Carbon Nanotubes for RF and Microwaves

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Abstract — **In this invited overview paper we provide a brief up-to-date summary of the potential applications of carbon nanotubes for RF and microwave devices and systems. We focus in particular on the use of nanotubes as ultra-high speed interconnects in integrated circuits.**

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 on the electronic properties of nano-scale devices. With this in mind, in this paper we provide an overview of potential applications of nanotube and nanowire devices in microwave technology.

II. BENCHMARKS

Three general benchmarks define the evaluation of any complementary or disruptive device technology: speed, power, and density. Although ideally all three benchmarks will be satisfied by the same technology, in general the end application will determine the required technology and the relative importance of each component of the technology.

A. Density

It is clear that nanotubes because of their small size have much to offer: Laboratory prototypes are already much narrower (down to ~ 1 nm) in diameter than any existing or predicted lithographic technique.

B. Power

Power density is currently a major issue for high speed integrated circuits. It is not clear what the solution will be, although this is a more general problem not specific to nanotechnology.

C. Speed

We have formerly predicted[2] that semiconducting nanotubes and nanowires can be employed as ultra-fast electronic devices. We also demonstrated the first GHz operation of a single walled carbon nanotube (SWNT) transistor[3]. The cutoff frequency has still not been measured because difficulties of impedance matching to single nanotube devices which have high on resistances (tens of kΩ). As a possible solution, we also proposed techniques to fabricate parallel devices for better impedance matching[4].

III. ACTIVE DEVICE AC PERFORMANCE

By now it is common knowledge that carbon nanotubes (Fig. 1) can perform as transistors because certain classes of nanotubes are semiconducting materials. (Other classes of nanotubes are metallic materials, and their applications in interconnects will be discussed later.) In this section we address their high frequency performance, both theoretical and experimental.

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 SWNT transistors are by our group at a spot frequency of 2.6 GHz[3]; these were performed at cryogenic temperatures where parasitic substrate coupling is negligible. Room temperature work has been limited to frequencies below 1 GHz so far[5-7], but it is anticipated that new results will be published soon on the performance of SWNT FETs at microwave frequencies at room temperature.

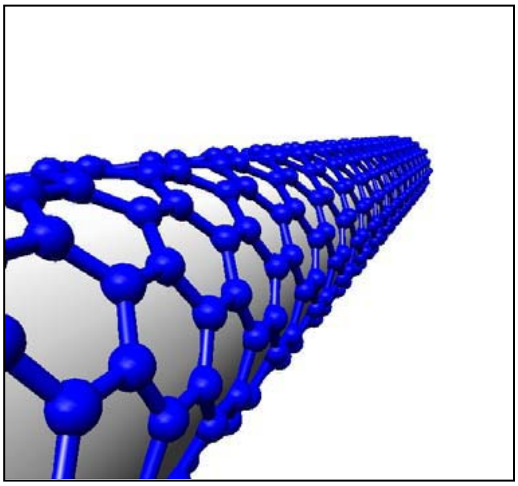

Fig. 1: Single walled carbon nanotube.

B. *Modeling*

The intrinsic speed response of nanotube FETs should be of order THz, as we recently calculated[2]. However, the effect of contact resistance and parasitic capacitance can dramatically reduce this ideal to around 10 GHz for realistic geometries. Our proposed circuit model which takes into account the parastitics is reproduced in Fig. 2 below.

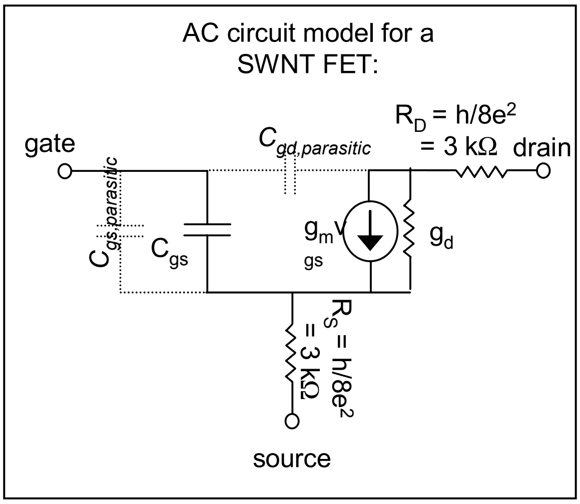

Figure 2: AC circuit model for SWNT FET. (From ref. 2.)

C. *Parallel devices*

One prospect to remove the effect of parasitics was proposed recently by us: to us parallel arrays of CNT FETs[4]. In Fig. 3 we show a recent SEM image of aligned arrays of SWNTs synthesized in our labs. By adjusting the growth procedure it may be possible to achieve finer pitch and hence have a high current density CNT FET appropriate for impedance matching to a 50 Ω system.

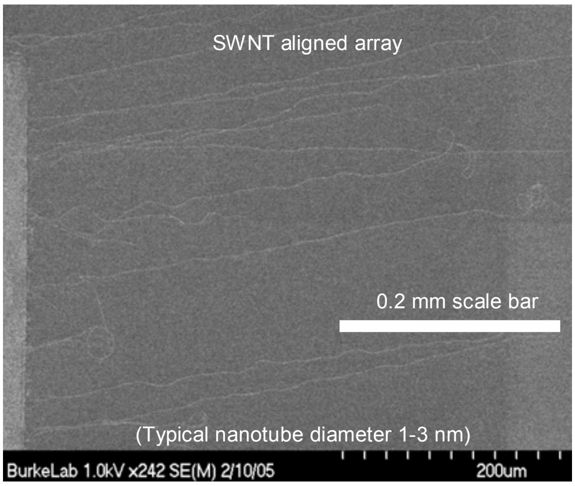

Figure 3: Aligned array SWNTs.

IV. INTERCONNECTS

A metallic nanotube has a diameter of order 1-3 nm, and can carry currents up to 25 μA or higher[8, 9]. 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. *Progress in growth of macroscopic nanotubes*

Interconnects typically carry current over several mm, yet nanotubes are only a few nm wide. However, as is shown in Fig. 4, the progress in growth of electrically contacted single walled nanotubes has been rapid. It is now possible to synthesize and electrically contact SWNTs of macroscopic dimensions. (Data for the chart is from references [10-20].) This, and other factors, open the door to the use of nanotubes as interconnects for dc and high frequency (GHz) signals.

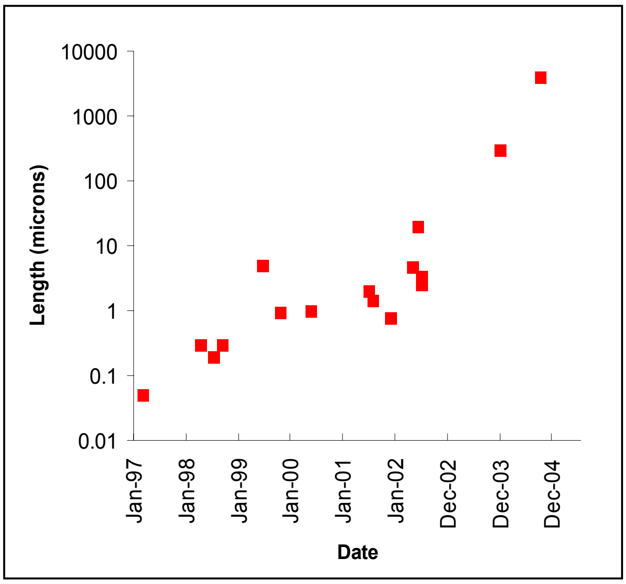

Fig. 4: Length of electrically contacted individual SWNTs vs. year.

B. *Nanotube resistance vs. length*

A single walled carbon nanotube is inherently a 1d conductor. Therefore, it is not possible to perform a four-terminal resistance measurement to determine the resistivity. There will always be some contact resistance. Quantum mechanics sets the lower limit on this contact resistance to be $h/4e^2$, which is about 6 kΩ.

For short nanotubes, the transport is ballistic from one end of the tube to the other. For long nanotubes, the transport may be diffusive, meaning there are many scattering events as the electron travels along the nanotubes. We and others recently developed a technique to synthesize ultra-long SWNTs[21-24]. With these, we were able to measure the resistance for a variety of different lengths[25, 26].

In Fig. 5, we plot the resistance vs. length for many different SWNTs measured in many different labs around the world. (This is an updated figure from our recent paper[26], and is compiled from references [8, 25-29]). In selecting the data we have chosen the lowest published resistance for each length. It is clear from this graph that the resistance per unit length is about 6 kΩ/µm.

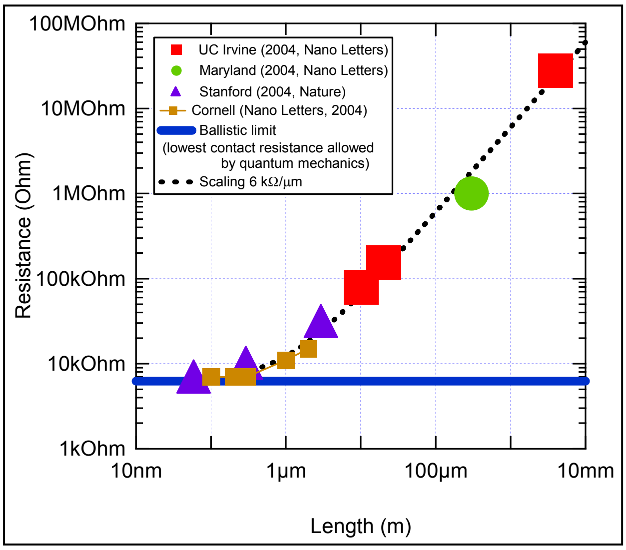

Figure 5: SWNT resistance vs. length.

C. Nanotubes vs. copper: resistivity

When scaled by the diameter of 1.5 nm, the resistance per unit length we measure gives a resistivity conductivity of 1 µΩ-cm, which is lower than that of bulk copper. In addition, copper interconnects typically suffer increased surface scattering as the dimensions are decreased below 100 nm[30], so that even the bulk conductivity of copper is not realized at that length scale. In addition the current density of carbon nanotubes exceeds that of copper. For all of these reasons it is clear that, per unit width, carbon nanotubes are superior materials to copper as interconnects in integrated circuits.

The "only" remaining problem is to develop economical and precise manufacturing, sorting, and placement techniques.

D. Nanotube vs. copper: inductance

One of us recently developed an RF circuit model for metallic nanotubes[31, 32]. This has given rise to some confusion in the device community regarding the effect of the kinetic inductance. We would like to discuss that issue here.

The kinetic inductance for an individual nanotube is about 4 nH/µm. Numerically this gives rise to an inductive impedance of iωL, where L is the inductance. However, the resistance per unit length (see above) is about 6 kΩ/µm. This means that the resistive impedance will dominate the inductive impedance at frequencies below about 200 GHz for a single walled nanotube. Therefore, when considering the applications of nanotubes as interconnects at microwave frequencies, the resistance should be the dominant consideration.

On the other hand, we have argued above that the conductivity of nanotubes is larger than copper. We argue that arraying nanotubes would allow for wiring with less resistance per unit length than copper of the same total cross sectional area. In addition, the kinetic inductance of an N-array of nanotubes is N times lower than the kinetic inductance of an individual nanotube.

In sum, for nanotubes resistance is the dominate circuit component (as opposed to inductance), and this resistance is smaller than copper wires of the same dimensions. Therefore it does not seem like kinetic inductance will be a major "show-stopper" for the use of nanotubes as interconnects.

As a final clarification, there is no cross-talk between nanotubes due to kinetic inductance. This is in contrast to magnetic inductance, which induces cross-talk. Therefore, considering all these factors, carbon nanotubes still seem superior materials to copper in all aspects of circuit performance.

The only aspect in which copper is superior is cost and manufacturability, both issues which in principle can be addressed by further research and development in nanotube synthesis.

E. Nanotube ac impedance to 10 GHz

We have recently verified experimentally the above claims: We showed that the dynamical impedance [33] of a metallic SWNT is dominantly real and frequency independent from dc to 10 GHz, and that the resistance is lower than a similar sized copper wire would be. Our measurements were performed on 1 and 25 µm long nanotubes that were thus in the ballistic and diffusive regime. These first experiments thus have validated our claims above that nanotubes could serve as a legitimate high frequency interconnect technology.

V. CONCLUSIONS

We have discussed some of the applications of nanotubes and nanowires in microwave electronics. Many research and manufacturing challenges remain to be solved before the technology is ready for system insertion, but progress in this field is rapid and expectations are high.

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