## Coversheet

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The authors sought to accurately and directly measure kinetic inductance and plasmonic waves of 1D conductor at GHz to THz frequencies. Two types of devices were fabricated using carbon nanotubes and quantum wires formed in the GaAs/AlGaAs interface as the 1D conductor. In the former case, the authors constructed devices consisting a single-walled nanotube and on-chip transmission lines. A scattering analysis was performed using a network analyzer to measure the kinetic inductance. The authors observed undesired resonances due to parasitic EM propagation modes, which interfered with the through-nanotube signaling. This has led to new device development with shorter lines to push the parasitic resonances beyond the measurement frequency range. For the parallel project using GaAs 2DEG quantum wire, scattering analysis showed conductance quantization at 3K, which behaved differently at different frequencies, possibly arising from kinetic inductance. Several devices with various designs and different types of 2DEG samples were analyzed for verification. Extensive model was also developed to account the parasitic conductance.

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1D conductor, nanoscale device, kinetic inductance, plasmonic wave

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# Report Document

## Introduction

The long-term goal of this project is 1) to accurately and directly measure kinetic inductance and plasmonic waves of 1D conductor at tens of GHz to a few THz frequencies, and 2) to exploit them to build a new class of GHz - THz amplifiers & oscillators. In this report, we will describe the first part on which we have been focused on so far.

In 1D conductor/semiconductor, electron scattering time is so reduced that at frequencies above tens of GHz, conduction electrons can oscillate many times before scattering. Thus, in the frequency range, collective electron oscillations lead to 1D plasmonic wave propagation, whose kinetic energy part corresponds to the kinetic inductance. Experimental characterizations of the 1D kinetic inductance and plasmonic waves are important, as this may add a new approach to THz electronics, and offer a frequency-domain means to study electron-electron interactions in 1D, a central problem in condensed matter physics.

1D kinetic inductance and plasmonic waves have not been measured either accurately or with unequivocal direct proof so far. The difficulty lies in the fact that only a little portion of the EM energy sent into a 1D system is used to excite electrons because the 1D system has only a few electron transport channels, and also the fact that parasitic input-output coupling of the EM energy can completely mask the weak electron excitations, because parasitic paths can easily offer far lower impedance than the 1D system.

To achieve accurate measurement, two types of devices were built using carbon nanotubes and quantum wires formed in the GaAs/AlGaAs interface as two model 1D conductors. They were carefully designed to efficiently send EM energy into the 1D system for excitation of collective electron oscillation, and to minimize parasitic signal coupling. 2-port scattering analysis was performed to measure the kinetic inductance and plasmonic waves, and to identify the parasitic coupling paths. In the following two sections, we describe in detail the design, fabrication and measurement methods of each device.

## Device using carbon nanotubes

Our first type of device consists of a single-walled carbon nanotube in a field-effect transistor (FET) configuration and tapered on-chip transmission lines that guide EM energy to and from the nanotube (Figure 1). To measure the kinetic inductance and plasmonic wave propagation, we drive one end of the nanotube with GHz signal via one transmission line, and extract information on the kinetic inductance by measuring the amplitude and phase of the signal transmitted *through* the nanotube.

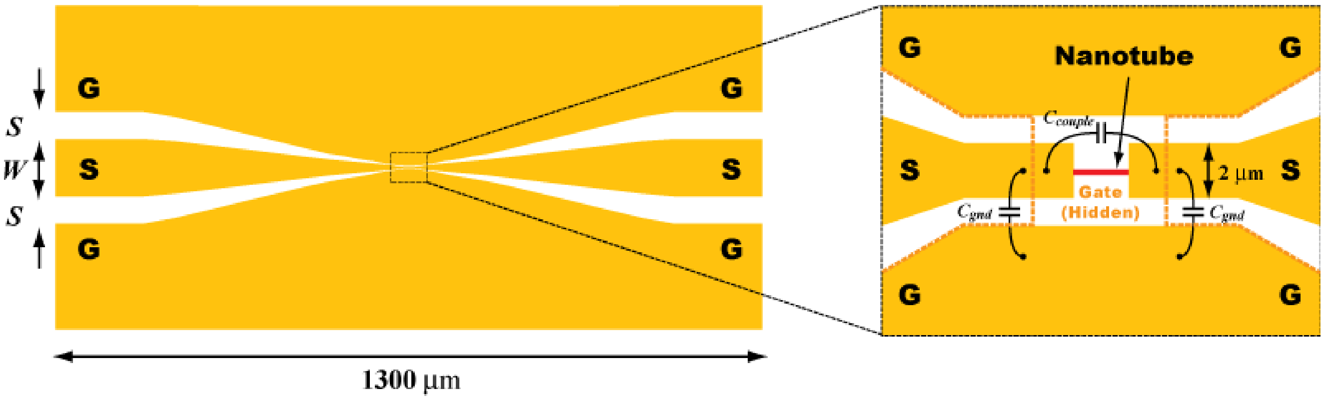



Figure 1. Design of the carbon nanotube device. The **G**, **S**, & **G** lines comprise an on-chip transmission line. Under the top gate shown in the right (dashed yellow lines), the two **S**-lines are not connected but have a gap in between, which is connected by a nanotube.

The design of the on-chip line is the crucial key to precise measurements of the kinetic inductance. The optimally designed line should address two major difficulties of the measurement. First, it is difficult to effectively guide microwave signals into the nanotube due to its small size (typically a few μm long and less than a couple nm wide). Second, the signal transmitted through the nanotube is very weak due to impedance mismatch between the nanotube (~10 kΩ) and the 50 Ω cable & on-chip line. This means that undesired signal coupling between the two signal lines (**S**-line leads in Figure 1) through other paths, such as the conductive substrate and parasitic capacitance ($C_{couple}$ in Figure 1), should be minimized in order not to mask the desired signal transmission through the nanotube.

To address the first difficulty, *i.e.*, to effectively guide signals into the nanotube, we designed, using an EM simulation tool called SONNET, an on-chip 50 Ω coplanar waveguide (CPW) that is tapered from 150 μm pitch GSG probes to the 2 μm wide **S**-line lead contacts of the nanotube (Figure 1). The simulated insertion loss is less than 0.5 dB when the gold metal thickness is 500 nm.

The second difficulty, *i.e.*, the minimization of the undesired signal coupling through a variety of mechanisms, is overcome as follows:

**(i)** The CPW structure is chosen over other forms of on-chip lines, e.g., coplanar striplines (CPS), in order to tightly confine the electromagnetic fields between the two ground lines. This minimizes *electromagnetic coupling* between the two ports of the line.

**(ii)** The whole device is built on an insulating sapphire substrate (C-plane cut) to eliminate *resistive coupling*, which would be significant if the substrate were conductive (e.g., doped silicon).

**(iii)** The rest of signal coupling is mainly the *capacitive coupling* through the parasitic capacitance, $C_{couple}$. Such a capacitive coupling contributes to the imaginary part (equivalently the phase) of the transmitted signal, just as the kinetic inductance of the nanotube does. We are to minimize this coupling capacitance so that its effect does not overwhelm that of the kinetic inductance. As far as the capacitive coupling is comparable to the desired signal transmission through the nanotube, the former can be calibrated out. We minimized the capacitive coupling by partially shielding the two **S**-line leads with the CPW ground lines and with the top gate over the nanotube. The EM simulation using SONNET shows that, for a 1 μm gap between the 2 μm-wide **S**-line leads, the coupling capacitance is less than 0.25 fF, whose effect on the transmitted signal phase is comparable to that of the kinetic inductance.

We finally note that the top gate is combined with the ground lines of the CPW for the ease of fabrication. The ground lines provide both *ac* ground for the microwave signal and *dc* gate bias for the nanotube. This approach also saves two lithography steps that would be necessary if a separate gate were used.

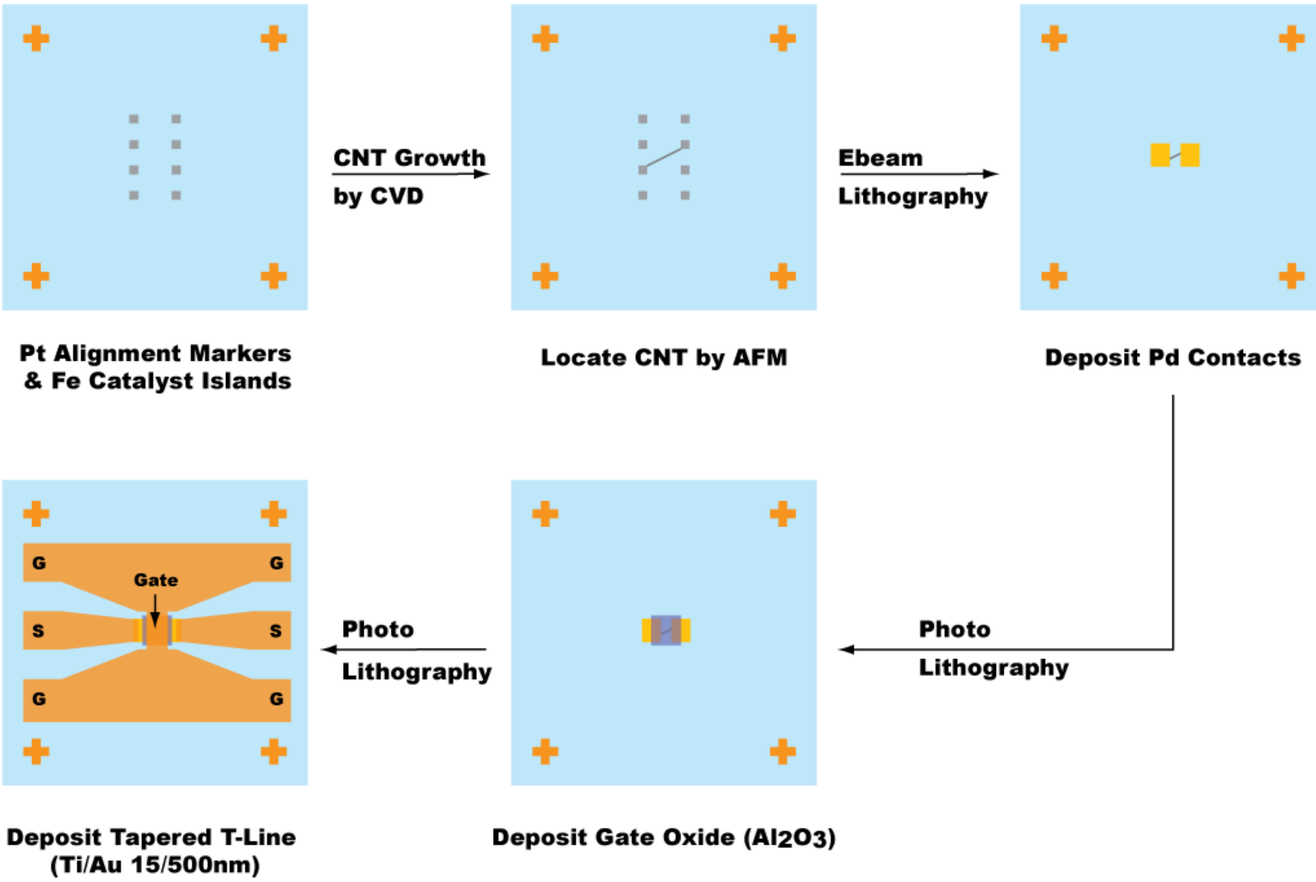
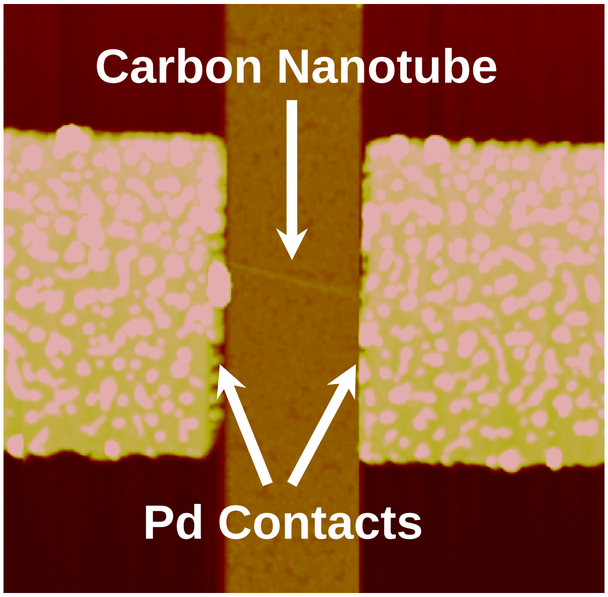



Figure 2. Fabrication process of the carbon nanotube device.

The device is fabricated as shown in Figure 2: 1) Alignment markers and iron catalyst islands are patterned on C-plane sapphire substrate. 2) Carbon nanotubes are grown on the substrate by chemical vapor deposition (CVD) and located by atomic force microscope (AFM) relative to the pre-patterned alignment markers. 3) Single-walled nanotubes (diameter < 3 nm) are selected and connected to palladium (Pd) contacts by Ebeam lithography. Pd is used to form low resistance contacts. 4) Gate oxide is defined by photo lithography and deposited by atomic layer deposition (ALD). 5) The thick metal transmission line structure is deposited by photo lithography. Note that Ebeam lithography is used in patterning the Pd contacts for accurate positioning, while photo lithography is employed in patterning the gate oxide region and transmission lines to minimize damage to the carbon nanotube and to increase the throughput of fabrication process. Images of a fabricated device are shown in Figure 3.



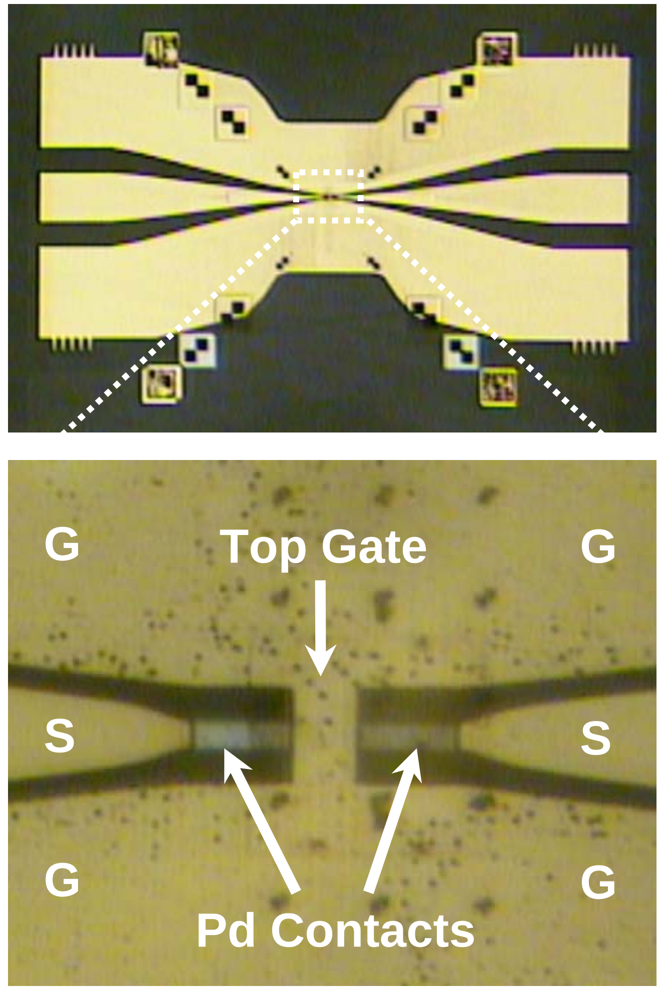




Figure 3. AFM (upper left) and photo images (right) of a carbon nanotube device

We performed a scattering analysis (or 2-port network analysis) upto 50 GHz using a network analyzer to measure kinetic inductance of the nanotube. In order to set the phase planes of the microwave signal right at the two ends of the nanotube, we have designed on-chip TRL (Through-Reflection-Line) calibration structures that take the tapered CPW as part of the probe. In the measurement, we observed undesired resonances about 30 GHz (Figure 4), which interfered with the through-nanotube signaling. We experimentally proved these resonances occur as the sapphire substrate sandwiched between the metallic chuck of the probe station and coplanar waveguide acts as a parasitic microstrip cavity. We inserted a microwave absorber between the substrate and chuck to attenuate the resonances, but the attenuation was only a few dB, for the absorber does not work well beyond 18 GHz. This has led to a new devices development with shorter on-chip lines to make the parasitic resonances occur beyond our measurement frequency range.  These new devices are currently under fabrication and will be characterized once they are ready.

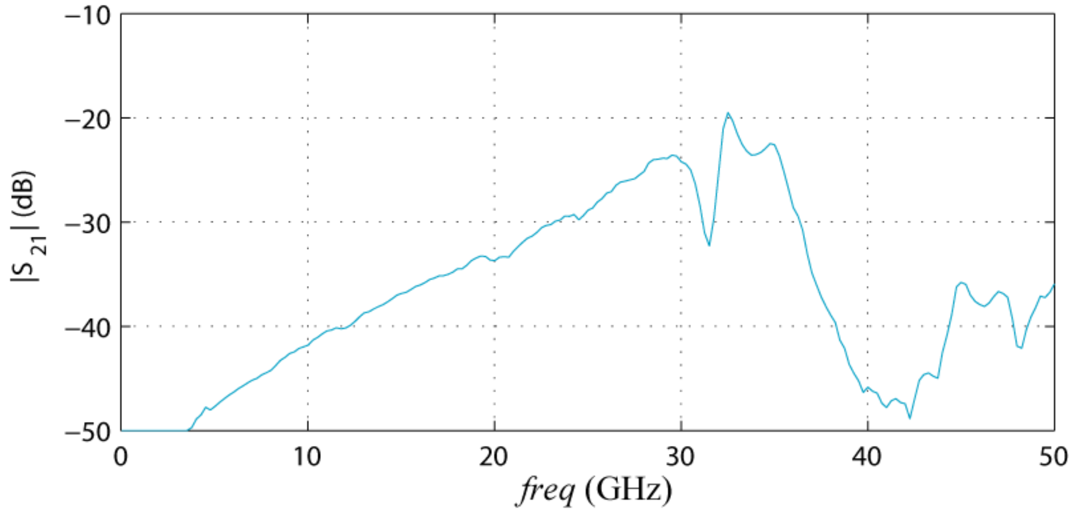



Figure 4. Undesired parasitic coupling between the two on-chip transmission line leads.

**Device using GaAs quantum wires**

In our parallel project, 1D quantum wire is built from two-dimension electron gas (2DEG) at the GaAs/AlGaAs interface, which shares the same 1D electron transport properties as the carbon nanotube case. The GaAs quantum wire is formed by etching and selectively depleting certain areas of the 2DEG using a split gate structure (Figure 5). Compared to the carbon nanotube device, where the main difficulty is to connect the existing 1D conductor (i.e. the single-walled nanotube) to the macroscopic measurement apparatus, the major challenge of the GaAs quantum wire device is to carve high quality 1D conducting channel out of the 2DEG. To achieve this, great care was taken in lithography and etching process to produce quantum wire with smooth edges – electrons can be easily scattered at rough edges.

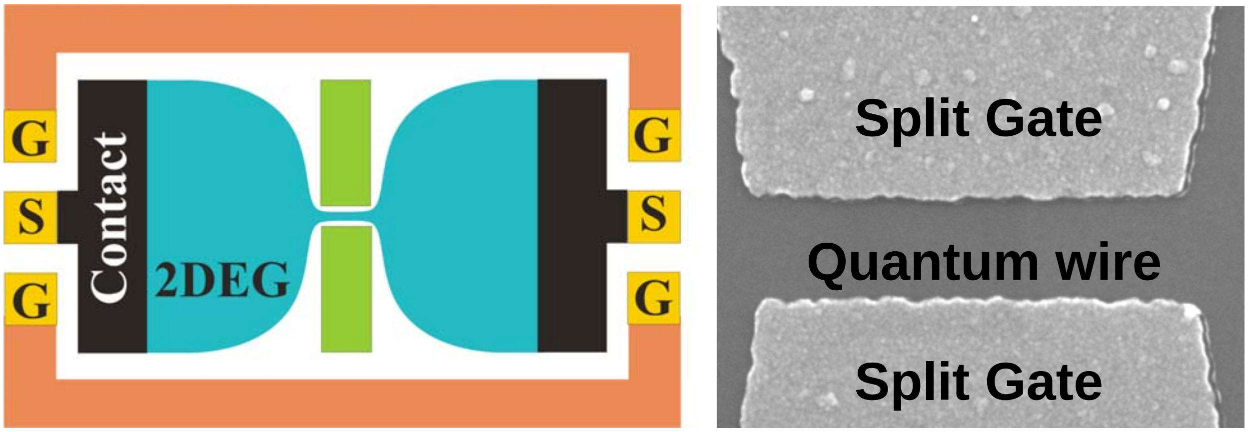



Figure 5. Layout (left) and SEM image (right) of device with 1D quantum wire carved from the GaAs/AlGaAs 2DEG.

Compared to the carbon nanotube devices, the GaAs quantum wire devices feature several advantages as well as challenges. First, connecting the GaAs quantum wire to the outside world is relatively easy as it is already connected to the rest of the 2DEG. Second, the electron density and number of conducting channels in the quantum can be adjusted by varying the bias voltage of the split gate, such that the value of kinetic inductance can be adjusted, adding one degree of freedom to our measurement. The challenge arises from modeling and de-embedding the 2DEG that connects between the quantum wire and the probe contacts.

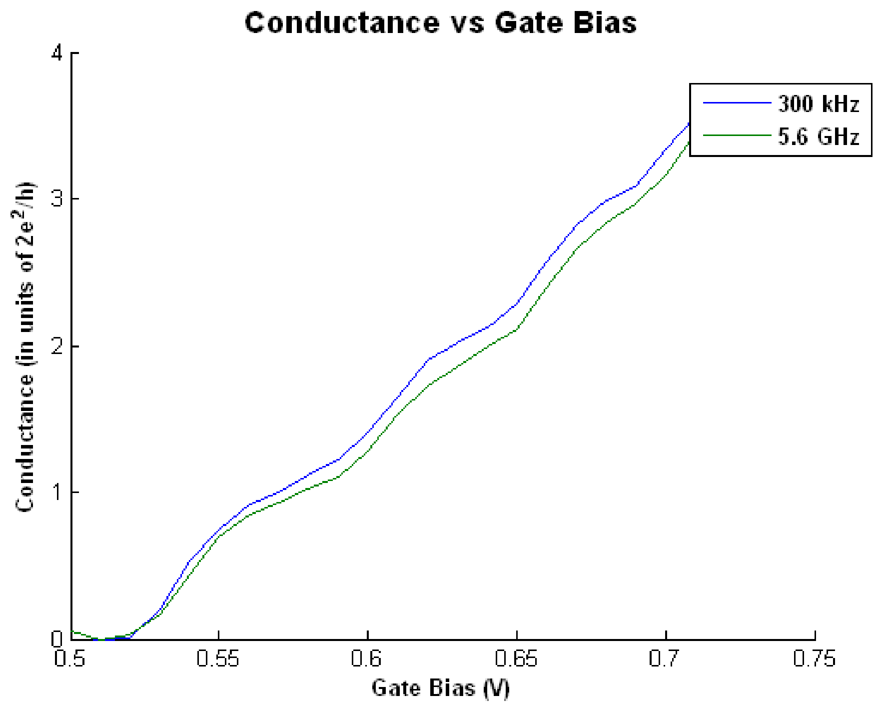



Figure 6. Quantized conductance of the 1D conducting channel. The dependence on frequency may originate from the kinetic inductance.

Scattering analysis showed conductance quantization at 3K, which behaved differently at different frequencies (Figure 6). We suspect the frequency dependence of conductance might originate from kinetic inductance. However the analysis of the data is more than easy, because of a not-fully depleted donor layer underneath the 2DEG. This layer acts as a parasitic conductance path, interfering with signaling through the quantum wire. We therefore acquired different types of 2DEG samples from Pfeiffer group (Princeton), from Heiblum group (Weizmann Institute), and from Yacoby group (Harvard) in which the donor layer effect has been mitigated and the mean free path has been increased. We think that with the new samples, we are close to obtaining new data that would facilitate analysis. We are in the process of designing and fabricating new chips to measure the quantum wires' kinetic inductance through scattering analysis. High frequency model was also developed to de-embed the 2DEG in order to obtain the sole physical properties of the quantum wire itself.