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SINGLE-WALLED CARBON NANOTUBES: APPLICATIONS IN HIGH FREQUENCY ELECTRONICS

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In this paper, we review the potential applications of single-walled carbon nanotubes in three areas: passives (interconnects), actives (transistors), and antennas. In the area of actives, potential applications include transistors for RF and microwave amplifiers, mixers, detectors, and filters. We review the experimental state of the art, and present the theoretical predictions (where available) for ultimate device performance. In addition, we discuss fundamental parameters such as dc resistance as a function of length for individual, single-walled carbon nanotubes.

Keywords: Nanotube; interconnect; amplifier; antenna.

1. Introduction

The development of carbon nanotube synthesis, both for single-walled nanotubes (SWNTs) and multi-walled nanotubes (MWNTs), and of nanotube device physics has been rapid in the previous decade. The sphere of potential applications is broad due to their superior mechanical, thermal, and electrical properties. These have been reviewed in several recent monographs[1-7], as well as other manuscripts in this volume. However, an intriguing sphere of application which has until recently received relatively minor attention is in the area of high speed (RF, microwave, mm-wave, and THz) electronics. At first glance, the idea of combining nanotechnology with RF circuitry may seem to be a rather poor match, due to the typically high impedance of nano-electronics devices. However, the intrinsic speed limit of carbon nanotube devices can be very high, up to the THz range, so that on further reflection it seems potentially feasible to fabricate high speed devices and ultimately systems out of carbon nanotubes. The topic of this paper is to discuss how far along we are on the road to this goal, and in what manner it makes sense to even continue development of the technology, at least for high speed systems. Since the progress in synthesis has been very rapid, it is our point of view (at least for this review) that one should evaluate the ultimate potential of the technology, assuming the problems of economical fabrication could be solved.

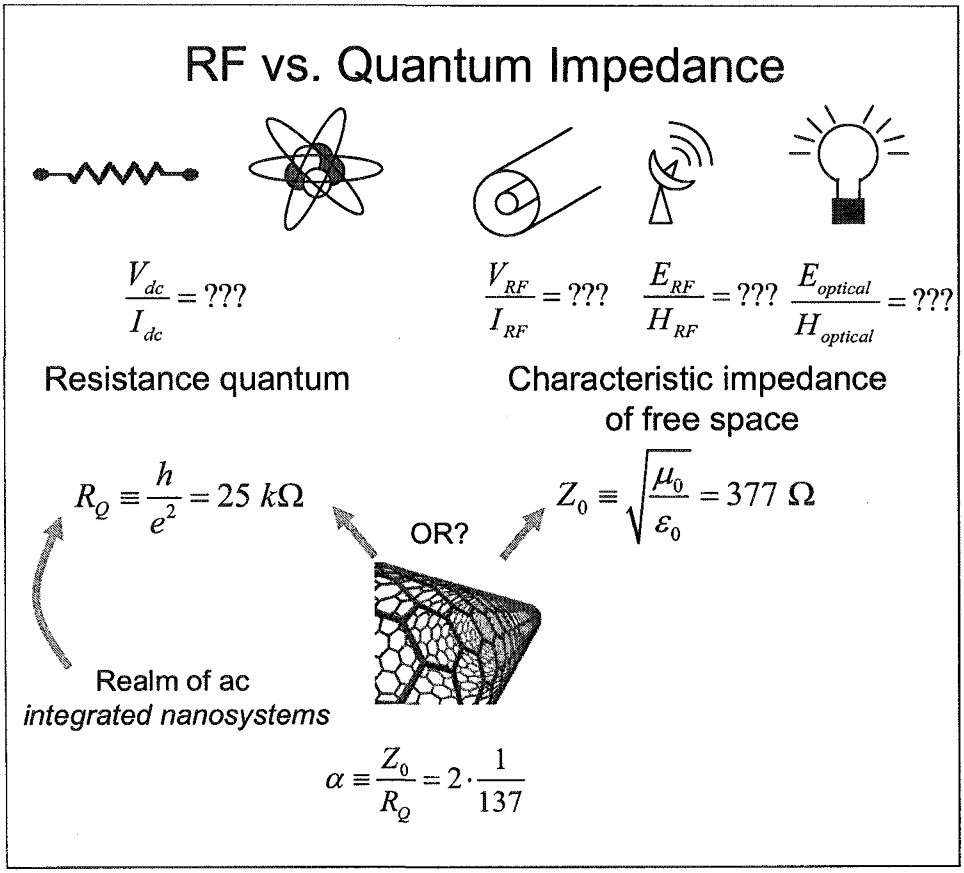


Fig. 1: Impedance matching and AC nanosystems.

2. AC Nanosystems

In RF waveguides, the ratio of the RF voltage to the RF current is of order the characteristic impedance of free space, i.e. 377 Ω. The ratio of the RF electric field to the RF magnetic field in free space plane waves is also of order 377 Ω. (The same is true for optical plane waves, as well.) On the other hand, nano-electronic devices such as resistors with dimensions of order the de Broglie wavelength of the electrons (typically the Fermi wavelength) have dc resistance values of order the resistance quantum[8, 9] $h/e^2 = 25$ kΩ. The ratio of these two impedances is known as the fine structure constant α, and is dependent on only three fundamental constants of the universe: the charge of the electron e, the speed of light c, and Planck's constant h. Therefore, there is an apparent built-in impedance mismatch between nanotechnology and RF. This mismatch has occupied the single-electron-transistor community for many years[10], and is now germane to the issue of nanotube based devices.

A general question thus arises: If one is interested in nano-electronic devices clocked at GHz or higher frequencies, to which domain do they belong: The quantum resistance domain, or the free space impedance domain? It appears that there is no general answer to this question. However, we can make the following general claims: First, if an individual nano-device is to talk to the outside world, it will need to drive an impedance of order the characteristic impedance of free space. In this case, the impedance matching problem must be dealt with and cannot be ignored.

However, a paradigm we have recently advocated[11] is one of *integrated nanosystems*, in which nanotubes and nanowires are used both as the active elements and as the interconnects. In this case, the devices can all be dealt with in the realm of the resistance quantum, and still operate at ultra-high speeds. Such a paradigm is worth further investigating, but our conclusions will become clearer on this issue below.

3. SWNT electronic properties

The electronic properties of SWNTs vary, depending on their diameter and chirality[12]. The chirality determines whether the nanotube behaves as a metal or semiconductor. Experimentally, metallic nanotubes are typically distinguished by the absence of a dependence of the small bias conductance on a gate voltage. Similarly, semiconducting nanotubes have a conductance that depends strongly on the gate voltage. The band-gap of semiconducting nanotubes is related to the diameter through the $E_g = 0.9$ eV/d[nm], where d is the diameter in nm.

4. Synthesis

Since the original development of chemical vapor deposition (CVD) for nanotube synthesis from lithographically defined catalyst pads was developed in 1998[13], many groups around the world have continued to focus on using CVD for synthesis. In this section, we focus on a particular metric, that is the synthesis of relatively long single-walled carbon nanotubes. The reason, as will become clear below, is that nanotubes may have a role to play as interconnects and the synthesis of long tubes is a necessary step in that direction. Additionally, long SWNTs allow one to measure the resistivity without worry about contact resistance effects. In Fig. 2, we show an SEM image (from ref. [14], with permission) of an electrically contacted, 0.4 cm long SWNT synthesized in our labs.

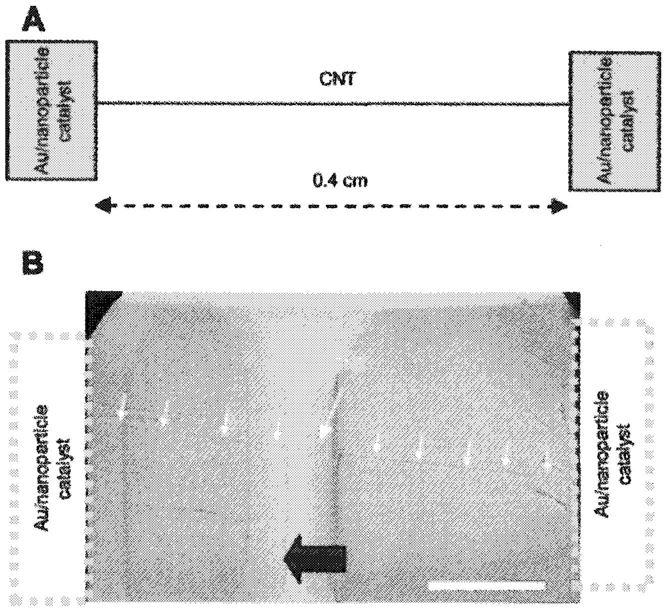


Fig. 2: Electrically contacted, 0.4 cm long SWNT, from [15].

In Fig. 3, we show a plot of length vs. year of electrically contacted, individual SWNTs (adapted from [15], with permission). (Data for figs. 3,4 from references [14, 16-37].) The progress has indeed been rapid. In addition, the tubes grown in CVD are highlighted in red, indicating that the growth technique has had a significant impact on the synthesis of long nanotubes. In Fig. 4, we show the length vs. year of all individual SWNTs. The electrically contacted SWNTs are circled in red. The progress has been about an order of magnitude increase in length per year. Such progress is rapid, even by the modern standards of electronics technology. It remains to be seen if and when such progress will plateau.

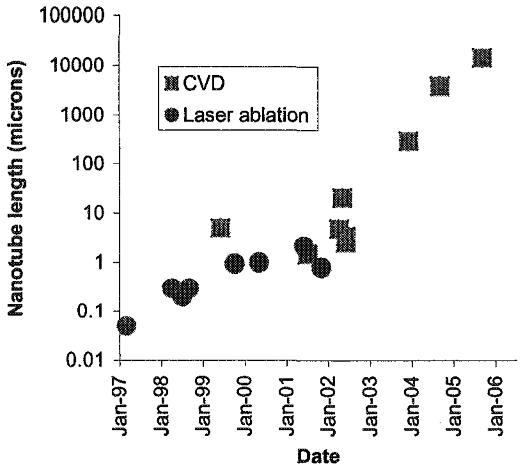


Fig. 3: Electrically contacted individual SWNT length vs. year.

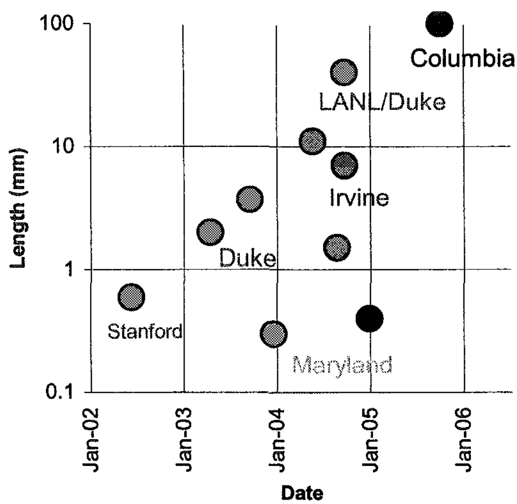


Fig. 4: Individual SWNT length vs. year.

5. Single walled nanotube DC resistivity

A nanotube can be considered a one-dimensional conductor, even at room temperature. It is by now well established[8, 9] that it is not possible to measure the resistivity of a 1d conductor using a four terminal measurement: any terminal attached to the conductor destroys the one dimensional nature of the conduction. Therefore, one can only perform a two-terminal measurement, and the contact resistance must be addressed.

For 1d systems that are in the ballistic limit (i.e. length less than the mean free path), the contact resistance is always greater than or equal to $h/e^2 = 25$ kΩ. In SWNTs, this number is modified by a factor of 2 for band structure degeneracy and a factor of 2 for spin[12], so that the lowest possible resistance a SWNT can have (when it is shorter than the m.f.p.) is $h/4e^2 = 6$ kΩ. However, in cases where the contact is poor (for example, if there is a Schottky barrier at the metal/nanotube interface), the resistance can be and typically is much higher. Recent work has shown that use of Pd as the contact material allows the theoretical limit to be reached, at least for very short SWNTs[38-40]. Prior to this, the more commonly used metal was Au and gave resistances of order MΩ, which was due to the poor contact.

On the other hand, if the nanotube is long compared to the mean-free path, then the resistance will have a component that scales linearly with length. Exactly how long is the mean free path in a SWNT? This question has not been definitively answered, but by plotting the resistance vs. length for tubes of a variety of different lengths, one can get a reasonable estimate. To date, no studies have been published investigating this in full detail, so we are forced to use results from the literature, which will be expected to have a variation due to different processing conditions, different nanotube diameters, different measurement temperatures, and different species (i.e. metallic or semiconducting). Although the amount of data on nanotubes in the limit that the contact resistance is small is not large (there are only a few publications), the curve plotted in Fig. 5 (adopted from ref. [14], using data from refs. [14, 35, 38, 40-43]) shows a remarkably consistent trend: nanotubes with length less than about 1 micron can approach the ballistic limit. On the other hand, nanotubes with length greater than about 1 micron have a resistance per unit length of about 6 kΩ/μm. This indicates a mean-free path of about 1 μm, since (neglecting the contact resistance) the equation for the m.f.p. in 1d diffusive conductors is[8]:

(1) $$R_{dc} = \frac{h}{4e^2}\frac{L_{nanotube}}{l_{m.f.p.}}$$

Remarkably, this indicates as 3d resistivity (assuming a diameter of 1.5 nm) of 1.1 μΩ-cm, which is lower than *bulk* copper (which has a value of 1.7 μΩ-cm). Thus, if a tightly packed array of SWNTs could be synthesized economically, the material would be a potentially disruptive technology for interconnects in integrated circuits. This motivates our discussion of the high frequency properties of single walled nanotubes as conductors.

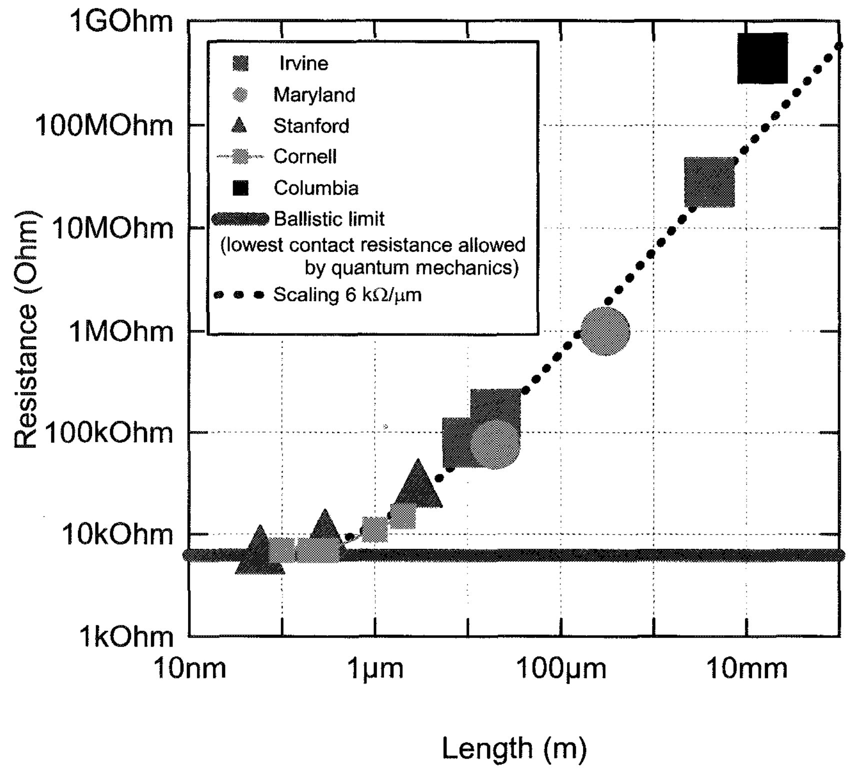


Fig. 5: Resistance vs. length for lowest published value at each length, from [14].

6. Metallic nanotubes as interconnects: RF properties (theory)

The RF circuit properties of a 1d conductor were originally discussed by Wesstrom[44], who developed a transmission line description. However, at the time the technology to experimentally address the concepts was lacking. In a related set of papers, theoretical physicists have been considering the ac impedance of 1d conductors from the Luttinger liquid point of view for over a decade[45-51]. We have recently applied the concepts of transmission line theory to develop a general RF circuit model for a single walled nanotube[52-55]. Salahuddin has generalized this approach to include multi-mode quantum wires[56]. Such a circuit model consists of distributed electrostatic capacitance and magnetic inductance, just as a classical transmission line. However, the model also includes quantum capacitance and kinetic inductance, which are absent in a classical transmission line. These extra elements describe a transmission line with characteristic impedance of order the resistance quantum, and a wave velocity of order c/100. Thus, the use of nanotubes as interconnects can allow one to stay in the realm of the resistance quantum even for transmission line work, and avoid the problems of impedance matching of active devices to the characteristic impedance of free space. Fig. 6 shows the equivalent RF circuit model for a SWNT over a highly conducting ground plane, neglecting damping (from Ref. [52], with permission).

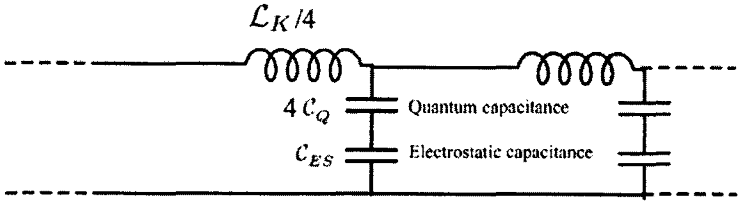


Fig. 6: RF circuit model for a SWNT, neglecting damping, from [52].

From the above section, we have a reasonable estimate of the dc resistance per unit length of about 6 kΩ/μm. Thus, if the ac damping is the same as the dc damping, the equivalent circuit model should include a resistance per unit length as well.

It may appear that the kinetic inductance is a problem for slowing down signal propagation on a nanotube. However, by comparing the kinetic inductance per unit length to the resistance per unit length, one comes to the conclusion that the resistive impedance will be more important than the inductive impedance for frequencies below about 200 GHz, at least for the 6 kΩ/μm number quoted above. These issues have also been recently discussed in Ref. [56]. For *integrated nanosystems*, this may result in some propagation delay.

A more critical issue to the propagation of information on nanotubes it that of dispersion, which will appear in any resistive system (including Cu) with capacitance. In fact, the resistivity of Cu is higher than that of nanotubes, so it is still possible that the dispersion on nanotubes is better than on Cu of the same dimensions, although this remains to be investigated more thoroughly. In Fig. 7, we plot our calculations of the real nanotube impedance vs. frequency for a realistic length of 100 μm and resistance per length of 1kΩ/μm. It is clear that the impedance is undergoing significant frequency dependence (i.e. dispersion) at around the technologically relevant frequency of 1 GHz. This issue still needs to be addressed in more depth based on the application in mind, but our general circuit simulation techniques[52-55] should allow for modeling of the electrical properties at high frequencies.

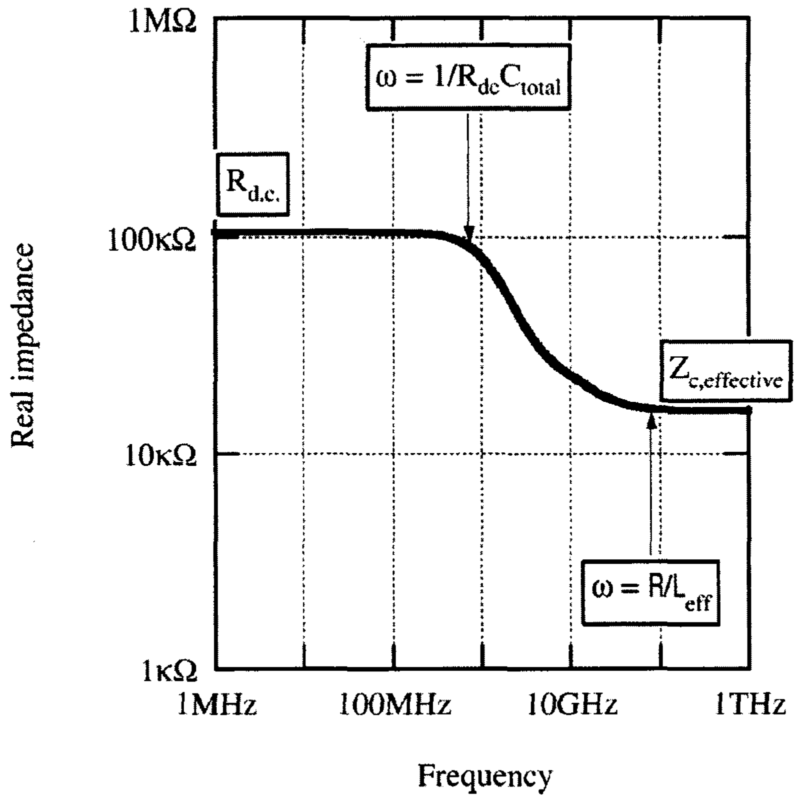


Fig. 7: Simulated real impedance for a 100 μm long SWNT, assuming a resistance per unit length of 1 kΩ/μm.

7. Metallic nanotubes as interconnects: RF properties (experiment)

Although the models provide some interesting intellectual exercises in understanding the interaction of microwave signals with 1d quantum systems, the fact remains that very few experiments to date have been performed to validate the proposed models. We recently measured the ac conductance of a 1 μm and 25 μm long SWNT (allowing both diffusive and ballistic transport to be probed), in both the low electric field and high electric field limit, up to 10 GHz. Prior work has demonstrated that the high electric field current in a metallic SWNT saturates at around 25 μA[57]. There, it was shown that the saturation behavior is due to a modified mean-free-path for electrons when the electric field is sufficient to accelerate electrons to a large enough energy to emit an optical phonon. This effect was studied more quantitatively with similar conclusions in [39, 41].

In our recent RF measurements, we measured the change in the RF conductance as a function of bias voltage, and found no frequency dependence out to 10 GHz. The central results are plotted in Fig. 8 (from Ref. [58], with permission.) This work demonstrated clearly that nanotubes can carry current up to 10 GHz just as well as at DC, which is clearly significant.

To date no time-domain studies have been performed on nanotubes as interconnects, and no experimental studies on dispersion have been performed. Thus, while the promise is clear, there is still much work remaining to be done to validate the technology for RF applications in interconnects.

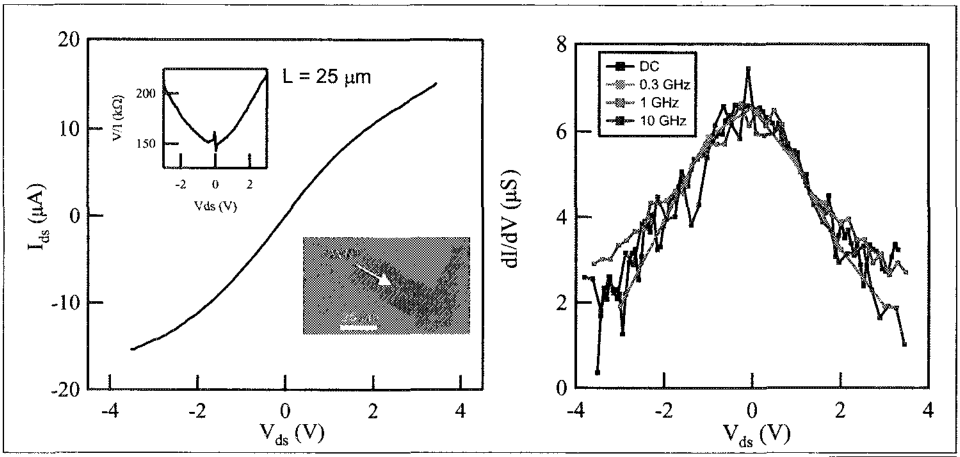


Fig. 8: I-V curve of 25 μm long SWNT and RF and DC conductance vs. V_{ds}, from [58].

8. Nanotube transistors: Cutoff frequency (theory)

A general figure of merit for any transistor technology[59] is the cutoff frequency f_T. In general, this can be limited by two timescales: an RC time, and a capacitance over transconductance time. For a SWNT field effect transistor (FET), the typical device geometry is shown in Fig. 9 below[60, 61], from Ref. [11] with permission. The on-state resistance of a SWNT FET is limited to 6 kΩ ($h/4e^2$) or higher. This is quite a high resistance compared to 50 Ω, so that the impedance matching and parasitics are a significant issue. Nonetheless, the intrinsic performance of the device is expected to be quite fast.

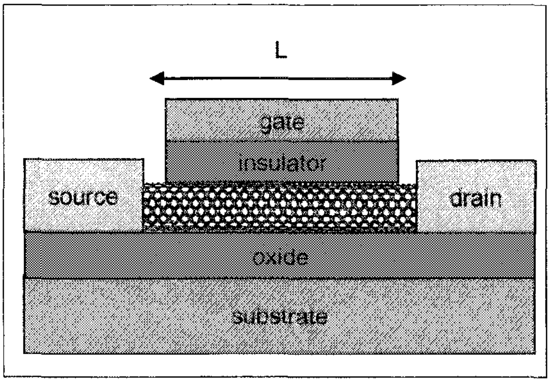


Figure 9: Typical geometry for a SWNT FET., from [61].

The intrinsic capacitance is typically of order 10s of aF. Therefore, the RC time for the intrinsic capacitance is extremely fast. The transconductance over the capacitance is the limiting factor. Here, measured transconductance values (which have been in the 10 μS range) also give rise to an extremely high intrinsic speed limit. Based on these arguments, we predict semi-phenomenologically a cut-off frequency of 80 GHz/L_{gate}[μm], where L_{gate} is the gate length in μm. This prediction was independently derived by more rigorous simulations recently[62]. Thus, for sub-micron gate lengths, THz cutoff frequencies may be possible. In Fig. 10, we plot the predicted intrinsic cutoff frequency vs. gate length, reproduced from Ref. [11], with permission.

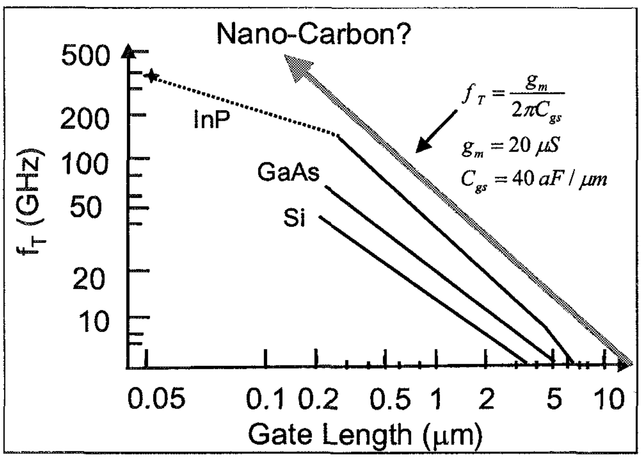


Figure 10: Cut-off frequency vs. gate length, from [61].

In order to quantitatively ascertain the effects of parasitics on realistic device performance, an effective circuit model for the device in the absence of parasitics is necessary. We recently proposed such a circuit model[11], and it is shown in Fig. 11. Here, by taking into account reasonable parasitics, we have predicted that the cutoff frequency for a typical example of a

0.1 μm gate length is about 10 GHz. Thus, the effects of parasitics are extremely important in SWNT FETs.

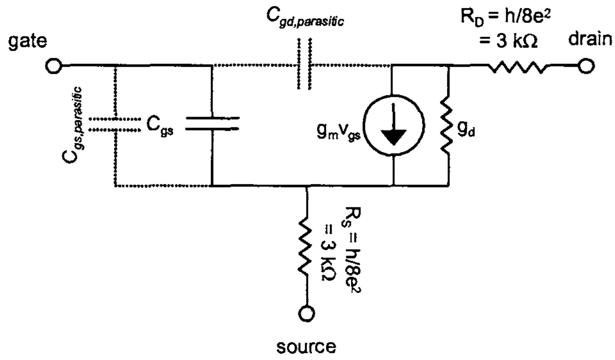
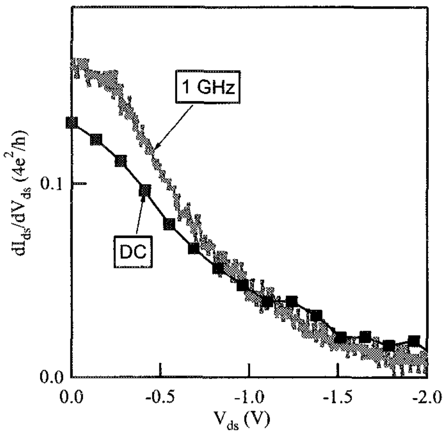


Figure 11: Small signal circuit model for SWNT FET, from [61].

9. Nanotube transistors: High frequency performance (experiment)

To date, only relatively few experiments have been performed on the high frequency properties of SWNT FETs. In 2003, we demonstrated that the small-bias source-drain 2.6 GHz conductance of a back-gate SWNT FET depended on the dc gate voltage[43]. This was performed by constructing an off-chip LC impedance matching circuit out of discrete components. That work was performed at cryogenic temperatures, where Coulomb blockade effects were also significant. More recently, we have demonstrated that the room temperature 1 GHz source-drain conductance at both low and high dc source-drain bias voltages was the same as the dc conductance of a back-gated SWNT FET, after the parasitics were subtracted from the measurement[63]. These measurement results are shown in Fig. 12 below.



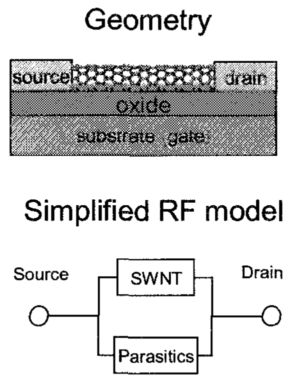


Fig 12: DC and AC source-drain dynamical conductance of SWNT FET, from [63].

In the time-domain, IBM has performed the first and so far only pulsed experiments[64], which show performance with sub-μs speed, again limited by parasitics, as we discussed above.

Thus, the experimental state of the art of SWNT FETs for high frequency applications is still in its infancy. While the intrinsic device cutoff frequency can by in the THz range, significant challenges remain, in particular the issue of the parasitic capacitances, to achieve this potential performance. One potential solution is to use aligned array SWNT FETs, discussed next.

10. Array devices

One possibility for impedance matching is to fabricate aligned array devices. We show this basic concept in Fig. 13 below, from [65]. To date such a vision has been difficult to achieve, since in practice techniques to synthesis aligned arrays have too large of a pitch (typically larger than 10 μm[36]), and also do not produce purely semiconducting nanotubes. If metallic nanotubes are present, the device will not turn completely off. Recent work on random mixtures of metallic and semiconducting nanotubes has been performed along these lines[66]. However, such an avenue holds promise for improving impedance matching for nanoscale electronics, in spite of the technological fabrication challenges.

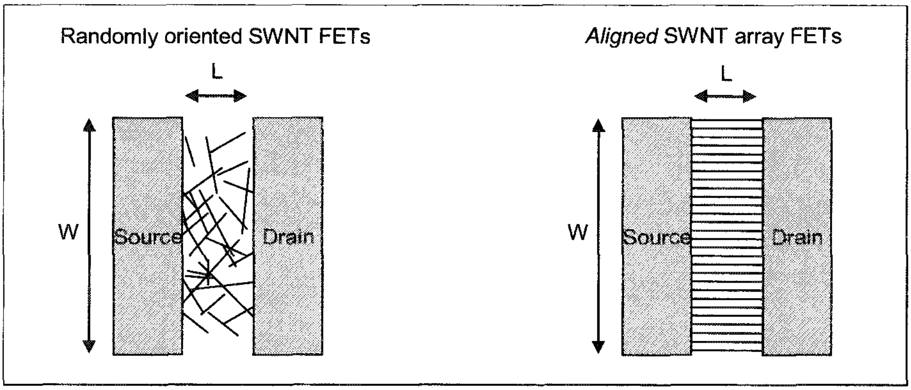


Fig 13: Concept for aligned array FETs, from [65].

11. Non-linear devices: Mixers and detectors

While transistor linear response data has been difficult to measure due to the impedance mismatch and effect of parasitics, device non-linear performance has been more clearly studied. A simple, straightforward experiment to study device non-linear performance is to apply an ac voltage to either the gate or the drain, and measure the induced dc current as a function of the ac frequency. In such a study, the nanotube performs as a non-linear detector (or a homodyne mixer) of RF voltages. Such studies probe whether the non-linearity in the transistor I-V curve persist up to high frequencies, and also give some quantitative information about parasitics.

IBM presented studies of these kinds initially on back-gated SWNT FETs up to 580 MHz[67, 68], and was limited by parasitics in going higher in frequency. Recently, Cornell has extended these studies to top-gated SWNT FETs, and measured results up to 50 GHz[69]. Interestingly, they observe a roll-off in the device response as a detector at around 10 GHz, which is exactly where we predicted parasitics would be important for linear device response. Thus, device non-linearities persist to microwave frequencies and possibly beyond, but impedance matching and parasitics are still critical to quantify, understand, and overcome.

12. Nanotube antennas

One final area of potential application is in the use of nanotubes as antennas[70, 71] antennas. So far in the RF and microwave, no experiments have been reported on this topic. However, there have been some theoretical developments. The essential idea is captured schematically in Fig. 14 below (from Ref. [72]). This idea could be useful for any application in which wireless contact to a nanoscale device is required, e.g. nano-scale sensors.

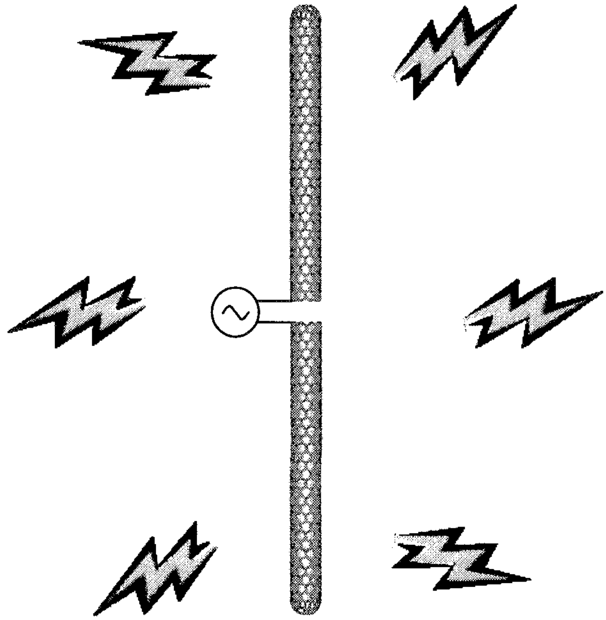


Fig 14: Concept for a nanotube dipole antenna, from [72].

One of the most fundamental parameters of any antenna is the current distribution on the antenna. This determines the radiation pattern, the radiation resistance and reactance, and many other properties of interest. Modern work on antenna theory is typically numerical because of the lack of analytical solutions. In contrast, early work on antenna theory (including some pioneers such as Hallen and Schelkunoff[73-77]) focused on deriving analytical expressions for the current distribution on an antenna.

In their work, the only geometry to which an analytical solution is available (to our knowledge) is the simple dipole antenna. Analytical expressions are available as series expansions in the parameter d/l, where d is the diameter and l the length. Virtually all of modern antenna theory takes as its canonical example the characteristics of a dipole antenna in the limit d/l goes to zero.

Now, with the advent of cm long carbon nanotubes, it is possible to fabricate conducting wires with unprecedented aspect ratios of order 10^7. This has led us to propose a nanotube antenna, shown in Fig. 14. At first sight, it would seem that this new system would be the closest physical realization to a dipole antenna (in the sense that d/l is small) mankind has ever manufactured. However, this is not the case, as we elaborate on below.

In original theoretical work on dipole antennas, it was assumed that the dipole radius was larger than the skin depth, *and* that the resistive losses were low enough to be neglected in determining the current distribution on the antenna. Both of these assumptions break down for nanotube antennas. Therefore, the original theory and hence the only analytical theory breaks down in the limit d/l becomes sufficiently small.

In a one-dimensional conductor such as a nanotube, the concept of skin-depth is almost meaningless, since the electrons are only free to move along the length of the wire, and not in the transverse direction. Therefore the current distribution is effectively one-dimensional. In addition to the electron transport occurring in only one dimension, we also have two more important effects: large resistance, and large inductance.

These effects give rise to very different behavior for a nanotube antenna, as compared to a classical antenna. The main difference is the current distribution is periodic with a wavelength about 100 times smaller than the free space wavelength for a given temporal frequency. The comparison of the current distribution on a nanotube dipole antenna to a classical dipole antenna is shown in Fig. 15 below (from Ref.[70], with permission). It is clear that the current distributions are dramatically different. Our work has been further developed numerically by Hanson[71].

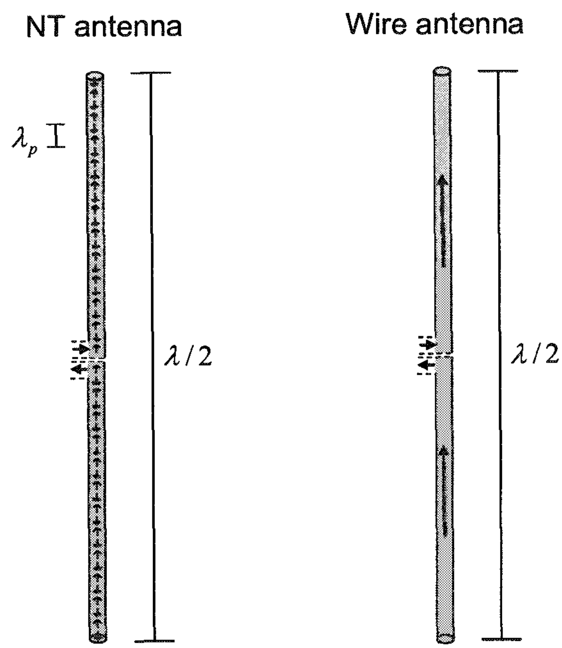


Fig 15: Current distribution on a nanotube antenna vs. classical wire antenna. λ is the free space wavelength (set by the frequency), and λ_p is the wavelength of the current distribution on a nanotube, which is typically about 100 times smaller than the free space wavelength, from [70].

Our calculations[70] show that the efficiency of a classical nanotube dipole antenna is poor, due to resistive losses. However, we have proposed that possibly other geometries (to be determined) could and should be investigated that take advantage of the unique materials and electronic properties of carbon nanotubes. An important issue is that of impedance matching the antenna to any generator, which will depend on the source impedance of the generator.

A more general theory of nanotube "antennas" which applies even in the optical frequency range to scattering experiments[78] has been developed in [79-84]. The application of the concept of antenna is really not limited just to the RF frequency range. However, much theoretical and experimental work remains to be done to truly understand and utilize the concepts in engineering applications.

13. Conclusions

In this paper, we have reviewed the potential applications of single-walled carbon nanotubes in three areas: passives (interconnects), actives (transistors), and antennas. In the area of actives, potential applications include transistors for RF and microwave amplifiers, mixers, detectors, and filters. While the experimental and theoretical state-of-the art is clearly in its infancy, the promise for high frequency electronics is great, and progress is extremely fast. It is not a stretch to predict that nanotubes will find applications in high frequency electronic systems sometime in the future.

14. Acknowledgements

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