RF Measurements of Nanoscale Devices: Challenges and Opportunities

P. J. Burke, C. Rutherglen
Integrated Nanosystems Research Facility
Department of Electrical Engineering and Computer Science
University of California, Irvine
Irvine, CA 92697

Abstract

This invited talk will describe some of the opportunities and challenges associated with RF measurements of nanoelectronic devices.

Introduction

The measurement of RF devices with impedances very far away from the characteristic impedance of free space (377 Ω) is very challenging. Below we discuss why nano-devices typically are in that limit, and present an example measurement on a single nano-device: A carbon nanotube. As this talk is meant to be a review of the field, this manuscript is a compilation of some of our prior publications in the area[1, 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[3, 4] 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[5], 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.

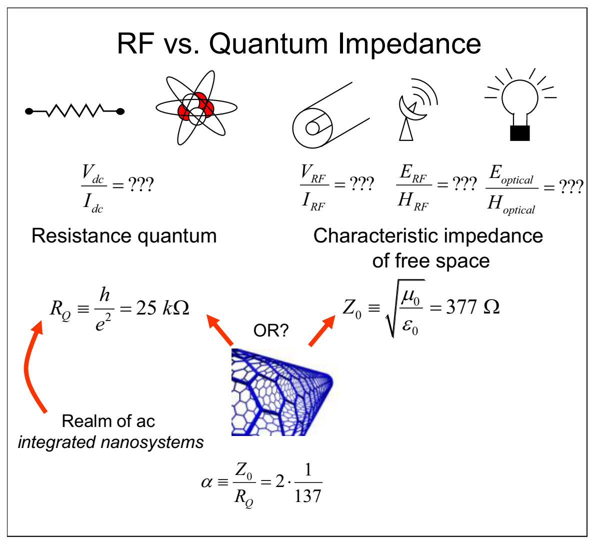

Fig. 1: Impedance matching and AC nanosystems[1].

An Example Measurement

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

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electric field current in a metallic SWNT saturates at around 25 μA[6]. 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 [7, 8].

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. [2], 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.

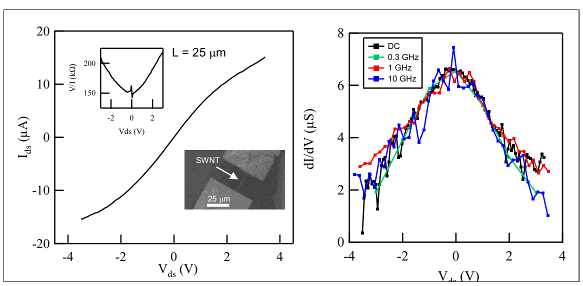

Fig. 8: I-V curve of 25 μm long SWNT and RF and DC conductance vs. Vds, from [2].

Summary

Few RF measurements on nanodevices have been performed due to the challenge impedance matching. Our talk will present our experience and the communities opportunities and challenges in this field of nanoscale electromagnetic metrology.

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