Phononics and thermoelectric materials

A better understanding of the quantum nature of heat will advance energy research

Phonons are the quantum mechanical description of vibrations. Similar to electromagnetic waves, they also have characteristic frequencies spanning from a few hertz (1 Hz=1 cycle per second) to hundreds of terahertz (1 THz=10^{12} cycles per second). Low-frequency phonons, such as human sounds or mechanical vibrations, are generally well understood and can be well controlled, whereas the physics of high-frequency (above 100 GHz, 1 GHz=10^{9} cycles per second) phonons are poorly understood. In fact, current technologies are unable to use high-frequency phonons, leading many to characterize them as “waste heat”.

At the Center for Condensed Matter Sciences, a unique center at NTU dedicated to concentrating professional knowledge at the frontiers of science, we have invented many new tools to begin charting several unexplored domains of research. These tools include tailored platforms to characterize the heat transfer properties of nanomaterials, sophisticated thermometers for precise temperature measurements, and advanced far-infrared spectroscopes to investigate the interactions between phonons and photons. Our recent discoveries include (1) the observation of ballistic thermal conduction over 5 micrometers in SiGe nanowires and (2) non-Fourier thermal conduction over 1 millimeter in carbon nanotubes. Remarkably, these experimental observations were made at room temperature, thus opening many possibilities to practically engineer the wave properties of heat in the near future.

The discovery of ballistic thermal conduction demonstrates that the thermal conductivity of microscale materials is lower than what was anticipated. Thus, this discovery has inspired new ideas to improve thermoelectric devices. Thermoelectric devices can convert waste heat into electricity, or they can be operated in reverse by converting electricity into refrigerating power. These devices will serve as new green energy resources as their operation does not emit greenhouse gases. Furthermore, because they are solid-state materials, they can be compact and durable.

At the Center for Condensed Matter Sciences at NTU, we hope to contribute new knowledge about phononics by using phonons for mass sensing, enhancing phononic interactions with electrons and photons, and introducing new unforeseen applications. However, research on thermoelectrics has a notorious history of poor reproducibility and a lack of standardization. Together with several faculty members at the Academia Sinica, we have formed a team to focus efforts toward fabricating, designing, and characterizing thermoelectric materials with rigorous methods. Our goal is to maintain the integrity of science even though scientists currently operate in a global, competitive market.

References

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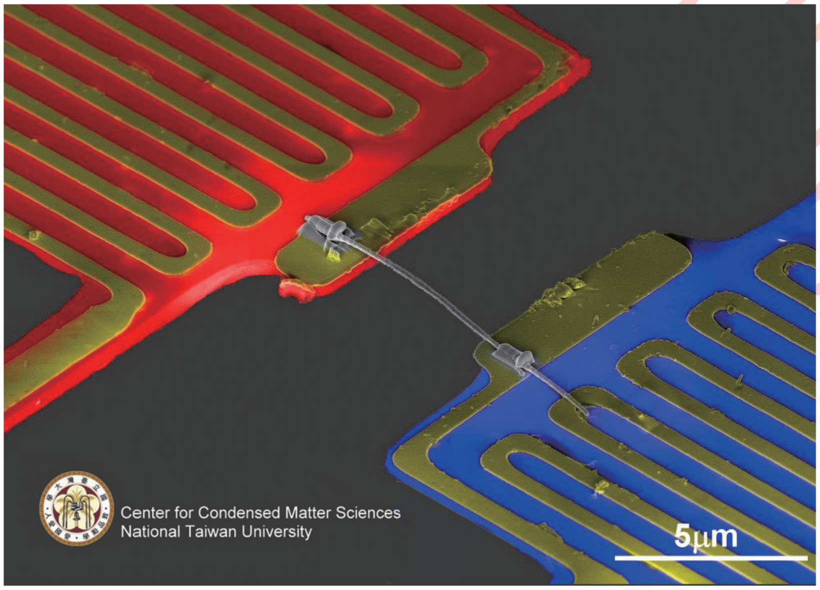

A tailored microscale platform for measuring phonon transport across an individual nanowire.

Toward low-cost and high-efficiency solar cells by solution processing

Global warming has led to ice in the Arctic and Antarctic to melt at an unprecedented rapid rate, and the excess water has caused many severe natural disasters worldwide. Solar cells are the most promising technology for producing renewable clean energy to meet the conditions of the 2015 Paris agreement signed by world leaders. The agreement calls to limit the global temperature rise tolower than 2°C, which requires CO_2 emissions to be reduced to at least 20% of the current amount by 2050 and 0% by 2100. However, the cost of generating electricity using Si solar cells is three times higher than that of burning fossil fuels. Recently, a new class of thin film solar cells, perovskite solar cells, has emerged as a technology that costs one-tenth of that of Si solar cells. Perovskite solar cells are fabricated from low-cost organic-inorganic perovskite materials using conventional solution processing.

The research group led by Professor Wei-Fang Su and Dr. Leeyih Wang, in the Department of Materials Science and Engineering and the Center for Condensed Matter Sciences at National Taiwan University, is the world leader in an effort to scale up and commercialize this technology. The team has studied the fundamental formation mechanism of crystalline perovskites using scanning tunneling microscopy, X-ray spectroscopy and scanning electron microscopy [1,2]. The results provide useful guidelines for controlling the composition, crystallization and morphology of perovskite films. Power conversion efficiencies of 18.2% for a small sized single cell and 12% for a 5 cm x 5 cm module of eight cells have been achieved [3].

Moreover, interface engineering of the TiO_2 electron-transport layer with amino acids can induce alignment of the (110) plane of the perovskite crystallites perpendicular to the TiO_2 surface. This preferential orientation of the perovskite crystals near the interface reduces the charge transfer resistance at the $TiO_2/CH_3NH_3PbI_3$ interface, leading to a considerable enhancement in photovoltaic performance [4]. Professor Su and Dr. Wang have also demonstrated that the incorporation of a