Scaling, Stacking, and Printing: How Nanomaterials Still Hold Promise for Electronics

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Silicon-based electronics remain the backbone of the ongoing digital revolution and continue to enhance the computational ability and accessibility of data. As the range of possible applications for electronics grows, so does the realization that there are distinct limits to what silicon can do. Meanwhile, nanomaterials have been studied for decades for their attractive electronic properties coupled with mechanical flexibility, thermal resilience, and compatibility with solution-phase processing. From 1D carbon nanotubes (CNTs) to 2D graphene and transition metal dichalcogenides (TMDs), there is a growing list of nanomaterial options (Fig. 1) [1]. Unfortunately, much of the electronics community has become disenchanted with nanomaterials because of years of overstated results and undelivered promises.

Despite what may have been suggested over the years, nanomaterials are not the cure-all for every present challenge or future application in electronics. Amidst this unfolding reality check, there is an upside as the core advantages offered by nanomaterials are becoming more evident. Some research has been able to focus on aspects of nanomaterials that are uniquely useful for future applications. Three of these advantages are scaling (Fig. 2), stacking (Fig. 3), and printing (Fig. 4).

In this talk, it will be shown how these unique advantages of nanomaterials enable transformative applications, including: 1) scalable low-voltage transistors, 2) printed electronic sensors, and 3) ultrasensitive biological sensing. All of these results draw from capabilities unique to nanomaterials [2-6], which leads to performance, fabrication, and/or function that are not possible with traditional semiconductors. For instance, the low-cost printing of electronic circuits and sensors that must operate within the harsh environment of an automobile tire, providing data that enhances safety and function, will be demonstrated. Low-voltage negative capacitance transistors from 2D TMDs that can prove transformative for future computing in terms of both voltage and size scalability, will be discussed. Finally, fully printed bioelectrical immunoassays will be shown that offer a path for revolutionizing point-of-care diagnostic healthcare. As the coverage of this talk will be relatively broad in terms of applications, the primary takeaway will be an overview of a new era of electronics that is uniquely possible using nanomaterials.

[1] A. Franklin, *Science,* 349:aab2750 (2015). [2] F. McGuire *et al.*, *Nano Lett.* 17:4801 (2017). [3] A. Franklin *et al.*, *IEEE-EDL*, 34:556 (2013). [4] P. Chen *et al.*, *Nanoscale* 8:3524 (2016). [5] T. Roy *et al.*, *ACS Nano* 8:6259 (2014). [6] C. Cao *et al.*, *ACS Nano*, 10:5221 (2016).

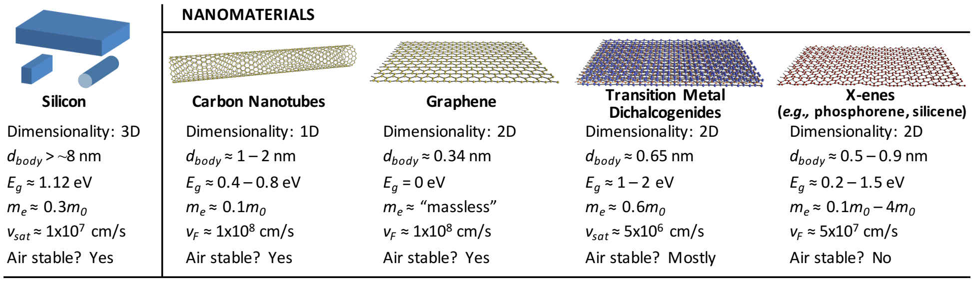

Figure 1: Toolkit of 1D and 2D nanomaterials: Approximations of key properties are provided, though it is noted that many factors could affect these values (adapted from [1]).

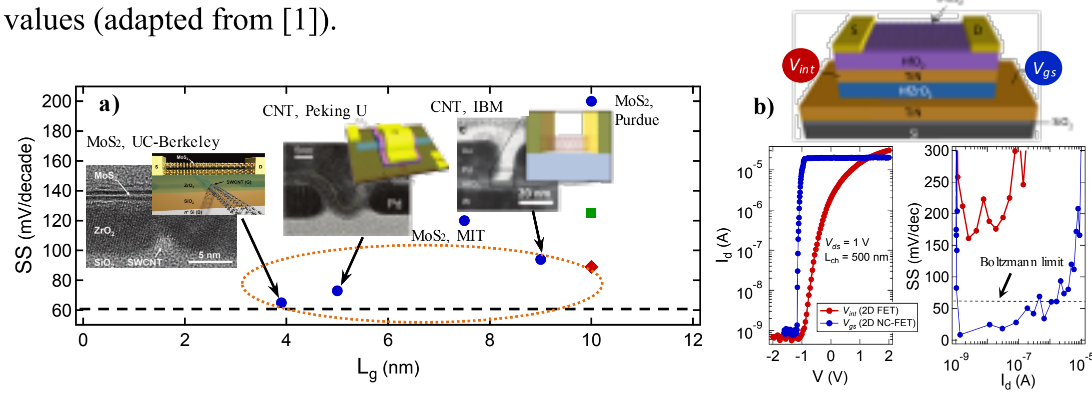

Figure 2: Scaling of size & voltage: a) Comparison of a) subthreshold swing (SS) (approximated when not given explicitly) from the shortest gate length 1D & 2D devices to date. b) Schematic and corresponding data from 2D MoS_2 negative capacitance FET (2D NC-FET) showing sub-60 mV/dec switching [2].

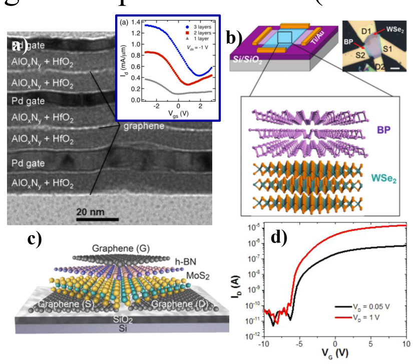

Figure 3: Stacking nanomaterials – heterostructures: a) Interdigitated stacking of 2D graphene channels in a FET [3]. b) Gate-tunable heterojunction between stacked BP and WSe_2 [4]. c) Schematic and d) subthreshold data from all-2D FET, with all layers formed using 2D materials [5].

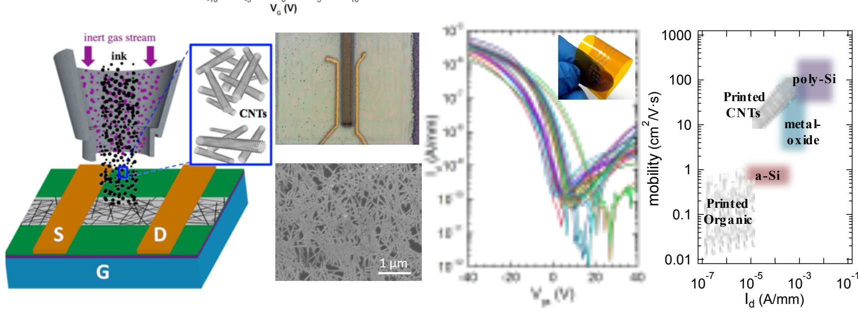

Figure 4: Printing of nanomaterials – additively: Fully printed CNT transistors on plastic with subthreshold curves shown (device yield is 100 %) [6]. b) Performance comparison of printed CNT-TFTs to printed organic TFTs and other non-printed TFTs.