2D Materials for Smart Life

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1. Abstract

Two-dimensional (2D) materials such as graphene and various transition metal dichalcogenides (TMDs) possess a wide range of remarkable properties that make them attractive for a number of applications, including sub-10 nm transistors, sensors, interconnect and passives [1]. In this lecture, I will highlight the prospects of 2D materials for building next-generation electronics targeted to support the emerging paradigm of the *Internet of Things*.

2. Applications Uniquely Enabled by 2D Materials

In contrast to conventional bulk materials, 2D materials (Fig. 1) are formed by weak interlayer van der Waals bonds . This unique structure enables many extraordinary properties such as extremely small thickness (few Å/layer), uniform band gap over large area, and pristine interfaces without out-of-plane dangling bonds [1], based on which novel applications can be explored. For example, TMDs allow efficient electrostatics, reduction of short channel effects for nanoscale transistors, fewer traps on a semiconductor-dielectric interface, and a high degree of vertical scaling. I will bring forward a few important developments on transistors [2-6], sensors [7], interconnects [8], and passives [9], all uniquely enabled by 2D materials, which have been realized in my lab.

More specifically, I will highlight the world's first "kinetic inductor" [9] that exploits the *kinetic inductance* at room temperature and thereby overcomes a 200 years old limitation of the original device designed by Michael Faraday. I will discuss the first 2D-channel band-to-band tunneling transistor [5] that can switch at 0.1V and potentially lead to significant (> 90%) lowering of power dissipation, as well as a radical interconnect technology based on intercalation doped graphene-nanoribbons [8], which overcomes the fundamental limitations of conventional metals and provides an attractive pathway toward an energy-efficient and highly reliable interconnect technology for next-generation integrated circuits. I will also bring forward a new class of ultra-sensitive and low-power sensors being developed in my lab using 2D materials for ubiquitous sensing and connectivity to improve quality of life. Progress on key issues in 2D electronics including large-area synthesis, contacts and interfaces [10], high-k gate dielectrics, and doping will be summarized.

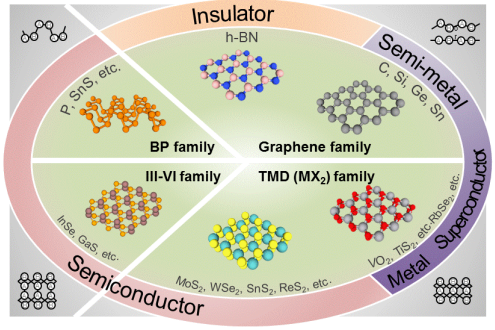

Fig. 1. 2D materials family [1].

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4. References

[1] P. Ajayan, P. Kim, and K. Banerjee, "Two – dimensional van der Waals materials," *Physics Today*, vol. 69, no. 9, 38-44, 2016.
[2] W. Cao, J. Kang, D. Sarkar, W. Liu, and K. Banerjee, "2D semiconductor FETs - Projections and design for sub-10 nm VLSI," *IEEE Trans. Electron Devices*, vol. 62, no. 11, pp. 3459–3469, 2015.
[3] W. Cao, W. Liu, J. Kang, and K. Banerjee, "An ultra-short channel monolayer MoS_2 FET defined by the curvature of a thin nanowire," *IEEE Electron Device Letters*, vol. 37, no. 11, pp. 1497-1500, 2016.
[4] J. Kang, W. Cao, A. Pal, S. Pandey, S. Kramer, R. Hill, G. Sandhu, and K. Banerjee, "Computational study of gate-induced drain leakage in 2D-semiconductor field-effect transistors," *IEDM Tech. Dig*., 2017, pp. 31.2.1-31.2.4.
[5] D. Sarkar, X. Xie, W. Liu, W. Cao, J. Kang, Y. Gong, S. Kraemer, P. M. Ajayan, and K. Banerjee, "A subthermionic tunnel field-effect transistor with an atomically thin channel," *Nature*, 526, pp. 91–95, 2015.
[6] W. Cao, J. Jiang, J. Kang, D. Sarkar, W. Liu, and K. Banerjee, "Designing band-to-band tunneling field-effect transistors with 2D semiconductors for next-generation low-power VLSI," *IEDM Tech. Dig*., 2015, p. 12.3.1-12.3.4.
[7] D. Sarkar, W. Liu, X. Xie, A. Anselmo, S. Mitragotri, and K. Banerjee, "MoS_2 field-effect transistor for next-generation label-free biosensors," *ACS Nano*, vol. 8, no. 4, 3992-4003, 2014.
[8] J. Jiang, J. Kang, W. Cao, X. Xie, H. Zhang, J. H. Chu, W. Liu, and K. Banerjee, "Intercalation doped multilayer-graphene nanoribbons for next-generation interconnects," *Nano Letters*, 17(3), pp. 1482-1488, 2017.
[9] J. Kang, Y. Matsumoto, X. Li, J. Jiang, X. Xie, K. Kawamoto, M. Kenmoku, J. H. Chu, W. Liu, J. Mao, K. Ueno, and K. Banerjee, "On-chip intercalated-graphene inductors for next-generation radio frequency electronics," *Nature Electronics*, 1(1), pp. 46-51, 2018.
[10] A. Allain, J. Kang, K. Banerjee and A. Kis, "Electrical contacts to two-dimensional semiconductors," *Nature Materials*, 14, pp. 1195–1205, 2015.