Terahertz Resonances and Bolometric Response of a Single-Walled Carbon Nanotube

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Abstract—**We describe an experiment to measure terahertz standing wave resonances on an individual single-walled carbon nanotube. These resonances are a probe of the strength of electron-electron interactions in this 1D system. The experiment is conducted in the interferometer originally developed in our lab for terahertz spectroscopy using an antenna-coupled superconducting bolometer as a detector. The superconducting bolometer allows us to characterize the frequency-dependent coupling using the same antenna geometry and experimental configuration as the nanotube. As a precursor to this work, we have also studied the response of an individual single-walled nanotube to dc and rf Joule heating. These measurements enable us to determine the thermal conductance of the nanotube, and also to clearly distinguish between the thermal and non-thermal high frequency response.**

I. INTRODUCTION

MANY electronic nanosystems have excitations in the THz range (0.1 - 10 THz, equivalent to 5 to 500 K). Exploration of the excitation spectrum can provide critical understanding of the microscopic interactions inside the nanosystem. However, this is a difficult energy range for such studies for several reasons: 1. the individual nanosystems are typically small, ~µm, and thus couple weakly to free-space radiation; 2. while conventional spectroscopy studies might be carried out on ensembles, these would average out the crucial properties that are sample specific and of particular interest, such as geometric- or conformation-specific resonances; 3. even if one can couple efficiently from free space to and from an individual nanosystem, the small sample size limits the photon intensity that can be used to probe the nanosystem in a transmission or reflection measurement.

We describe a method for performing measurements of sample-specific THz absorption that uses antenna coupling for the input photons and a change of dc properties as the indication of photon absorption. This method is being applied to study the novel one-dimensional electronic state of an individual single-walled carbon nanotube (SWNT). The basic concept is that of the familiar antenna-coupled bolometer. Here the goal is to study the frequency-dependent properties of the absorber - the nanotube - rather than to develop an improved detector. We believe that this approach will be generally applicable for probing the THz response of a conducting nanosystem. We also describe studies of the low frequency bolometric response of a SWNT that establish the needed scientific background for the THz measurements.

II. EXPERIMENTAL TECHNIQUE

The SWNT, with a diameter of 1-2 nm, is an excellent test bed for one-dimensional physics. The lack of screening in 1D gives rise to strong electron-electron interactions. Low energy excitations are thus collective rather than single-particle. These collective excitations are known as plasmons and are described by the Luttinger liquid model.[1] The strength of electron-electron interactions is characterized by the Luttinger parameter g. The case of g = 1 corresponds to non-interacting electrons or Fermi liquid behavior, while g < 1 corresponds to repulsive electron-electron interactions.

Burke has described a SWNT over a ground plane in terms of a transmission line model that is effectively a recasting of the Luttinger liquid model in the language of microwave engineering.[2] The plasmon velocity on the nanotube transmission line is equal to the known Fermi velocity divided by g. Previous work has determined g indirectly through measurements of the tunneling conductance[3] and the capacitance.[4] A measurement of the plasmon velocity would be a more direct determination of the Luttinger parameter and would test the transmission line model of the nanotube.

A recent THz time-domain measurement of a SWNT field-effect transistor saw picosecond resonances corresponding to ballistic electron transport at the Fermi velocity (g = 1).[5] Plasmon resonances (g < 1) were not observed, although the experiment may not have sufficient time resolution or signal-to-noise to see these faster excitations.

We propose an alternate experimental approach. We utilize the temperature-dependent resistance, or bolometric response, of a metallic SWNT as a measure of the power coupled to the tube. The dc resistance as a function of temperature for a 2 µm SWNT is shown in Figure 1. Bolometric THz detection has recently been demonstrated in samples consisting of bundles of nanotubes,[6] but has not yet been measured in an individual SWNT.

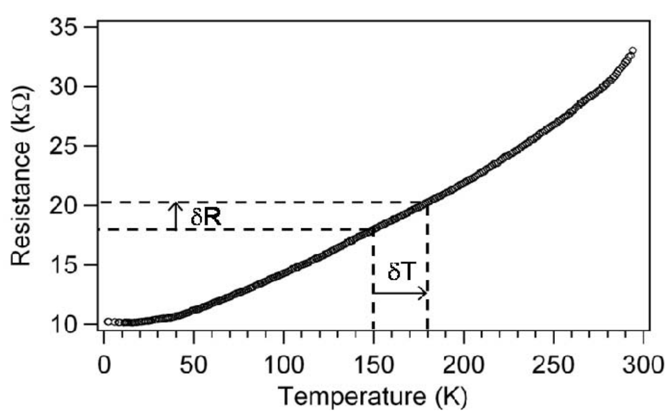

Fig. 1. Measured dc resistance versus temperature of a 2 µm long quasi-metallic SWNT with a gate voltage of -30 V. THz power coupled to the nanotube will cause a temperature rise δT, producing a measurable resistance change δR.

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For an antenna-coupled SWNT, the input impedance of the nanotube transmission line varies with frequency corresponding to standing wave resonances along the length of the tube. The power coupled to the tube, and hence the bolometric response, is a maximum at half-wave resonances and a minimum at quarter-wave resonances. From the periodic variation in the device response with frequency, we can determine the velocity of the THz excitations on the nanotube.

The highest quality nanotubes produced to date have a contact resistance R_c approaching the quantum contact resistance $R_q = h/4e^2 \approx 6.4$ kΩ, as well as an internal resistance $R_{int} \approx 1$ kΩ/μm at 4.2 K.[7] This restricts us to tubes of length L ~ 1 μm, as the high resistance of significantly longer tubes would damp out the standing wave resonances. A micron-length tube has its first half-wave resonance at ~1 THz. As an example, we plot in Figure 2 a calculation of the real part of the nanotube impedance as a function of frequency for g = 0.25 and g = 0.50, based on the transmission line model of Burke. The calculation assumes L = 1 μm, R_c = 6.4 kΩ, and R_{int} = 1 kΩ.

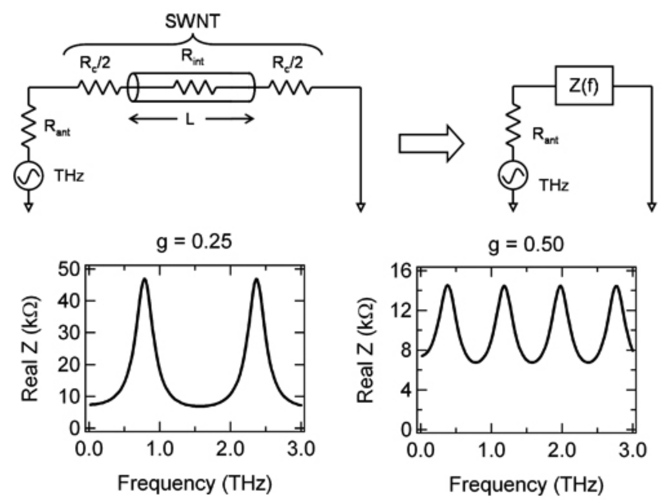

Fig. 2. Top: Circuit model of antenna-coupled SWNT. The characteristic (plasmon) impedance of the SWNT transmission line is $Z_{char} = (1/g)(h/8e^2) \approx$ 3.2 kΩ/g. Bottom: Calculated real part of the nanotube input impedance Z(f) for g = 0.25 and g = 0.50, based on the transmission line model. Impedance maxima correspond to quarter-wave resonances at L = (2n+1)/(λ/4), with n an integer. Impedance minima occur at L = n(λ/2).

The experiment will be conducted in the far-infrared Fourier-transform spectrometer in our lab.[8] It is a Michelson interferometer with a hot blackbody source, and was originally developed for applications in THz spectroscopy using a superconducting niobium bolometer as a detector. The active element of the niobium bolometer has essentially real and frequency-independent absorption. Thus the superconducting bolometer can be used to establish the frequency-dependent coupling of the same antenna geometry and experimental configuration as the nanotube.

Micrographs of niobium bolometers and a nanotube device fabricated with planar THz antennas on a silicon substrate are pictured in Figure 3. For testing in the THz interferometer, devices are mounted on a hyperhemispherical silicon lens for through-substrate coupling. The lens-mounted device is then situated inside an optical-access cryostat for testing at bath temperatures down to 2 K.

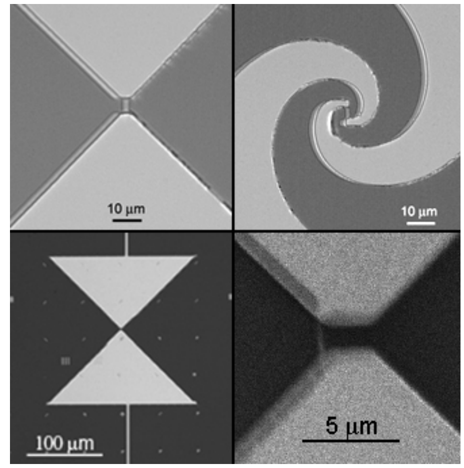

Fig. 3. Top: Optical images of superconducting niobium bolometers with bowtie and log-spiral antennas. Bottom: Optical image of a nanotube with a bowtie antenna and SEM image of 2 μm long nanotube at the antenna feed.

III. Bolometric Response

In order to first understand the bolometric response of a SWNT, we have also studied the effects of dc and microwave heating. The applied gate voltage was V_g = -30 V. These lower frequency measurements allow precise calibration of the input power. In the low current regime, two mechanisms contribute to the current-dependence of the differential resistance dV/dI. The first is characterized by an increase in the differential resistance dV/dI with increasing bias current. Using Johnson noise thermometry, we have confirmed that this is due to self-heating of the electron system. The second mechanism is characterized by a local maximum in dV/dI at zero current. This is attributed to Schottky barrier contacts. This feature is only present below ~10 K for samples with good contacts (R_c approaching $h/4e^2$), but can be seen at significantly higher temperature in samples with high contact resistance.

Both mechanisms produce an IV nonlinearity and hence give a heterodyne (mixing) response. However, only the bolometric response depends on the frequency-dependent power dissipated in the SWNT. The THz current, and thus the power absorbed at a THz frequency f, increases with Re[1/Z(f)]. (The antenna impedance $R_{ant} \ll |Z(f)|$, providing an ac voltage bias at the THz frequency.) Thus the temperature increase due to photon absorption, and δR, depend periodically on frequency. The Schottky nonlinearity does not depend periodically on f. We conclude that only the bolometric response will exhibit the frequency-dependent periodic structure indicative of standing wave resonances on the nanotube.

The measured heating response also enables us to determine the thermal conductance of the SWNT. In measurements of tube lengths between 2 and 20 μm, we find a thermal conductance that scales linearly with the nanotube length. This suggests that the temperature profile is relatively uniform

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along the length of the tube and that cooling is predominately into the substrate. The thermal conductance below ~150 K has a linear dependence on the nanotube temperature.

These results are important in understanding the electro-thermal properties of nanotube devices, and they establish the necessary scientific foundation for the proposed THz measurements. The dc and microwave frequency measurements were conducted on quasi-metallic SWNT fabricated on a degenerately doped oxidized silicon substrate. This allows the substrate to be used as a back gate to bias the SWNT away from the curvature-induced band gap. For THz testing, high resistivity silicon substrates must be used to avoid significant attenuation of the THz signal. This requires use of a local gate, such as a lithographically-defined side or top gate. The optimization of samples for THz testing is currently in progress. Ultimately, the goal of these measurements is to shed light on the question of whether high frequency charge excitations in 1D nanosystems are plasmon-like or single particle-like.

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