Carbon Nanotube Devices for GHz to THz Applications

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ABSTRACT

The study of the ac properties of nano-electronic systems is still in its infancy. In this paper we present an overview of recent work aimed at advancing the understanding of this new field. Specifically, we first discuss the passive RF circuit models of one-dimensional nanostructures as interconnects. Next, we discuss circuit models of the ac performance of active 1d transistor structures, leading to the prediction that THz cutoff frequencies should be possible. We recently demonstrated the operation of nanotube transistors at 2.6 GHz. Third, we discuss the radiation properties of 1d wires, which could form antennas linking the nanoworld to the macroworld. This could completely remove the requirements for lithographically defined contacts to nanotube and nanowire devices, one of the greatest unsolved problems in nanotechnology.

Keywords: Nanotube, nanowire, GHz, THz, antenna.

1. INTRODUCTION

In this invited paper, we present an overview of the high-frequency properties and applications of carbon nanotubes, one realization of nano-electronic devices, and where the challenges and opportunities lie in this new field. The study of the ac properties of nano-electronic systems is still in its infancy.

The first step towards understanding the high-frequency electronic properties of carbon nanotubes is to understand the passive, ac impedance of a 1d quantum system. We have recently proposed[1, 2] an effective circuit model for the ac impedance of a capacitively contacted nanotube, and a dc contacted nanotube. We also recently demonstrated[3] the operation of carbon nanotube transistors at microwave frequencies (2.6 GHz). In our lab, we have also been able to synthesize the world's longest electrically contacted nanotubes[4, 5] (up to 0.4 cm in length), allowing us to elucidate the relationship between contact resistance and bulk resistance. Finally, we recently developed a model for nanotubes as antennas[6], which could be useful in connecting nano-electronics systems to the outside world via a wireless communications link, thus completely eliminating the need for lithographically defined contacts. In this conference paper, we review this recent significant developments, summarizing what we know and what work remains to be done.

2. NANOTUBES AS INTERCONNECTS

Since nanotubes (and nanowires) can operate as transistors, it is natural to discuss their properties as interconnects, as well. As transistors, we have predicted[7] that the cutoff frequency can be in the THz range. However, this is only possible if the parasitic capacitances can be minimized. One way to do this is to use nanotubes and nanowires themselves as the interconnects. Therefore, the RF properties are of some technological importance.

While our model below is formulated for single-walled metallic nanotubes, it should be approximately correct for semiconducting nanotubes as well. In the presence of a ground plane below the nanotube or top gate above the nanotube, there is electrostatic capacitance between the nanotube and the metal. Due to the quantum properties of 1d systems, however, there are two additional components to the ac impedance: the *quantum capacitance* and the *kinetic inductance*. Thus, the equivalent circuit of a nanotube consists of three distributed circuit elements, which we summarize in Figs. 1 and 2 below.

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2.1. Electrostatic capacitance

The electrostatic capacitance between a wire and a ground plane as shown in Fig. 1 is given by[8]

$$C_E = \frac{2\pi\varepsilon}{\cosh^{-1}(2h/d)} \approx \frac{2\pi\varepsilon}{\ln(h/d)}, \tag{1}$$

where the approximation is good to within 1 % for h> 2d. (If the distance to the ground plane becomes larger than the tube length another formula for the capacitance has to be used, which involves replacing h with the length of the 1d wire.) For a typical value of h/d, this can be approximated numerically as

$$C_E \approx 50\,\mathrm{aF/\mu}m\,. \tag{2}$$

2.2. Quantum capacitance

Because of the finite quantum energy level spacing of electrons in 1d, it costs energy to add an electron to the system. By equating this energy cost ΔE with an effective quantum capacitance e^2/C_Q, one arrives at the following expression for the (quantum) capacitance per unit length:

$$C_Q = \frac{e^2}{\hbar\pi v_F}, \tag{3}$$

where ħ is Planck's constant and v_F is the Fermi energy. The Fermi velocity for graphene and also carbon nanotubes is usually taken as $v_F = 8\ 10^5$ m/s, so that numerically,

$$C_Q \approx 100\,\mathrm{aF/\mu}m\,. \tag{4}$$

2.3. Kinetic Inductance

Due to the inertia of electrons, the instantaneous velocity lags the instantaneous electric field in time. This means the current lags the phase, which can be described as a kinetic inductance. For 1d systems we have the following expression for the kinetic energy per unit length:

$$L_K = \frac{\hbar\pi}{e^2 v_F}. \tag{5}$$

Numerically,

$$L_K = 16\,\mathrm{nH/\mu}m\,. \tag{6}$$

In reference[2], we show that in 1d systems, the kinetic inductance will always dominate the magnetic inductance. This is an important point for engineering nano-electronics: In engineering macroscopic circuits, long thin wires are usually considered to have relatively large (magnetic) inductances. This is not the case in nano-wires, where the kinetic inductance dominates. This inductance can in principle be used as part of a tank circuit for on-chip, GHz passive signal processing components, currently under development[9].

2.4. Band structure, spin degeneracy

A carbon nanotube, because of its band structure, has two propagating channels. In addition, the electrons can be spin up or spin down. Hence, there are four channels in the Landauer-Buttiker formalism. Taking this into account, in reference[2] we show that the circuit model of Fig. 2 is still valid as an effective circuit model for the charged mode if L_K is replaced by $L_K/4$ and C_Q is replaced by $4C_Q$.

Thus, the ac impedance of a nanotube consists of significant capacitive and inductive elements in addition to the real resistance which must be considered in any future nano-electronics system architecture.

2.5. Unsolved problems

This model provides the basis for understanding the RF properties of nanowires and nanotubes as interconnects. However, there are a number of unsolved problems. First, the ground plane will not always be present. Second, the effect of distributed resistance is currently not well-understood. Is the ac performance predictable if the dc resistance is known? Finally, the effect of multiple occupied sub-bands is not yet modeled. For example, in multi-walled nanotubes there are many more occupied sub-bands. The same is also true for semiconducting nanowires.

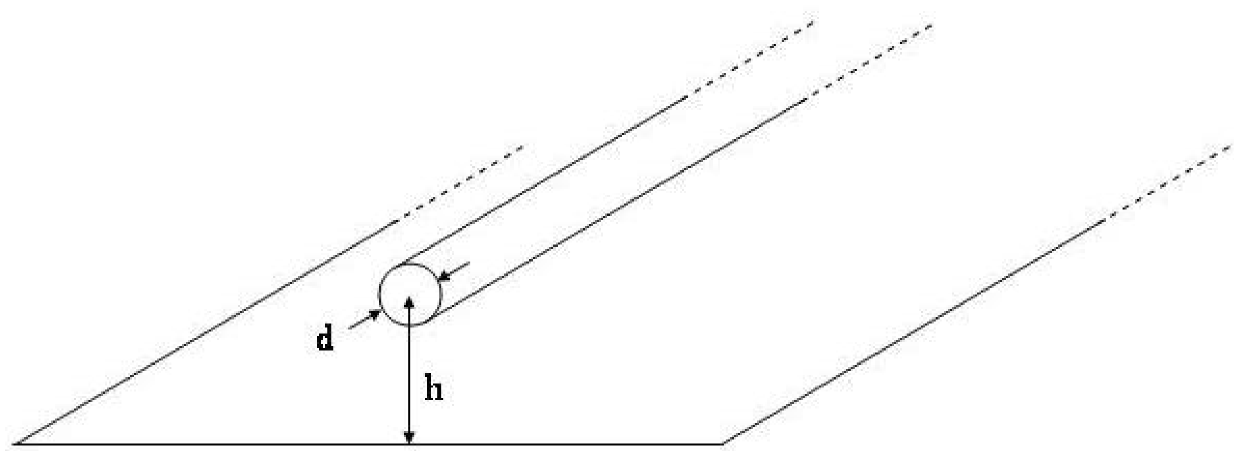

Figure 1: Nanotube over ground plane, used for electromagnetic calculations. Adapted from ref. [7]

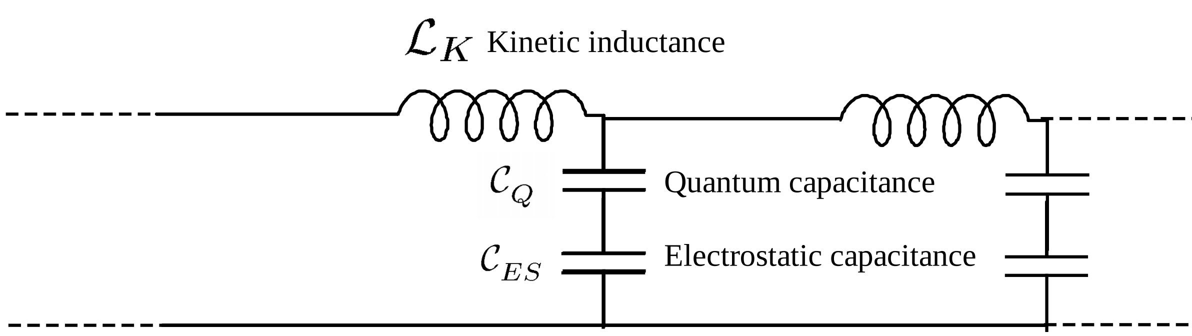

Figure 2: Equivalent RF circuit model for a nanotube. Adapted from ref. [1]

3. ACTIVE DEVICES: NANOTUBE TRANSISTORS

In this section, we extend our discussion to include active nanotube devices. In contrast to silicon transistors, the fundamental physical mechanism responsible for transistor action in nanotube transistors is still not completely understood. One action of the gate may be to modulate the (Schottky barrier) contact resistance[10]. Experiments also indicate that the source-drain voltage drops at least in part along the length of the nanotube[11], indicating that the contact is only one important element of the total source-drain resistance. We recently demonstrated transistor action in 0.4 cm long carbon nanotube transistors[5], and we argue that the action of the gate in that case should have a significant effect on the bulk of the nanotube as well as the contact.

Complicating the issue is the question of whether the transport is diffusive or ballistic[12] (i.e. scatter free) from source to drain. Experiments[13] indicate that the mean free path in semiconducting nanotubes at room temperature is at least 1 μm, so that nanotubes shorter than 1 μm may behave as ballistic transistors. Rather than try to settle these issues, for the purposes of this paper, we will use experimentally measured parameters to predict device high-frequency performance.

3.1. Relevant frequency scales

We begin by estimating the frequency scales for the most important processes: the RC time and the transconductance.

3.1.1. RC time

The first important effect for high-frequency performance is the RC time. For a typical nanotube geometry of 0.1 μm length, C is of order 4 aF. R can be as small as 6.25 kΩ[13]. Therefore, the RC frequency is given by

$$\frac{1}{2\pi RC} \approx 6.3\,\mathrm{THz} \tag{7}$$

This shows that the speed limit due to RC times intrinsic to a nanotube transistor is very large indeed.

3.1.2. Transconductance

The transconductance g_m over the gate-source capacitance C_{gs} sets another important frequency. Using an experimentally measured value[14] of 10 μS, this gives

$$\frac{g_m}{2\pi C_{gs}} \approx 400\,\mathrm{GHz} \tag{8}$$

The above estimates indicate that a carbon nanotube transistor could be very fast, in spite of its high impedance. For more realistic estimates of device performance a small-signal equivalent circuit model would be very useful, especially for input and output impedance calculations and in order to investigate the effects of parasitic impedances on device performance.

3.2. Small signal equivalent circuit

In this section, we propose a small signal equivalent circuit model based on a combination of known physics in the small signal limit and generally common behavior for all field effect type devices. Our proposed active circuit model is not rigorously justified or derived. Rather, we hope to capture the essential physics of device operation and at the same time provide simple estimates of device performance.

We show in Fig. 3 our predicted small-signal circuit model for a nanotube transistor. In the following sections we discuss each of the important components.

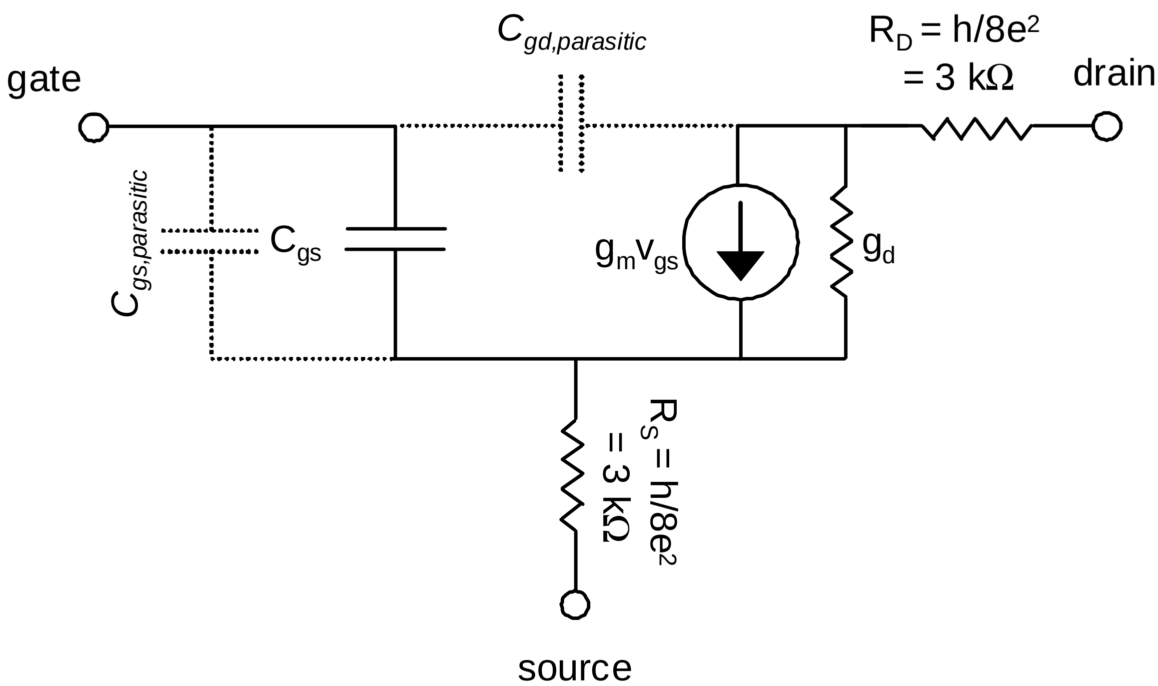

Figure 3: Small-signal equivalent circuit model for carbon nanotube transistor. Adapted from ref. [7].

3.2.1. Gate-source capacitance

The capacitance of a passive nanotube in the presence of a gate was discussed extensively in the first section; this can be used as an estimate of the gate-source capacitance C_{gs} in active mode; shown in Fig. 3. This capacitance includes the geometrical capacitance (50 aF/μm) in series with the quantum capacitance; the quantum capacitance is multiplied by 4 because of the band structure degeneracy. Thus:

$$\frac{1}{C_{gs}} \approx \frac{1}{C_E} + \frac{1}{4C_Q} = \frac{1}{44\ \mathrm{aF}/\mu m}. \qquad (9)$$

3.2.2. Transconductance, drain resistance

While the transconductance is the most critical parameter, the underlying mechanism is the least understood. In Fig. 3, g_d represents the output impedance of the device, if it does not appear as an ideal current source. Since at present we do not have a detailed theoretical model, in order to predict device high frequency performance, we use experimental data from dc measurements as our guide.

3.2.3. Series Resistance

In most conventional transistors the series resistance consists of the metallization layer and the ohmic contact resistance. We argue that, in nanotube transistors, the intrinsic contact resistance will be of order the resistance quantum because of the 1d nature of the system. We elaborate.

At dc, the lowest value of resistance possible for a carbon nanotube is $h/4e^2$. This is because there are four channels for conductance in the Landauer-Buttiker formalism, each contributing h/e^2 to the conductance. To date very little experimental work has been done to measure the ac impedance of ballistic systems.

From a theoretical point of view, Buttiker and Christen[15] have carefully analyzed the case of a capacitive contact to a ballistic conductor (in his case a 2DEG without scattering) in contact with one dc electrical lead through a quantum point contact. They find that the ac impedance from gate to lead includes a real part, equal to half the resistance quantum $h/2e^2$. Based on this work we argue that a reasonable value for the contact resistance in our small-signal model would be $h/2e^2$ per channel. Since there are 4 channels in parallel, this gives a contact resistance of $h/8e^2$. There will be an additional imaginary contribution to the contact impedance (not shown) due to the kinetic inductance on the order of a few nH.

3.2.4. Parasitic capacitance

The parasitic capacitance is due to the fringing electric fields between the electrodes for the source, drain, and gate. While these parasitic capacitances are generally small, they may be comparable to the intrinsic device capacitances and hence must be considered.

There are no closed-form analytical predictions because the geometry of the electrodes will vary among different electrode designs. In order to estimate the order of magnitude of the parasitic capacitance, we can use known calculations for the capacitance between two thin metal films, spaced by a distance w. For this geometry, if w is 1 μm, the capacitance is ~ 10^{-16} F/μm of electrode length[16]. For a length of 1 μm, this gives rise to ~10^{-16} F. Thus, typical parasitic capacitances are of the same order of magnitude as typical intrinsic capacitances.

3.3. Cutoff frequency

In this section, we provide estimates of the cutoff frequency f_T, a standard yardstick for transistor high-speed performance, defined as the frequency at which the current gain falls to unity[17]. Based on the circuit model in Fig. 3, it can be shown[17] that f_T is given by:

$$\frac{1}{2\pi f_T} = (R_S + R_D)C_{gd,p} + \frac{1}{g_m}\left(C_{gs} + C_{gd,p} + C_{gd,p}\right) + \frac{g_d}{g_m}(R_S + R_D)\left(C_{gs} + C_{gd,p} + C_{gd,p}\right) \tag{10}$$

Here the p subscript denotes "parasitic". Using the experimentally measured transconductance of 10 μs, a parasitic capacitance value of 10^{-16} F, and a C_{gs} of 4×10^{-17} F (appropriate for a 1 μm long tube), we predict a cutoff frequency of 8 GHz. For this value, the parasitic capacitance is the most important contribution. Thus, minimizing the parasitic capacitance is of prime importance in increasing f_T for nanotube transistors.

3.3.1. Parasitic capacitance

While the above calculations show that the parasitic capacitance is important, in principle it should be possible to significantly reduce the parasitic capacitance by detailed electrode geometry design. Another (better) way to reduce the parasitic capacitance would be to use the nanotube itself as an interconnect electrode from one nanotube transistor to another. Then, the parasitic capacitance would be dramatically smaller than that with lithographically fabricated electrodes.

3.3.2. Scaling with gate length

If we assume the parasitic capacitances can be reduced to negligible values, Eq. 10 simplifies to

$$\frac{1}{2\pi f_T} = \frac{C_{gs}}{g_m} \tag{11}$$

C_{gs} scales linearly with gate length, and was calculated above. In the ballistic limit, g_m should be independent of gate length. Using a transconductance of 20 µs, this gives rise to the following prediction for f_T:

$$f_T = \frac{80\,\text{GHz}}{L_{gate}(\mu m)} \tag{12}$$

We plot in Fig. 4 our predictions for f_T vs. gate length for a nanotube transistor, and compare to other technologies. The predictions are very promising, suggesting that a nanotube transistor with THz cutoff frequencies should be possible.

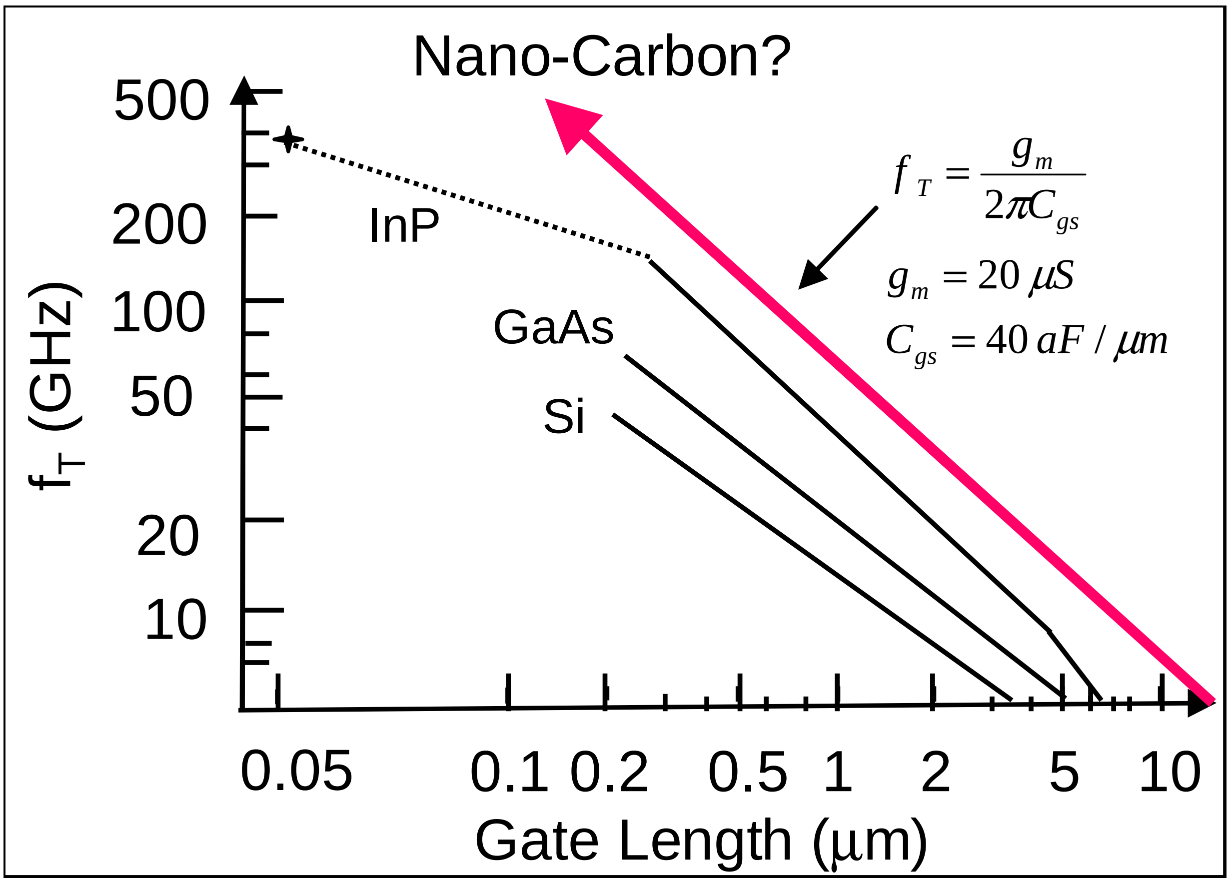

Figure 4: Predicted scaling of f_T with gate length, adapted from ref.[7] .

4. NANO-ANTENNAS

Since the wavelength of microwaves of order cm, and since we have recently been able to synthesize electrically continuous and electrically contacted single-walled nanotubes of order cm in length[4, 5], it is appropriate to consider their possible use as nano-antennas. In this spirit, we recently developed[6] a quantitative theory of nanowires and nanotubes as antennas. Below, we elaborate on potential applications of these “nano-antennas.”

4.1. APPLICATIONS OF NANOTUBE ANTENNAS

4.1.1. A solution to the nano-interconnect problem

Progress to date on nanoelectronics has been significant. Essentially all devices needed to make the equivalent of a modern digital or analog circuit out of nanotubes and/or nanowires have been demonstrated in prototype experiments, and elementary logic circuits have been demonstrated[18-21]. However, one of the most important unsolved problems in nanotechnology is how to make electrical contact from nanoelectronic devices to the macroscopic world, without giving up on the potential circuit density achievable with nanoelectronics. All of the nanotube and nanowire devices developed to date have been contacted by lithographically fabricated electrodes. A canonical research theme is to fabricate a nanodevice, contact it with electrodes fabricated with electron beam lithography, then publish a paper reporting the electrical properties. This is not a scalable technique for massively parallel processing, *integrated nanosystems*. The potential high density circuitry possible with nanowires and nanotubes will not be realized if each nanowire and nanotube is contacted lithographically.

One potential solution to this problem is to use wireless interconnects, which can be densely packed. If each interconnect is connected to a nanotube of a different length (hence different resonant frequency), then the problem of multiplexing input/output signals can be translated from the spatial domain to the frequency domain, hence relaxing the need for high resolution (high cost) lithography for interconnects. This is in contrast to previous approaches which, ultimately, rely on lithography and its inherent limitations to make electrical contact to nanosystems. This idea is indicated schematically in Fig. 5.

4.1.2. Wireless interconnect to nano-sensors

Another application is in the area of sensing. For example, nano-devices could be use as chemical and biological sensors, sensitive to their local chemical environment. A nanotube could be used as an antenna to couple to these nano-sensors, without the need for lithographically fabricated electronics.

4.1.3. Unsolved problems in nano-antennas: Transition from nano-antenna to thin-wire antenna

Our recent theory applies only to quantum mechanically 1-d nanowires and nanotubes. A future problem, which has not been solved yet, is to determine the transition from nano-antenna behavior to thin-wire behavior. This problem is germane to, for example, multi-walled nanotubes and also nanowires not in the strict 1d limit. Additionally, it may shed light on loss mechanisms in thin metallic antennas whose size approaches the nano-domain.

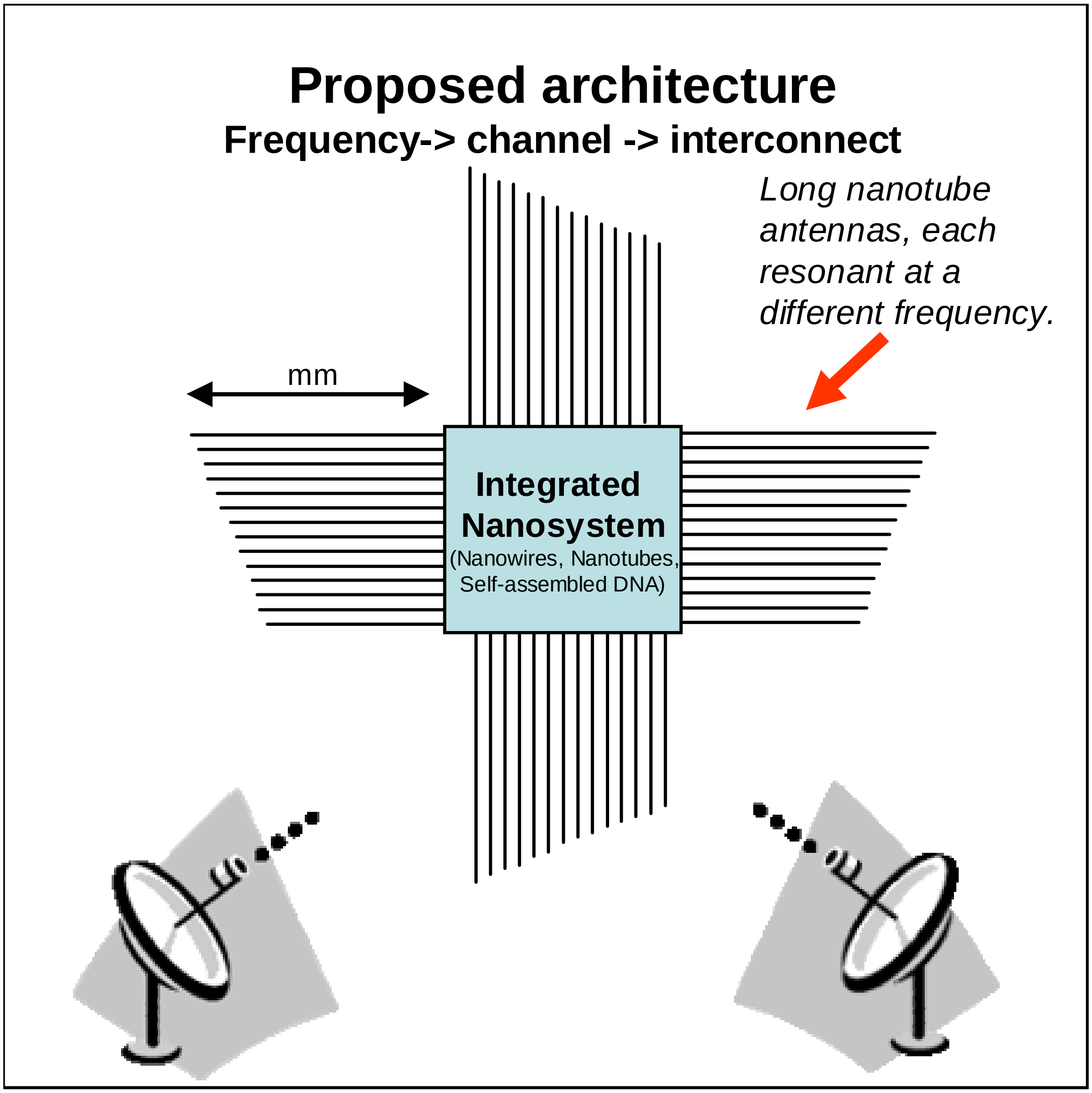

Figure 5: Possible architecture for a non-lithographic, wireless connection from the nano-world to the macroworld. Adapted from ref. [6].

5. CONCLUSIONS

We have presented modeling and predictions for nanoelectronics as interconnects, transistors, and antennas. It is clear that nano-electronic devices can fulfill all three of these roles, with outstanding predicted performance. Future work remains to be done on understanding non-linear nano-electronic devices for applications such as mixers and detectors. Finally, many of the circuit models presented in this work need to be experimentally validated.

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