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Broadband Microwave AC Conductance Spectroscopy on Carbon Nanomaterials

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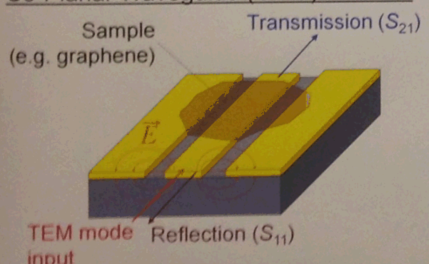
Impact: Despite the wealth of DC electrical data on carbon nanomaterials, their basic electrodynamic properties remain relatively unexplored. This work presents an accurate method for measuring the complex AC conductance of graphene and carbon nanotube "silk" from 0.1 to 50 GHz to elucidate the effects of low dimensionality, quantum confinement, and possible ballistic transport on their interactions with electromagnetic fields.

Project Description

Goal: Determine fundamental linear electrodyamic response properties of carbon-based nanomaterials across the entire microwave band 0.1 to 50 GHz.

Challenges: Size & dimensionality creates strong impedance mismatch between nanomaterials (typical impedance ~ $h/e^2 \approx 25$ kΩ) and microwave systems (50 Ω) – results in low signal-to-noise & reproducibility.

Co-Planar Waveguide (CPW) Platform

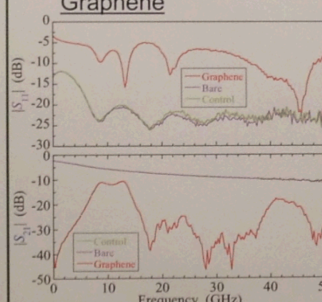


- Adaptation of broadband CPW designed at Sandia to be compatible with nanomaterial integration
- Vector network analysis measurement of full complex S_{11} and S_{21} coefficients to determine complex AC response

Major Results

Nanomaterials: Carbon nanotube (CNT) "silk" from UTD's Nanotech Center and single-layer exfoliated graphene

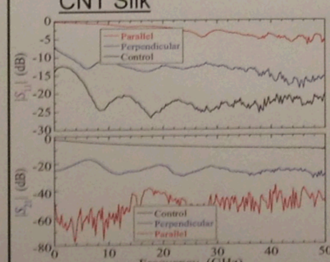
Graphene



- Control = CPW that never has nanomaterial
- Bare = CPW prior to putting on nanomaterial
- Graphene = Graphene flake placed on previously Bare CPW

- Graphene flake clearly alters reflection and transmission coefficients of CPW
- Very high signal-to-noise and reproducibility
- Change in CPW propagation constants can be used to determine graphene's AC conductance

CNT Silk

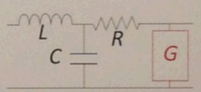


- Control = CPW that never has nanomaterial
- Parallel = CPW with CNT silk oriented parallel to E-field polarization
- Perpendicular = CPW with CNT silk oriented perpendicular to E-field polarization

- CNT silk clearly alters reflection and transmission coefficients of CPW
- Parallel orientation interacts more strongly with EM field than perpendicular orientation
- Change in CPW propagation constants can be used to determine CNT silk's anisotropic AC conductance

Future Work

Analysis: De-embed nanomaterial's intrinsic conductance spectrum $G(f)$ from CPW properties using transmission line model:



Propagation constants k (Bare CPW) and k' (CPW + nanomaterial) obtained from measured S_{ij} matrix:

$$k = \frac{1}{\ell}\cos^{-1}\left(\frac{1-DetS}{2S_{21}}\right) \qquad \frac{k'}{k} = \sqrt{\frac{G-i\omega C}{-i\omega C}}$$

Difficulty: Nanomaterials do not cover CPW uniformly. Must model as cascaded transmission lines based on observed coverage geometry .

Upcoming Materials to be Studied:

- CNT "ribbons"
- III-Nitride nanowires
- pnictide magnetic superconductors (e.g. FeSe): penetration depth & superfluid density vs. temperature
- Topological insulator (e.g. Bi_2Se_3) thin films & nanowires: effect of surface conduction on skin depth?

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