Low Power and High Performance Flexible Electronics

Prof. Eric M. Vogel

Professor, Materials Science & Engineering

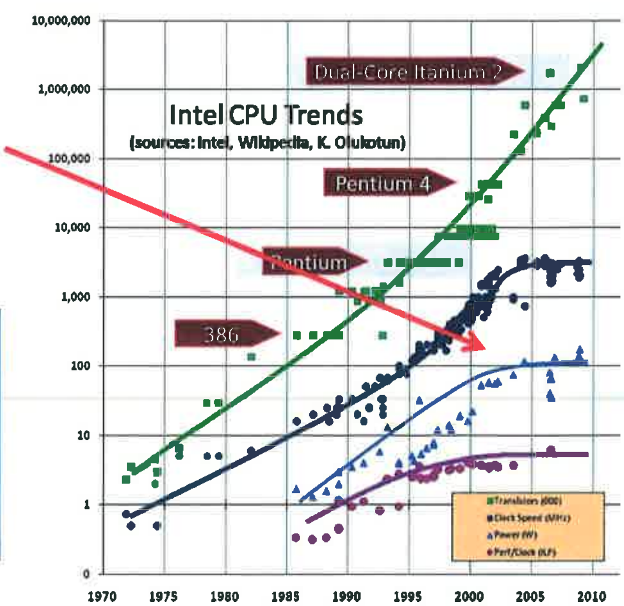
Deputy Director, Institute for Electronics and Nanotechnology

Associate Director, Institute for Materials

Georgia Institute of Technology

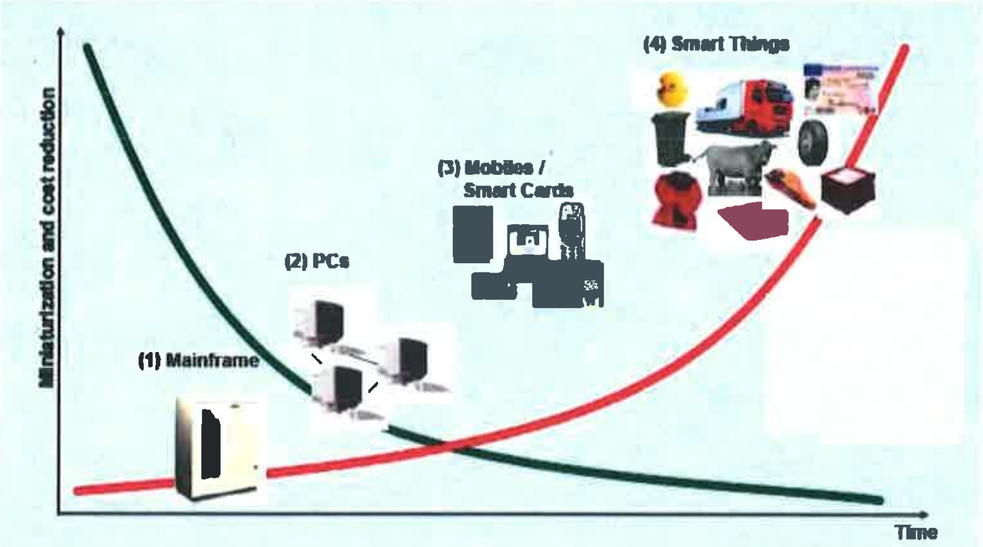
Moore's Law: *CMOS and Beyond*

- Numerous new materials have been developed to maintain **energy efficiency (low power)** while increasing the transistor density at constant transistor performance.



Next Generation Electronics:
Embedding Everyday Flexible Materials w/ Function

- Internet of things
- Pervasive and ubiquitous electronics
- Wearable electronics
- **Energy efficiency will be key in the long run**



Next Generation High Performance Electronics:
Embedding Everyday Flexible Materials w/ Function

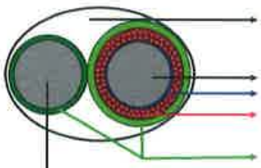
<u>Short Term: Evolution</u>

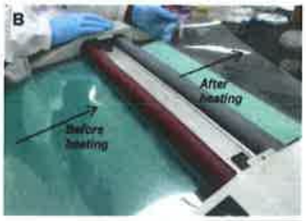
- Tiny conventional electronics are separately fabricated.

One example: An ant-sized radio on chip recently developed by Stanford and UC Berkeley

<u>Long Term: Revolution</u>

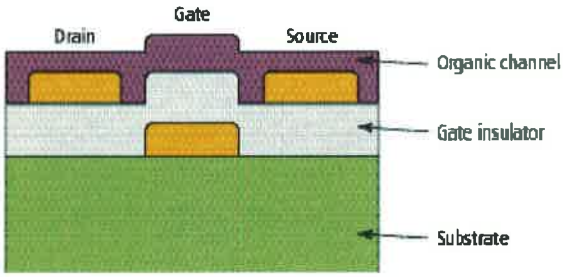
- The fabrication processes for conventional materials (textile fibers, paper, etc.) are modified to embed intelligence.





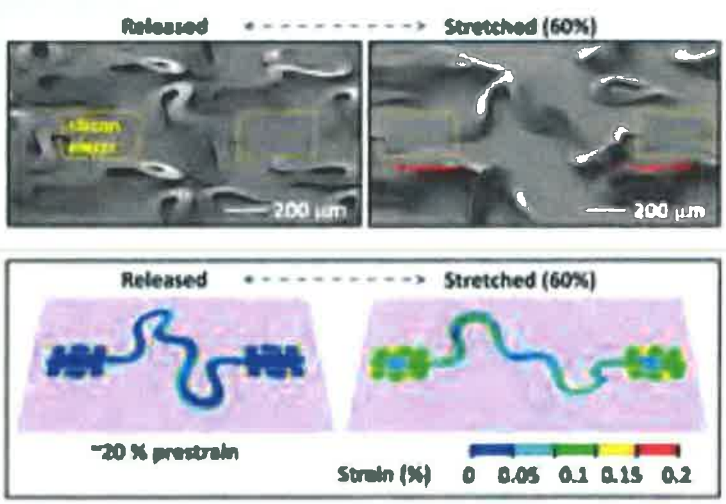
Technologies for Flexible Electronics: Organic Electronics with Ink-jet Printing

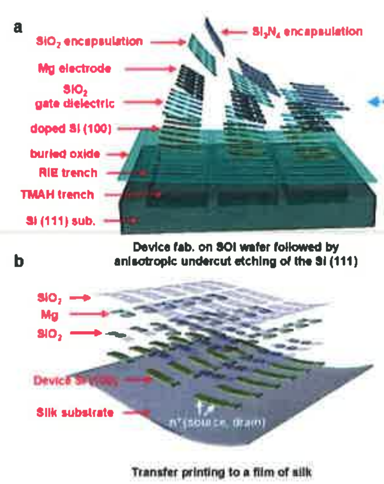
- High throughput, solution-based processing
- Numerous potential materials: metals, semiconductors, insulators
- Low performance, high operating voltage, poor reliability/stability



Technologies for Flexible Electronics: Conventional 3D Materials (Si, GaAs, Cu)

- Numerous potential materials: metals, semiconductors, insulators
- Better performance, lower operating voltage, better stability/reliability
- Thickness limited due to surface defects
- Limited pathway to high-throughput, large area processing



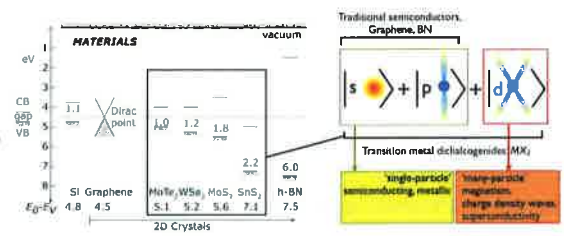


Prof. John Rogers, UIUC

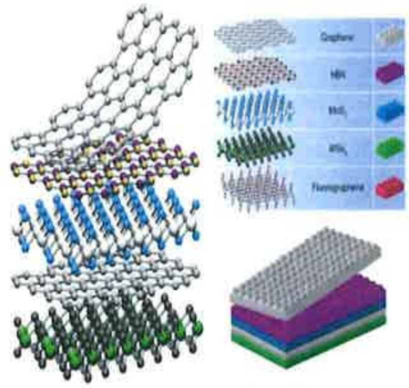
Technologies for Flexible Electronics:
2D Materials (Graphene, MoS_2, hBN)

- Numerous potential materials: metals, semiconductors, insulators
- Hexagonal crystal structure with no out-of-plane bonds: no dangling bonds, monolayer thickness control, no strain
- High performance, low power, stable and reliable
- High-throughput manufacturing schemes

S. Bae, *et al.*, *Nature Nanotechnology* **5**, 574 (2010)



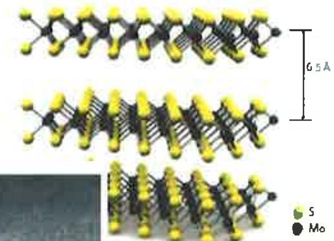
D. J. Jena, *Proc. IEEE* **101**, 1585 (2013)

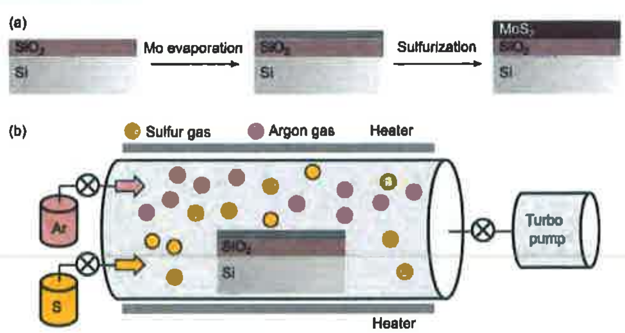


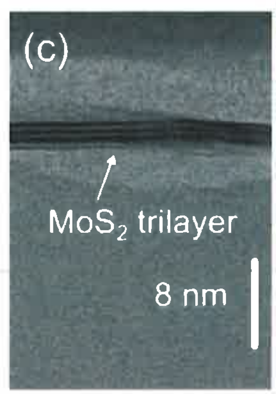
A. K. Geim and I. V. Grigorieva, *Nature* **499**, 419 (2013).

MoS_2 Synthesis

- We have previously developed a synthesis technique for highly uniform, high quality MoS_2.
- MoS_2 is a semiconductor with ~1.5 eV bandgap.





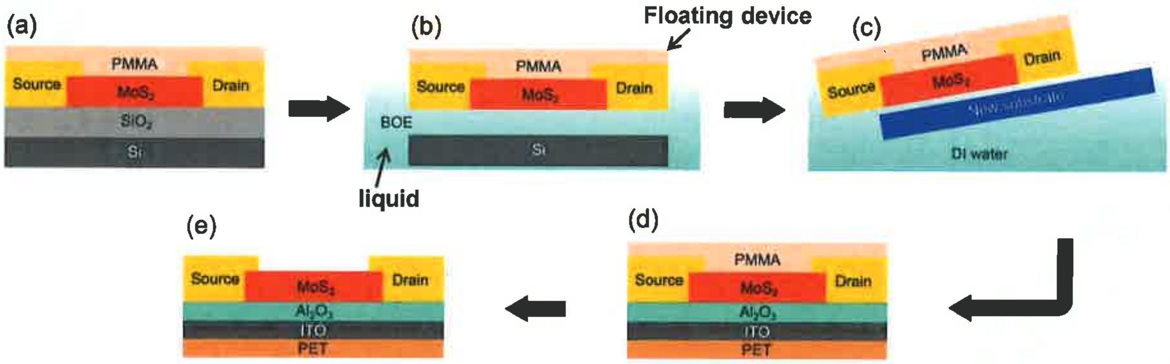


A. Tarasov, P. M. Campbell, M.-Y. Tsai, Z. R. Hesabi, J. Feirer, S. Graham, W. J. Ready, and E. M. Vogel, "Highly Uniform Trilayer Molybdenum Disulde for Wafer-Scale Device Fabrication," *Advanced Functional Materials* (2014).

Device Fabrication Followed by Transfer

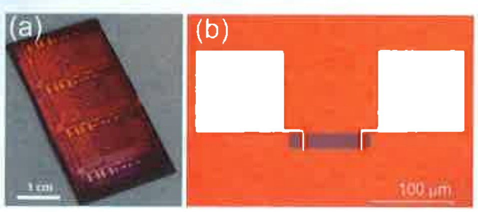
Fabrication of flexible devices

- High temperature and photolithography processes need to be avoided
- **Transfer completed devices from growth substrate to desired substrate**



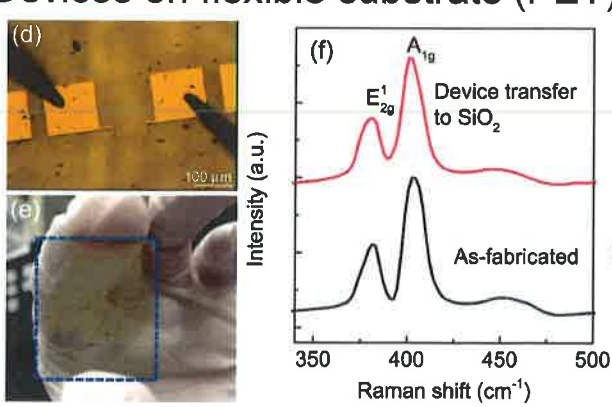
Device Fabrication Followed by Transfer

Devices on rigid growth substrate (SiO_2)

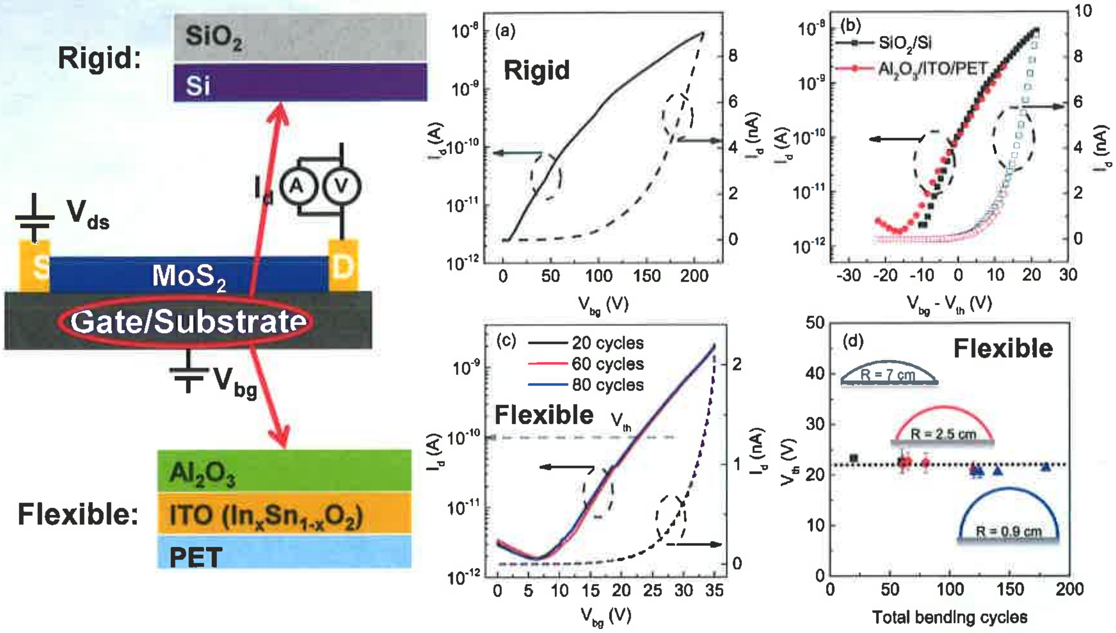


Devices float on water

Devices on flexible substrate (PET)



Bending stable flexible MoS_2 transistors

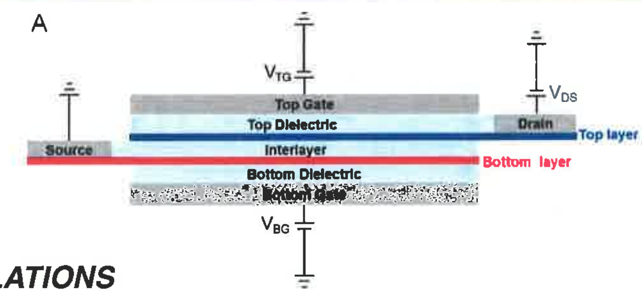


- MoS_2 transistors are still operational after 200 bending cycles.

Vertical Heterostructures of 2D Materials

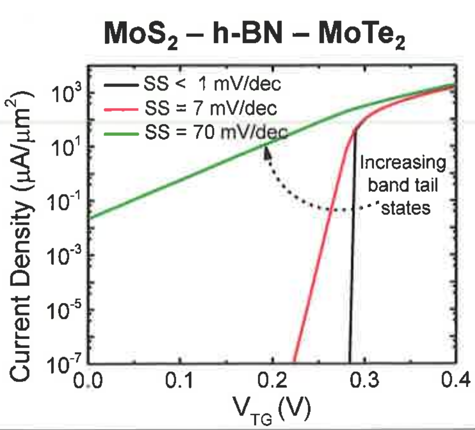
- Vertical heterostructures of 2D materials can provide unique current-voltage relationships such as steep subthreshold slope and negative differential resistance.

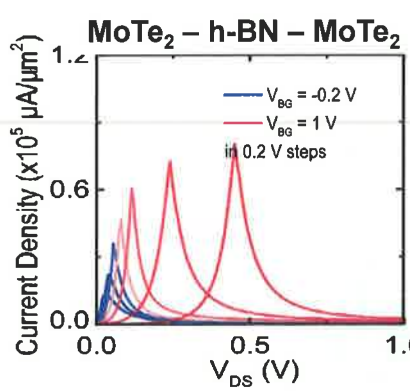
A



SIMULATIONS

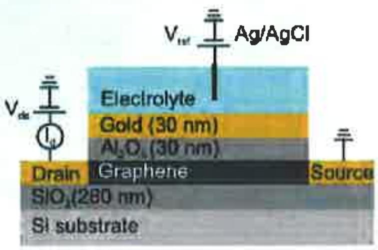
B



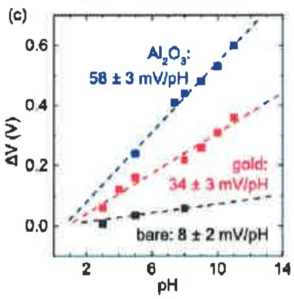


2D-based Chemical and Biological Potentiometric Sensors

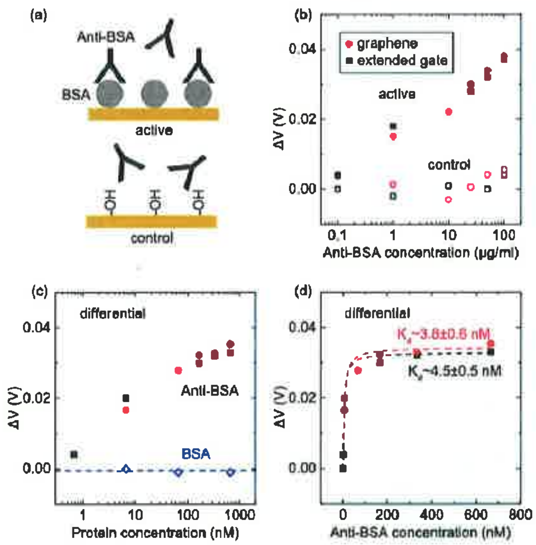
- The low noise of graphene transistors make them ideal for chemical and biological sensors on arbitrary substrates.



pH Sensing

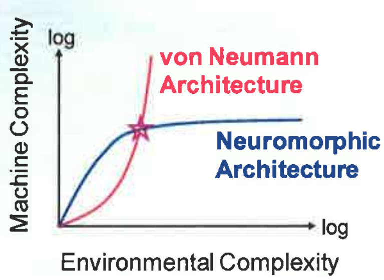


Bio Sensing

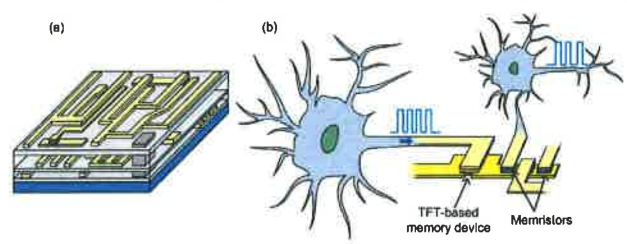


Materials/Devices for Neuromorphic Computing on Flexible Substrates

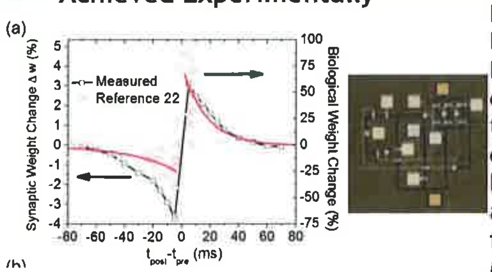
Motivation



Our Approach: Nanocrystalline silicon TFTs with TiN/HfO_2 memristors permit flexible substrates

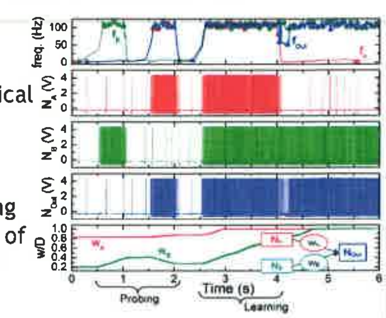


Spike Timing Dependent Plasticity Achieved Experimentally



Association and Other Circuits Demonstrated

Demonstration of associative learning that is analogous to Pavlov's experiments on classical conditioning in dogs. In the three-neuron network configuration shown at the bottom right, increased spiking activity of N_A represents sight of food, N_B ringing of a bell, and N_{out} the salivation response.



Conclusions

- Being able to bring cutting-edge technologies to flexible substrates is a promising opportunity for innovation.
- In the long-run, materials (e.g. 2D) and designs (e.g. neuromorphic) for low power, high performance flexible technologies will be key.

Acknowledgements

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  - Renewable Bioproducts Institute
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Some Representative Publications

- A. Tarasov, S. Zhang, M.-Y. Tsai, P. M. Campbell, S. Graham, S. Barlow, S. R. Marder, and E. M. Vogel, "Controlled Doping of Large-Area Trilayer MoS2 with Molecular Reductants and Oxidants," *Advanced Materials* **27**, 1175–1181 (2015).
- A. Tarasov, P. M. Campbell, M. Y. Tsai, Z. R. Hesabi, J. Feirer, S. Graham, W. J. Ready, and E. M. Vogel, "Highly uniform trilayer molybdenum disulfide for wafer-scale device fabrication," *Advanced Functional Materials* **24**, 6389-6400 (2014).
- T. Roy, L. Liu, S. De La Barrera, B. Chakrabarti, Z. R. Hesabi, C. A. Joiner, R. M. Feenstra, G. Gu, and E. M. Vogel, "Tunneling characteristics in chemical vapor deposited graphene-hexagonal boron nitride-graphene junctions," *Applied Physics Letters,* **104** 123506 (2014).
- B. Chakrabarti, T. Roy, and E. M. Vogel, "Nonlinear switching with ultralow reset power in graphene-insulator- graphene forming-free resistive memories," *IEEE Electron Device Letters,* **35** 750-752 (2014).
- A. Subramaniam, K. D. Cantley, R. A. Chapman, H. J. Stiegler, and E. M. Vogel, "Low-temperature Fabrication of Spiking Soma Circuits using Nanocrystalline-silicon TFTs," *IEEE Transactions on Neural Networks and Learning Systems* **24**, 1466 - 1472 (2013).
- A. Subramaniam, K. D. Cantley, G. Bersuker, D. Gilmer, and E. M. Vogel, "Spike-timing-dependent Plasticity using Biologically Realistic Action Potentials and Low-temperature Materials," *IEEE Transactions on Nanotechnology* **12**, 450 – 459 (2013).
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- X. Li, C. W. Magnuson, A. Venugopal, R. M. Tromp, J. B. Hannon, E. M. Vogel, L. Colombo, and R. S. Ruoff, "Large-Area Graphene Single Crystals Grown by Low-Pressure Chemical Vapor Deposition of Methane on Copper," *Journal of the American Chemical Society* **133**, 2816-2819 (2011).