Nanotube Technology for Microwave Applications

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***Abstract* — In this paper we present an overview of the high-frequency properties nanotube and nanowire technology for microwave applications. We discuss circuit models of the ac performance of active, ballistic 1d transistor structures, leading to the prediction that THz cutoff frequencies should be possible. Issues of economics and manufacturability, as well as device-to-device variation, constitute a major challenge to be met before the technology will be ready for system insertion. Still, speed is one of the promises of nanotechnology, and nanotube and nanowire devices are worth serious consideration for microwave applications.**

***Index Terms* — Nanotube, nanowire, nanotechnology.**

I. Introduction

The realistic or claimed end of the “Roadmap”[1], in which features sizes of integrated circuits will approach the 10 nm length scale, has motivated research in the electronic properties of nano-scale devices. Among other devices that have been investigated, nanotubes and nanowires are among the most recent. In this invited conference paper, we provide a broad overview of the state of the art in synthesis, fabrication, and electronic performance of nanotube and nanowire field effect transistors, with particular emphasis on their possible application in microwave and mm-wave electronics. While much work remains to be done, it is our contention that the microwave community should sooner or later seriously consider nanotube and nanowire devices as active components in microwave circuits because of their potentially extremely high cutoff frequencies.

II. Motivation

Modern techniques of electron-beam lithography can achieve critical dimensions of order 10 nm. However, the general term nanowire and nanotube is usually taken to mean long, thin pieces of material that are synthesized chemically and not via lithography. One of the main motivations here is that chemical forces can control the critical dimensions. In principle this could allow for three key advantages:

- Smaller dimensions than achievable by lithography
- Economical fabrication
- High speed

In practice, the promise of these technologies has not yet been fully realized; however the field is still relatively young and progress is occurring at a very rapid pace.

II. Classification

In the following sections, we discuss the two major classes of interest: carbon nanotubes, and semiconducting nanowires.

A. Carbon nanotubes

Carbon nanotubes are the most studied class of nanotube/nanowire FETs[2]. A carbon nanotube consists chemically of a sheet of graphite rolled up into a tube (Fig. 1). Because the chemical bonds are all satisfied, there are no “dangling” bonds, minimizing surface scattering and leading to high mobility transport. Carbon nanotubes can be single-walled (SWNT) or multi-walled (MWNT). Typical dimensions are 1-3 nm for SWNTs and 20-100 nm for MWNTs. Clearly, for single walled nanotubes, they realize the promise of critical dimensions smaller than any current lithographic technique.

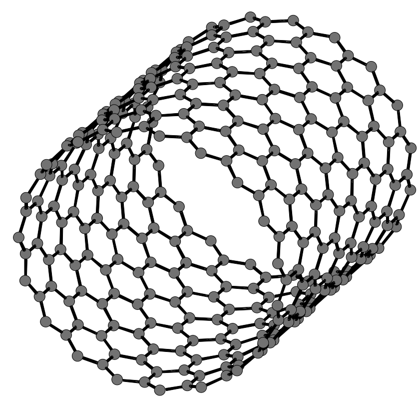

Fig. 1: Single walled carbon nanotube.

The electronic properties of carbon nanotubes depend on both their diameter and chirality (analogous to the number of turns per inch of a screw). Depending on the chirality, the nanotube can be either metallic or semiconducting. While Raman scattering can determine the chirality, the common test of whether a nanotube is semiconducting or metallic is to test whether the resistance changes with a backgate voltage. For semiconducting nanotubes, the bandgap is approximately 1 eV/d[nm], where d is the diameter in nm. Currently, there is no technique to control chirality of the nanotube during synthesis, and precise control of the diameter is also a challenge. One method of avoiding this problem would be to develop size-sorting and chirality-sorting techniques to isolate a particular nanotube from a heterogeneous mixture.

B. Semiconducting nanowires

Semiconducting nanowires can be synthesized in a technique similar to carbon nanotubes (see below), even though their chemical structure is different. Virtually any semiconductor material that can be realized in bulk can be used to make a nanowire, including Si, GaAs, InP, and GaN, as well as tertiary compounds[3]. Because they have dangling bonds, surface scattering is more of an issue. Typical diameters of nanowires studies is of order 50-100 nm, although diameters as small as 3 nm have been realized[4].

II. SYNTHESIS

The current paradigm in nanowire and nanotube synthesis is to use chemical vapor deposition[5], which is outlined in Fig. 2. (Laser ablation and arc-discharge can also be used.) The principle of the synthesis is that nanoparticles of various transition metals act as catalysts to seed the growth of nanowires or nanotubes, using the feedstock gas as ingredients. This synthesis technique is still being developed by many companies and universities around the world.

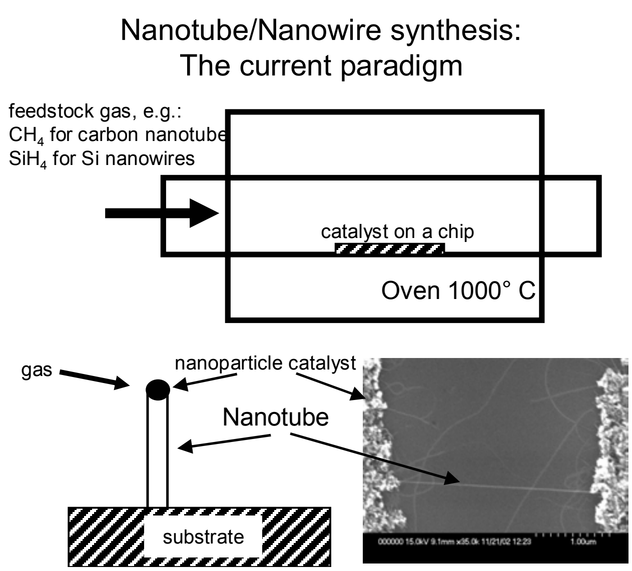

Fig. 2: Current synthesis paradigm.

At present, there are some significant drawbacks for the synthesis techniques used in nanowire and nanotube devices. In bullet form, here are the things we cannot do now:

- No clear path to integration
- Synthesis is high temperature (600-900 C)
- Length, diameter not well controlled

These challenges will have to be met before the technology is ready for system insertion.

VII. ACTIVE DEVICES

A typical device geometry is shown in Fig. 3. The source/drain electrodes are typically formed by evaporating metal onto the top of the nanotube after it is deposited or grown on top of a solid substrate, such as oxidized Si. In initial studies, the substrate was used as the gate. However, in order to allow individual addressing of SWNT FETs on a wafer, and in order to reduce source-gate capacitance (important for high-speed), top-gates can be deposited if a suitable dielectric can be found which does not damage the SWNT[6-8].

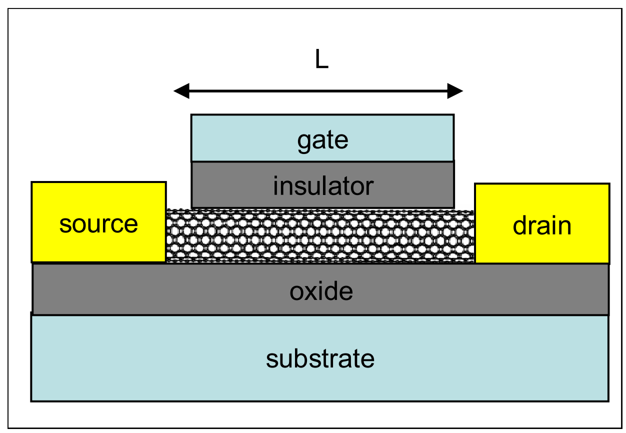

Fig. 3: Schematic of a nanotube transistor.

A. Ballistic 1d transport

In carbon nanotubes, the transport of electrons is in the quantum mechanical 1d limit, even at room temperature. This severely reduces the scattering probability for the following simple reason: for an electron to scatter, it cannot scatter up/down or left/right: it must completely reverse its direction (umklapp scatter). The probability for this to occur is quite low. The mean-free-path for small field transport is of order 1 μm (see below) at room temperature, so that it is possible to achieve ballistic 1d transport at room temperature in a SWNT transistor.

C. Lowest "ON" resistance is 6 kΩ

According to quantum mechanics, the lowest "on" resistance for a SWNT FET is 6 kΩ.. This has a significant effect on the high frequency performance (see below). According to the Landauer-Buttiker theory of conductance in quantum confined geometries (such as a SWNT), the lowest value of resistance for a ballistic, one-channel conductor (with perfect, adiabatic contacts) at dc is given by $h/e^2 \approx 25$ kΩ. In a SWNT, there are four effective channels, so that the lowest dc resistance is given by $h/4e^2 \approx 6$ kΩ. This can be thought of as a "contact resistance".

It should be noted that achieving this theoretical limit from a practical point of view is not trivial, and special attention must be paid to the contact between the nanotube and the source/drain electrode. Recently, this theoretical limit on the dc resistance was achieved in SWNT FETs experimentally[9]. Currents up to 100 μA through a SWNT FET have been reported in the literature[10].

B. Mechanism of transistor action

For short nanotubes, the mechanism of transistor action is generally believed to be due to the modulation of the contact resistance at the boundary of the metal/nanotube system, which forms a Schottky barrier. This Schottky barrier, if it is large, prevents the "on" resistance from approaching the 6 kΩ limit[11]. As mentioned above, Javey[9] has recently developed contact technology to significantly suppress the Schottky barrier contact resistance, so that the mechanism of transistor action in those devices is more complicated. Durkop[12] recently studied 300 μm long nanotubes, and concludes that they are classical field effect transistors, i.e. that the contact resistance is not the dominant part of the nanotube resistance. Additionally, Durkop found a field-effect mobility of 200,000 cm^2/V-s, higher than any other material known to man. This was followed by our recent work on SWNT FETs an order of magnitude longer, 0.4 cm, which came to similar conclusions[13]. It is clear that the contact resistance, as well as the resistance due to scattering along the nanotube, can be significant, depending on the geometry involved. A quantitative theoretical statement of this qualitative conclusion would be a useful development.

VII. Active Device AC performance

A. *Experiment*

In contrast to work on the dc performance of SWNT FETs, the ac performance is only now beginning to be studied. To date, the only microwave measurements on the ac performance of nanotube transistors are by our group at a spot frequency of 2.6 GHz[14]; these were performed at cryogenic temperatures where parasitic substrate coupling is negligible.

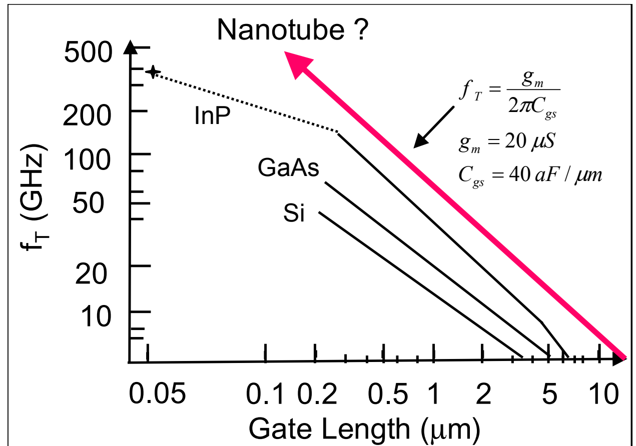

Figure 4: Predicted cutoff frequency. (From ref. 15).

B. Modeling

We recently developed the first equivalent circuit model of a SWNT transistor[15], and predicted that a cutoff frequency of THz should be achievable. This prediction is based on the calculated capacitance and measured transconductance. The prediction is repeated in Fig. 4 above.

C. Effect of on resistance

The above (somewhat optimistic) prediction for the cutoff frequency neglects RC time effects. Even though the on resistance for SWNT transistors is of order 10 kΩ, the intrinsic capacitance is small enough that the RC time is not important compared to the transconductance (time-of-flight). However, in realistic circuits with lithographically fabricated source-drain contacts, there will be parasitic capacitance. In ref. [15], we showed this can significantly limit the cutoff frequency, bringing it down to about 10 GHz. There, we proposed using nanotubes as the interconnects to minimize the parasitic capacitance. We now turn to the issue of interconnects in more detail.

VII. Interconnects

A metallic nanotube has a diameter of order 1-3 nm, and can carry currents up to 25 μA[16]. This translates into an enormous current density, of order 10^9 A/cm^2. In this final section we discuss the dc and ac properties of SWNTs as interconnects.

A. *DC resistance and resistivity*

How does the dc resistance of a SWNT depend on its length? Normally, this is a difficult question to answer, because all measurements are two-probe and the contact resistance is usually larger than the distributed resistance. We recently developed a technique to synthesize ultra-long SWNTs[17], and were able to measure the resistance for a variety of different lengths[12, 13]. In our measurements, the contact resistance was small compared to the bulk resistance, so this allowed is to determine how the resistance depends on the length. Our measurements indicate that the resistance per unit length is around 10 kΩ/μm. When scaled by the diameter of 1.5 nm, this gives rise to a conductivity which is larger than copper. At present, the scattering mechanism (impurity or electron-phonon) is unknown. If the mechanism is dominantly impurity scattering, then it should be possible to improve the conductivity through adjusting the processing parameters to minimize the impurity density.

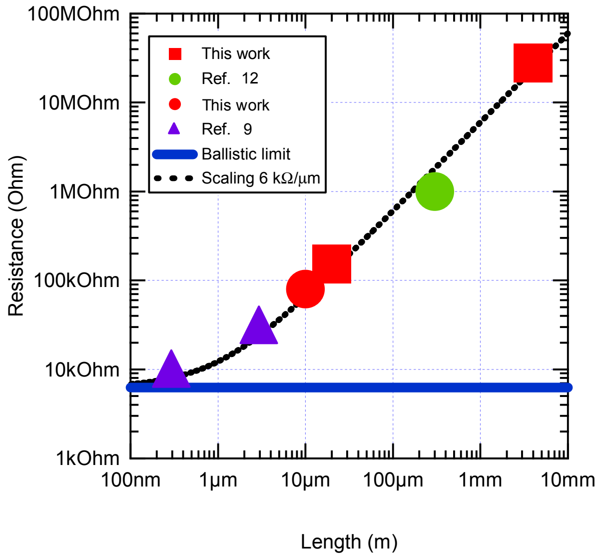

Figure 5: Resistance vs. length of a SWNT (from ref. 13).

B. AC impedance

So far there have been no measurements of the microwave impedance of a SWNT. However, we have developed extensive circuit models that take into account the quantum capacitance, electrostatic capacitance, and kinetic inductance, as well as resistive damping[18, 19]. There, we showed that a SWNT forms a quantum transmission line with characteristic impedance of order the resistance quantum (10 kΩ), and wave velocity about c/100.

A critical issue for the ac performance is to understand whether the resistive, inductive, or capacitive impedance is the dominant component of the total impedance. If the ac resistance per unit length is the same at microwave frequencies as the value we measured at dc, then the microwave impedance will be dominantly real for frequencies below about 100 GHz.

VIII. CONCLUSIONS

The development of nanowire and nanotube electronics is in its infancy. If manufacturing challenges can be met, simple estimates show that cutoff frequencies of order THz should be possible.

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