carrier with an 80% modulation depth was performed using sinusoidal modulation frequencies of 0.01-100 kHz. The receiver (RX in Figure 3) was the CNT, in addition to a sense resistor and a lock-in amplifier (SR-810). The modulation signal from the RF carrier was extracted by the CNT, and the lock-in amplifier, tuned to the modulation frequency, was used ultimately to measure the voltage drop of the signal across the sense resistor.

Critical Fundamental Issues

An essential property of carbon nanotubes that makes such experiments work, as the one described above, is the nonlinear current-voltage curve. Without this nonlinear property, CNTs would be unable to

[12] Rutherglen *et al.*, 2007
[13] Rutherglen *et al.*, 2007

demodulate an amplitude modulated RF signal. It is not well understood what causes such non-linearities, though it is thought to originate from phonon scattering processes.[14] Electron-phonon coupling is described by the Hamiltonian, $H_{ep} = \sum_{k,q} D^{\alpha}_{k,q} c^{\gamma}_{k+q} c_k u^{\alpha}_q$, $u^{\alpha}_q = \sqrt{\frac{\hbar}{2L\rho\Omega^{\alpha}_q}}\left(b^{\alpha}_q + b^{\alpha\gamma}_{-q}\right)$, where q and α label the phonon wavevector and branch, respectively, u is the phonon displacement, c^{γ} and c (b^{γ} and b) are electron (phonon) creation and annihilation operators, respectively, L is the length of the nanotube, and ρ is the mass density.[15] From a higher-level perspective, nonlinearities on the current-voltage curve are a result of a change in the rate of flow of charge carriers with increasing applied voltage. The nonlinearities can resolve a portion of the RF current utilizing Equation 1 below.

$$I = I_0 \frac{1}{4}\frac{d^2 I}{dV^2} {V_{RF}}^2$$

Equation 1: V_{RF} is the applied RF signal voltage, d^2I/dV^2 represents the nonlinear current-voltage characteristics of the CNT.[16]

The application of this equation to the designed system is supported by the results obtained by Rutherglen *et al.*, in Figure 5 below.

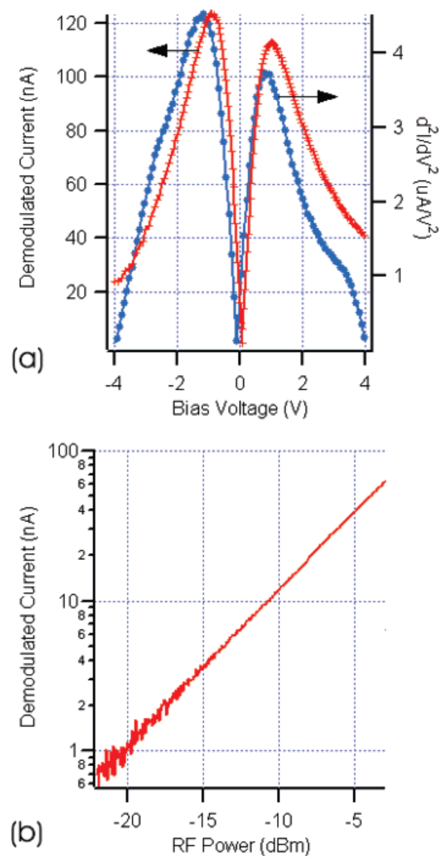

Figure 5: (a) Comparison of demodulated current (red crosses) and |d^2I/dV^2| (blue dots) with respect to the bias voltage, V_B, showing a very good match. (b) Linear modulation current detected by a lock-in amplifier across a 100 kΩ resistor.

[14] Park *et al.*, 2003
[15] Park *et al.*, 2003
[16] Pozar, 1998

As demonstrated in Figure 5 (a), the demodulated signal is very close to the absolute value of the numerical second derivative of the current-voltage trace. A direct relationship between the applied RF power and the detected output signal is essentially linear, indicating that $I_{resolved}$ is proportional to V_{RF}^2, supported by the plot in Figure 5 (b).

Challenges and Opportunities

One significant difference between various methods of utilizing CNTs to demodulate amplitude modulated signals is two-terminal vs. three-terminal nonlinear devices. The sole advantage with a three-terminal device is that it can be optimized in terms of signal amplification (i.e. one additional variable to adjust). The fact that two-terminal devices cannot be optimized in this way is a fundamental property of such devices. However, two-terminal devices are much simpler and easier to work with and analyze. Rutherglen *et al.*'s development of such a two-terminal device represents the first physical demonstration, originally proposed by Manohara *et al*. in 2005.[17]

Interestingly, and as a testament to the utilization of CNTs as an effective demodulator, detecting the modulation signal up to 100 kHz was determined by Rutherglen *et al.* to be limited not by the CNT, but by extrinsic parameters of the experimental setup. As such, a potential improvement would be simply improving environmental factors; for example, enclosing the entire setup in a Faraday cage could reduce electromagnetic interference, improving detection and demodulation.

One difficulty that could interfere with effective demodulation is the existence of parasitic capacitance, described above, even with the processing techniques used to reduce this effect (*i.e.* growing CNTs on high-resistivity Si wafers). This could cause high-frequency interference with the demodulation process. Consequently, a potential improvement to this setup could be implementing a low-pass filter, either analog or digital, with the frequency cutoff (-3 dB) set somewhere above 20 kHz, which is approximately the top of the range of human hearing (because this particular experiment was conducted to transmit amplitude modulated radio signals for auditory interpretation). Another straightforward way to minimize the effects of parasitic capacitance is to reduce the size of the contact pads (1000 µm × 300 µm).

As described by Rutherglen *et al*., there is a fundamental upper limit on the noise equivalent power of the CNT. Noise measurements were conducted on the CNT demodulator system, operating at a carrier frequency of 1 GHz and bias voltage of 2.5 V. The system voltage-noise density, including noise from the lock-in amplifier, sense-resistor, and CNT, was determined to be 40×10^{-9} (V/Hz$^{1/2}$) at an audio frequency of 1 kHz. Using the measured responsivity, β_I, of 125 nA/mW together with the device resistance of 100 kΩ, the noise-equivalent power (NEP) is calculated using NEP = $v_n/(\beta_I R)$ (W/Hz$^{1/2}$) and is 3 nW/Hz$^{1/2}$.[18] Therefore, the upper limit on the noise equivalent power for a CNT is 3 nW/Hz$^{1/2}$.

[17] Manohara *et al*., 2005
[18] Rutherglen *et al*., 2007

One further method to optimize CNT demodulation would be to modify the length of the nanotube to a value to optimize demodulation responsivity. Doing this would, in a sense, be maximizing the intrinsic nonlinear influence of the CNT, as length is inversely proportional to nonlinearity as shown in the equation presented above. There is a trade-off between mean-free-path length, ballistic transport, and various scattering phenomena. The ideal CNT length to maximize mean-free-path length is about 100 nm. Further decreasing the length causes ballistic transport to dominate the transport mechanism, reducing the nonlinearity in the I-V curve. Other scattering processes become significant, like defect-induced elastic scattering, for long nanotubes (> 10 µm).[19]

In this report, carbon nanotubes and general nanotechnology has been applied to the wireless realm. Critical issues in fabrication of a CNT-based amplitude modulated RF signal demodulation device have been discussed, a few differentiating factors between approaches were identified, fundamental issues concerning this technology were detailed, different approaches to demodulation (two-terminal vs. three-terminal) were discussed, advantages and disadvantages were outlined, and future directions in improving the device were proposed. With some improvements in the process and device detailed in this report, it seems likely that nanotechnology will play a big role in the future of wireless transmission.

[19] Rutherglen *et al*., 2007

Works Cited

[1] Rutherglen, Chris; Burke, Peter. Carbon Nanotube Radio. *Nano Letters* **2007**, *7* (11), 3296 – 3299.

[2] Tans, Sander J.; Verschueren, Alwin R.M.; Dekker, Cees. Room-temperature transistor based on a single carbon nanotube. *Nature* **1998**, (393), 49 – 52.

[3,4,5] McEuen, Paul L.; Fuhrer, Michael; Park, Hongkun. Single-Walled Carbon Nanotube Electronics. *IEEE Transactions on Nanotechnology* **2002**, *1* (1), 78 – 85.

[6,7] Rutherglen, Chris; Burke, Peter. Carbon Nanotube Radio. *Nano Letters* **2007**, *7* (11), 3296 – 3299.

[8] Kocabas, Coskun; Kim, Hoon-sik; Banks, Tony; Rogers, John A.; Pesetski, Aaron A.; Baumgardner, James E.; Krishnaswamy, S. V.; Zhang, Hong. Radio frequency analog electronics based on carbon nanotube transistors. *Proc. Natl. Acad. Sci. U.S.A.* **2008**, (105) 1405 – 1409.

[9] Rosenblatt, Sami; Lin, Hao; Sazonova, Vera; Tiwari, Sandip; McEuen, Paul L. Mixing at 50 GHz using a single-walled carbon nanotube transistor. *Appl. Phys. Lett.* **2005**, (87) 153111.

[10] Rodriguez-Morales, F.; Zannoni, R.; Nicholson, J.; Fischetti, M.; Yngvesson, K. S.; Appenzeller, J. Direct and heterodyne detection of microwaves in a metallic single wall carbon nanotube. *Appl. Phys. Lett.* **2006**, *89* (8), 083502-1 – 083502-3.

[11] Alley, Charles L.; Atwood, Kenneth W. *Electronic Engineering, 3rd Ed.* **1973**, New York: John Wiley & Sons., 199. ISBN 0471024503.

[12,13] Rutherglen, Chris; Burke, Peter. Carbon Nanotube Radio. *Nano Letters* **2007**, *7* (11), 3296 – 3299.

[14,15] Park, Ji-Yong; Rosenblatt, Sami; Yaish, Yuval; Sazonova, Vera; Ustunel, Hande; Braig, Stephan; Arias, T. A.; Brouwer, Piet W.; McEuen, Paul L. Electron-Phonon Scattering in Metallic Single-Walled Carbon Nanotubes. *Nano Lett.* **2001**, 4 (3), 517 – 520.

[16] Pozar, D. M. *Microwave Engineering*. Wiley: New York, **1998**.

[17] Manohara, H. M.; Wong, E. W.; Schlecht, E.; Hunt, B. D.; Siegel, P. H. Carbon nanotube Schottky diodes using Ti-Schottky and Pt-Ohmic contacts for high frequency applications. *Nano Lett.* **2005**, *5* (7), 1469 – 1474.

[18,19] Rutherglen, Chris; Burke, Peter. Carbon Nanotube Radio. *Nano Letters* **2007**, *7* (11), 3296 – 3299.