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Van der Waals Integration beyond 2D Materials

Semiconductor heterostructures are central for all modern electronic and optoelectronic devices. Traditional semiconductor heterostructures are typically created through a "chemical integration" approach with covalent bonds, and generally limited to the materials with highly similar lattice symmetry and lattice constants (and thus similar electronic structures) due to lattice/processing compatibility requirement. Materials with substantially different structure or lattice parameters can hardly be epitaxially grown together without generating too much defects that could seriously alter their electronic properties. In contrast, *van der Waals* integration, where pre-formed materials are "physically assembled" together through van der Waals interactions, offers an alternative "low-energy" material integration approach (*vs.* the more aggressive "chemical integration" strategy). The flexible "physical assembly" approach is not limited to materials that have similar lattice structures or require similar synthetic conditions. It can thus open up vast possibilities for damage-free integration of highly distinct materials beyond the traditional limits posed by lattice matching or process compatibility requirements, as exemplified by the recent blossom in *van der Waals* integration of a broad range of 2D heterostructures. Here I will discuss *van der Waals* integration as a general material integration approach beyond 2D materials for creating diverse heterostructures (*e.g.*, semiconductor/semiconductor, dielectric/semiconductor and metal/semiconductor) with minimum integration-induced damage and interface states, enabling high-performing devices (including high speed transistors, diodes, flexible electronics) difficult to achieve with conventional "chemical integration" approach. A particular highlight is the creation of *van der Waals* metal/semiconductor contacts free of interfacial disorder and Fermi level pinning, thus for the first time enabling experimental validation of the Schottky-Mott rule first proposed in 1930s.

References

[1] L. Liao, J. Bai, Y. Qu, Y. Lin, Y. Li, Y. Huang and X. Duan. *Proc. Natl. Acad. Sci.* **107**, 6711-6715 (2010) (DOI: 10.1073/pnas.0914117107).

[2] L. Liao, Y. Lin, M. Bao, R. Cheng, J. Bai, Y. Liu, Y. Qu, K.L. Wang, Y. Huang and X. Duan. *Nature* **467**, 305-308 (2010) (DOI: 10.1038/nature09405).

[3] R. Cheng, J. Bai, L. Liao, H. Zhou, Y. Chen, L. Liu, Y. Lin, S. Jiang, Y. Huang and X. Duan. *Proc. Natl. Acad. Sci.* **109**, 11588-11592 (2012) (DOI: 10.1073/pnas.1205696109).

[4] W. J. Yu, Z. Li, H. Zhou, Y. Chen, Y. Wang, Y. Huang and X. Duan. *Nature Mater.* **12**, 246–252 (2013) (DOI: 10.1038/nmat3518).

[5] R. Cheng, S. Jiang, Y. Chen, Y. Liu, N.O. Weiss, H.-H. Cheng, H. Wu, Y. Huang and X. Duan. *Nature Commun.* **5**, 5143 (2014) (DOI: 10.1038/ncomms6143).

[6] Y. Liu, N. O. Weiss, X. Duan, H. C. Cheng, Y. Huang and X. Duan. *Nature Rev. Mater.* **1**, 16042 (2016) (DOI: 10.1038/natrevmats.2016.42).

[7] Y. Liu, J. Guo, E. Zhu, L. Liao, S. Lee, M. Ding, I. Shakir, V. Gambin, Y. Huang and X. Duan. *Nature* **557**, 696-700 (2018) (DOI: 10.1038/s41586-018-0129-8).

[8] C. Wang, Q. He, U. Halim, Y. Liu, E. Zhu, Z. Lin, H. Xiao, X.D. Duan, Z. Feng, R. Cheng, N. Weiss, G. Ye, Y.C. Huang, H. Wu, H.-C. Cheng, L. Liao, X. Chen, W.A. Goddard, Y. Huang and X. Duan. *Nature* **555**, 231-236 (2018) (DOI: 10.1038/nature25774).

[9] B. Yao, S.-W. Huang, Y. Liu, A. K. Vinod, C. Choi, M. Hoff, Y. Li, M. Yu, Z. Feng, D.-L. Kwong, Y. Huang, Y. Rao, X. Duan and C. W. Wong. *Nature* **558**, 410-414 (2018) (DOI: 10.1038/s41586-018-0216-x).

[10] Z. Lin, Y. Liu, U. Halim, M. Ding, Y. Liu, Y. Wang, C. Jia, P. Chen, X. Duan, C. Wang, F. Song, M. Li, C. Wan, Y. Huang and X. Duan. *Nature* (2018) (DOI: 10.1038/s41586-018-0574-4).