Electro-Thermal Transport in 2D Materials, Devices, and Applications

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Abstract

This talk will describe our group's recent work on two-dimensional (2D) materials and devices, with focus on electron and phonon transport. I will also describe some of their 'mainstream' as well as unconventional applications, which take advantage of the unique properties of 2D materials, including their anisotropy, band gap, and ultrathin nature.

Electronic Transport & Applications

From the point of view of electronic properties, 2D semiconductors have good mobility in ultrathin, sub-1 nm (i.e. monolayer) films. This indicates they could be used in applications where their ultrathin nature provides distinct advantages, such as flexible electronics [1], light-weight solar cells [2], or nanoscale transistors [3]. They may not be useful where conventional materials work well, or where their integration cost cannot be justified.

In the first part of this talk, I will focus on 2D materials for three-dimensional (3D) heterogeneous integration of electronics, which has major advantages for energy-efficient computing [4]. Here, 2D semiconductors (e.g. MoS_2, WSe_2) could be used as monolayer transistors with low leakage, used to access high-density memory [5], leveraging advances in topological interconnects [6], themselves based on ultrathin semimetallic NbP.

Recent efforts from our group [7-10] and others [11] have demonstrated well-behaved monolayer transistors which can rival conventional semiconductors, and we found the 2D performance can be further enhanced by strain [10,12]. Because experimental devices have defects and imperfections, we have also used simulations to understand quantum capacitance [8] and high-field transport in 2D semiconductors including strain and self-heating [13].

Thermal Transport & Applications

The thermal properties of 2D materials are of interest due to their anisotropic and tunable thermal conductivity. We have studied this behavior as part of transistors [14,15] and memory [5,16], where self-heating directly affects device operation and reliability. For instance, the electron saturation velocity in MoS_2 transistors is approximately doubled when self-heating is removed [13,17].

For monolayer 2D materials, molecular dynamics (MD) simulations suggest that their thermal conductivity on a substrate is always lower than in suspended films [18,19]. For multilayer 2D materials, we uncovered very long cross-plane phonon mean free paths, ~200 nm at room temperature in MoS_2 [20]. We have also layered heterogeneous 2D monolayers, achieving an effective cross-plane thermal conductivity ~3x lower than air [21]. A similar concept can be used with layered superlattices in phase change memory, enabling ultralow power operation [5]. Finally, I will also describe some applications of 2D materials as thermal switches [22] and heat spreaders in integrated circuits [23].

Combined, these studies reveal fundamental limits and some applications of 2D materials, which take advantage of their unique properties.

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