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Electronic, Thermal, and Unconventional Applications of 2D Materials

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Abstract

This invited talk will present recent highlights from our research on two-dimensional (2D) materials and devices including graphene, boron nitride (h-BN), and transition metal dichalcogenides (TMDs). The results span from fundamental measurements and simulations, to device- and several unusual system-oriented applications which take advantage of unique 2D material properties. We describe ~10 nm scale transistors and contacts with record-high current drive (>400 μA/μm) and record-low contact resistance based on monolayer semiconducting MoS_2, grown by large-area chemical vapor deposition (CVD). We will also describe measurements and simulations of high-field transport and power dissipation in functioning 2D devices, as well as basic thermal and thermoelectric properties of 2D materials, including their anisotropy and the thermal resistance of their interfaces. Our studies reveal fundamental limits and some new applications that could be achieved with 2D nanomaterials, while taking advantage of unique 2D material properties.

1. Introduction

Two-dimensional (2D) materials have applications in low-power electronics and energy-conversion systems. These are also rich domains for fundamental discoveries as well as technological advances. This talk will present recent highlights from our research on graphene, h-BN, and transition metal dichalcogenides (TMDs), with an emphasis on their electrical, thermal, and unconventional applications.

2. Summary of Graphene Results

We have studied graphene starting with basic transport measurements and simulations, such as velocity saturation [1], thermal conductivity [2], as well as self-heating effects in graphene field-effect transistors (GFETs) [3]. Most recently we have measured velocity saturation in pristine single-layer graphene encapsulated by h-BN and uncovered values from 3 to 6 × 10^7 cm/s [4], which are a record for any 2D material and comparable to InSb. We have also contributed to GFET simulations, particularly by self-consistently including electrical and thermal effects during operation [5]. Taking advantage of its low cross-plane thermal conductance, we have found unexpected applications of graphene as an ultra-thin electrode to reduce the power consumption of phase-change memory devices [6].

More recently, we have demonstrated 4” wafer-scale growth and integration of GFETs, realizing analog dot product nanofunctions with application to image processing and neural networks (Fig. 1) [7].

3. Summary of TMD Results

We have recently succeeded in growing monolayer TMDs by chemical vapor deposition (CVD) over cm^2 scales, including MoS_2 (Fig. 2), WSe_2, and $MoSe_2$ [8,9] and multilayer TMDs including $MoTe_2$, $HfSe_2$, and WTe_2 [10,11]. Importantly, $HfSe_2$ and $ZrSe_2$ have been uncovered to be 2D materials with native high-K dielectrics HfO_2 and ZrO_2 [11]. For transistor applications, these materials are similar to silicon and unlike other semiconductors, benefitting from reduced interface state density with their own native high-K oxide.

Recent results include low-resistance contacts (500 to 700 Ω·μm) obtained on monolayer to few-layer MoS_2 using ultra-high vacuum deposition of Au contacts (Fig. 3) [12]. We have also demonstrated 10-nm scale transistors on monolayer MoS_2, realizing the highest current density reported to date (>400 μA/μm) in this atomically thin semiconductor [13]. In this talk, we will also describe recent measurements of high-field velocity saturation in monolayer MoS_2, revealing $v_{sat} \approx$ 2 to 4 × 10^6 cm/s, dependent both on temperature and on carrier density [14]. In all such high-field and high-current measurements, the device self-heating plays a significant role, as predicted by our electro-thermal self-consistent transistor simulations [15] and directly confirmed by Raman thermometry (Fig. 4) [16].

Thermal measurements have uncovered the low thermal boundary conductance (TBC ~ 14 $MW/m^2/K$ between MoS_2 and SiO_2), which strongly limits heat dissipation in TMD devices [16,17]. Additional experiments and simulations have also explored the anisotropic thermal conductivity of such 2D materials (Fig. 5) [10,18], which could ultimately lead to unconventional applications including thermal switches and thermal routing. Such thermal circuit elements could enable the nanoscale control of heat in a manner similar to the control of current in electronic circuits.

4. Conclusion

Our studies reveal fundamental limits and new applications that could be achieved through the co-design and heterogeneous integration of 2D nanomaterials, while taking advantage of unique 2D material properties.

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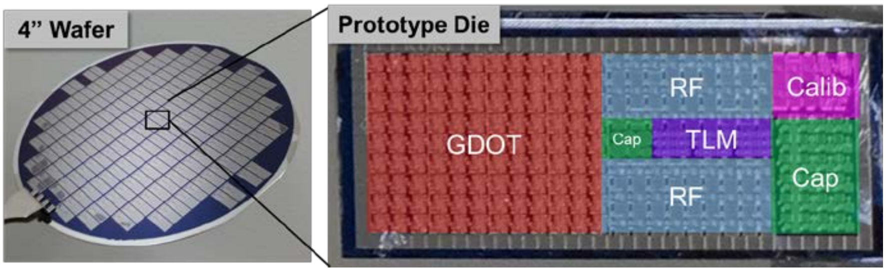

Fig. 1. Images of wafer-scale graphene circuits, and individual die with prototype graphene dot product (GDOT) analog circuits. Such circuits take advantage of unique graphene properties, like high mobility, while tolerating its drawbacks, like the relatively low on/off ratio of GFETs. Reproduced after Ref. [7].

Fig. 2. Image of *monolayer* MoS_2 grown over centimeter scale by chemical vapor deposition (CVD) on SiO_2/Si substrate. The Stanford logo was patterned to provide contrast. The electrical properties of these films are comparable to those of the best exfoliated MoS_2 monolayers [8,9].

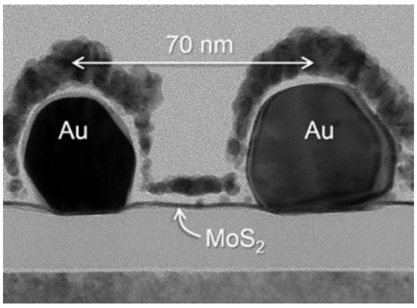

Fig. 3. Transmission electron microscopy (TEM) cross-section of MoS_2 transistor with nanoscale Au contacts, reproduced after Ref. [12]. The contact pitch is 70 nm, corresponding to the "14 nm" modern silicon technology node (however, here in a back-gated device). These studies [12,13] have highlighted the need to proportionally scale both the channel and contacts of TMD-based atomically thin transistors.

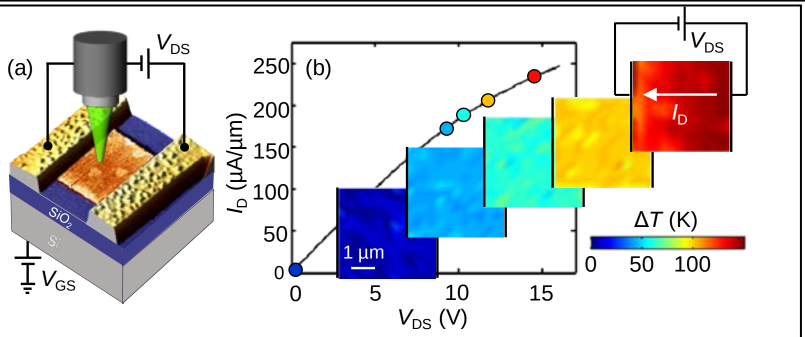

Fig. 4. (a) Schematic of Raman thermal measurement of monolayer MoS_2 transistor during operation [15]. (b) Electrical *I-V* and Raman thermometry. The temperature maps correspond to the colored circles on the *I-V* curve. The MoS_2 is on 90 nm SiO_2 on Si substrates, capped with a ~15 nm Al_2O_3 layer, which provides long-term stability during operation and measurement. The measurements reveal a relatively low TBC ~ 14 $MW/m^2/K$ between MoS_2 and SiO_2 [16,17].

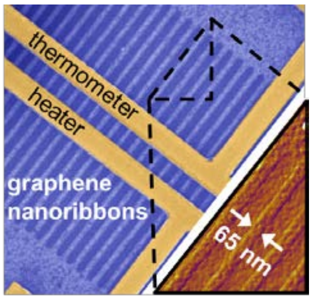

Fig. 5. Thermometry test structure for measuring heat flow in graphene nanoribbons, reproduced after Ref. [18]. Such measurements have revealed that graphene thermal conductivity becomes a function of both width and length in samples with dimensions smaller than approximately 1 μm, even at room temperature. This behavior arises due to phonon-edge scattering and quasi-ballistic phonon conduction at such length scales.