Broadband Microwave AC Conductance of Silicon Nanowire Arrays

by **M. Lee and C. Highstrete**

Motivation—Semiconductor nanowires are thought to have novel electrodynamic properties that are relevant to both fundamental nanomaterial physics and applications in high-speed electronics and sensors. Recent reports of ballistic transport characteristics in Ge/Si and InAs nanowires suggest that such materials may have extremely fast, very low dissipation microwave response beyond the limit of conventional Drude diffusion-based electronic response. The sensitivity of the DC electrical properties of nanowires to molecules adsorbed on their surface also raises the question of whether similar AC conductance changes exist and can be exploited for chemical sensor purposes. Although there is a large body of research on DC electrical properties, little is known about the microwave electrodynamic response of any type of nanowire. One reason for this is that an individual nanowire presents a very small scattering cross-section to a 1 cm wavelength microwave field, so the interaction between a nanowire and the field usually produces a signal below instrumental background. Extracting the small nanowire signal from the background gives rise to large systematic uncertainties in microwave experiments on single or few nanowires.

Accomplishment—We have successfully measured broadband microwave conductance spectra of silicon nanowires (SiNWs) assembled into arrays spanning the electrode gaps of coplanar waveguides (CPWs). Using a relatively large number of SiNWs and guiding the electromagnetic field using the CPW maximized overlap with the nanowires yielded excellent signal levels and a very high degree of reproducibility. This allowed us to accurately extract the conductance spectra of the SiNWs from the combined CPW/SiNW system across a broad frequency range of 0.1 to 50 GHz.

Doped (n- and p-type) and undoped SiNWs were synthesized by vapor-liquid-solid growth by collaborators at Penn State. Using SiNWs suspended in deionized water or ethanol, arrays consisting of 10^3 to 10^4 SiNWs of each doping type were assembled by AC dielectrophoresis (ACDEP) across the electrode gaps of several CPWs (the "test" CPWs) on a wafer, as shown in Fig. 1, while at least one CPW remained bare (the "control" CPW). Using a vector network analyzer, the complex reflection and transmission coefficients on the CPW were measured before and after assembly of the SiNWs. The change in these coefficients was due to scattering and absorption by the SiNWs and was used to deduce their AC conductance as a function of frequency.

The complex AC conductance of the SiNW arrays exhibited a sub-linear power law increase with frequency as shown in Fig. 2. Such frequency dependence is inconsistent with ordinary Drude conductivity, but is consistent with a theory of universal AC transport in disordered electronic systems.

Significance—This is the first quantitatively reliable and reproducible data on the fundamental AC conductivity properties of any semiconductor nanowire. The finding that the AC conductance is not describable by standard Drude theory and is dominated by disorder is of major importance to both scientific understanding and potential applications of such nanomaterials in high-frequency applications.

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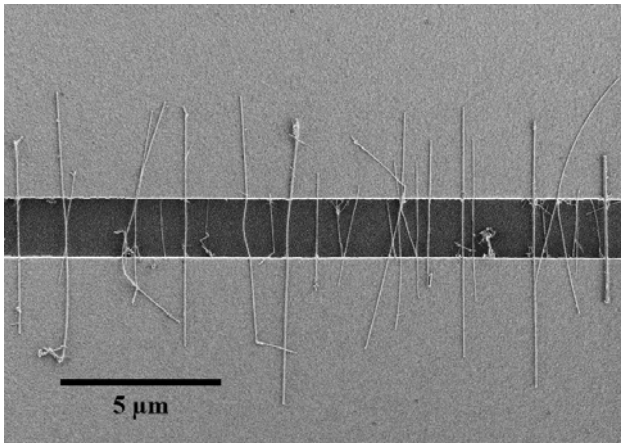

Figure 1. Scanning electron microscope image of an array of n^+ doped silicon nanowires assembled via the ACDEP process across the gaps of a broadband microwave co-planar waveguide.

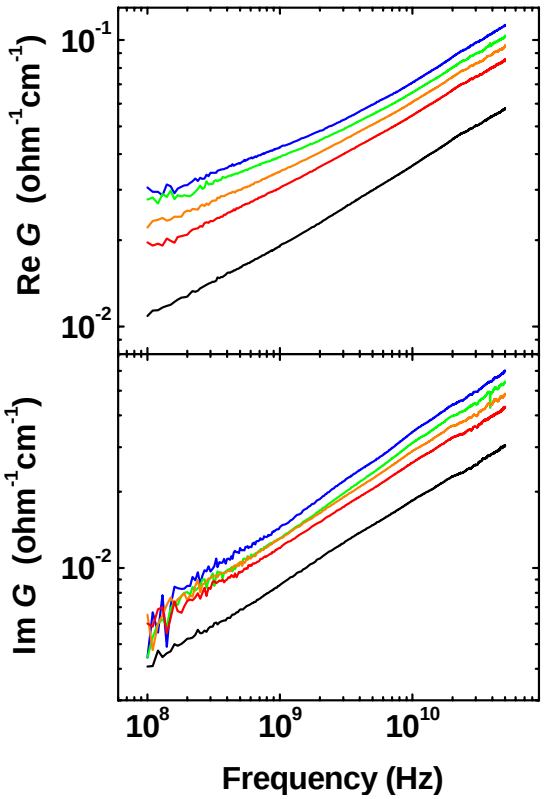

Figure 2. Real and imaginary parts of the SiNW array conductance spectrum at several temperatures for an n^+ doped sample. The top four curves are data taken in vacuum of 10^{-5} Torr at 4 K (blue), 100 K (green), 200 K (orange), and 293 K (red), from top to bottom. The bottom curve (black) represents data taken at 293 K in atmosphere.