Microwave Dissipation in Carbon Nanotubes and Silicon Nanowires

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Motivation—Single-wall carbon nanotubes (SWCNTs) and silicon nanowires (SiNWs) are predicted to have novel electrodynamic properties that could be exploited to push nanotechnology into the microwave frequency domain. For example, there are claims in the literature that short, pure SWCNTs and SiNWs support ballistic charge transport at room temperature, meaning that electrons cross these nanomaterials without scattering. From the point of view of microwave response, ballistic transport implies a "magic" microwave material with no high-frequency power dissipation. Such dissipationless behavior has some experimental as well as theoretical support in the literature, but the signal-to-noise levels in reported empirical work are poor and remain controversial. It remains unclear whether nanomaterials such as SWCNTs and SiNWs are truly "magic" or whether they have microwave loss characteristics that are simply too small to be detected by the methods reported.

Accomplishment—We succeeded in using AC dielectrophoresis (ACDEP) directed self-assembly to incorporate arrays of between 10^2 to 10^4 SWCNTs or *n*-doped SiNWs onto a broadband co-planar waveguide (CPW) microwave measurement platform. These nanomaterials are assembled in such a way that they are parallel to the electric field polarization of the propagating microwave mode on the CPW, maximizing their interaction with the electromagnetic field. Figure 1 shows an optical microscope image of SiNWs assembled across the signal-to-ground plane gaps of a CPW.

The CPW's complex reflection and transmission coefficients before and after ACDEP assembly of nanomaterials were measured using a precisely calibrated vector network analyzer on a broadband probe station. Most importantly we developed a carefully calibrated and controlled measurement procedure that yielded signal-to-noise and systematic reproducibility that is a factor of 10 to 100 times better than what has been reported in the literature.

Because of this very high measurement quality, we were able to reliably calculate from the measured data the change in power loss as a function of frequency between having nanomaterials assembled on a CPW and the original CPW without nanomaterials. Such additional power loss is attributable to high-frequency dissipation by the nanomaterials.
Figure 2 shows the microwave loss coefficient α as a function of frequency measured for three different samples with SWCNT arrays and one with an *n*-doped SiNW array. The loss coefficient is always positive and frequency-dependent, proving that these nanomaterials dissipate microwave power.

Significance—The data shown in Fig. 2 are the first reliable measurements of frequency-dependent microwave power loss in SWCNTs and SiNWs. This proves that, at least at room temperature, these are not lossless "magic" microwave materials, contradicting several prominent claims in the existing literature. However, an estimate of the loss per nanotube or per nanowire shows that the high-frequency loss in a single nanotube/wire is nonzero but extremely small. Thus these nanomaterials are an extremely good microwave material.

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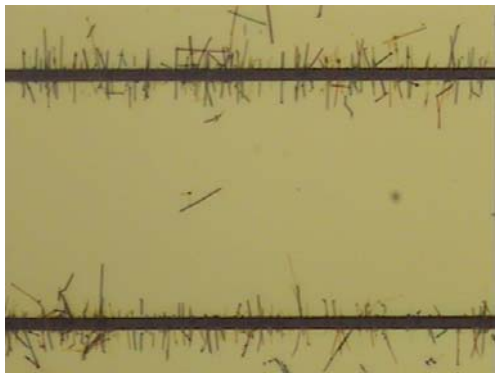

Figure 1. Optical microscope image of an array of n-doped silicon nanowires assembled via the ACDEP process across the gaps of a broadband microwave co-planar waveguide. The gap width between signal line (center gold strip) and the outer ground planes is 5 µm.

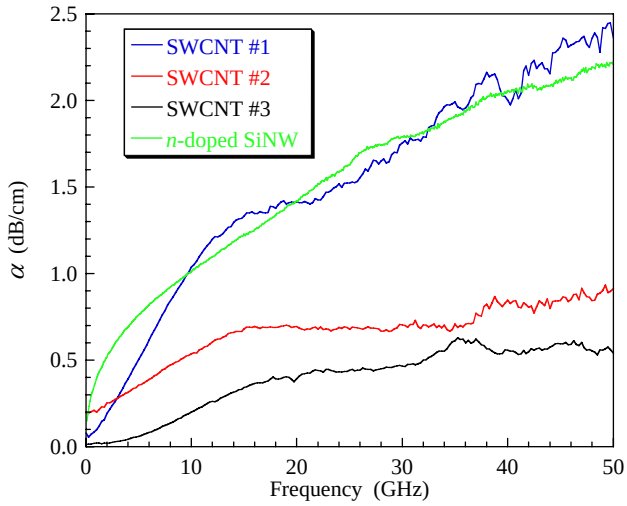

Figure 2. Microwave loss coefficient measured as a function of frequency for three different SWCNT arrays with different numbers of nanotubes and one array of *n*-doped SiNWs. A positive value for α means that the material dissipated microwave power.