Microelectronics: Anticipating the 2050 Alligators

Nancy M. Haegel
National Renewable Energy Laboratory
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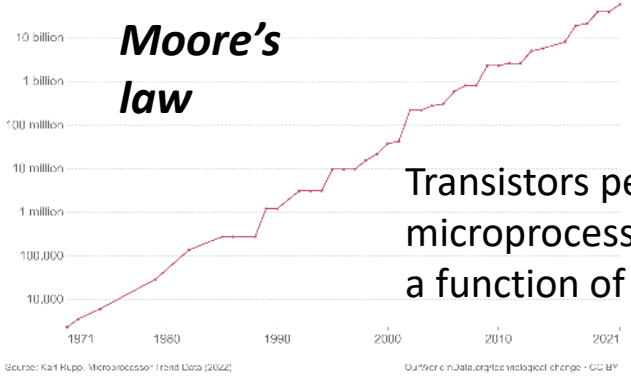
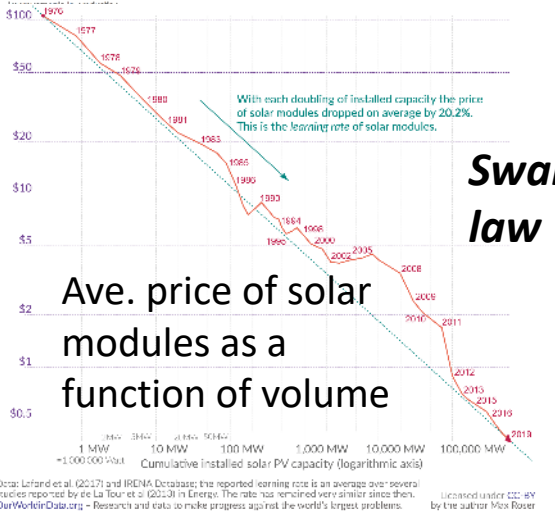
Photo from iStock-627281636

Information and energy – simultaneous transitions on the path to 2050



Moore's law

Transistors per microprocessor as a function of time



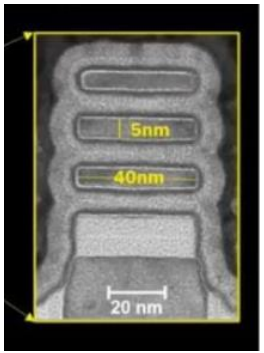
Swanson's law

Ave. price of solar modules as a function of volume

Five decades of semiconductor science and technology have driven one revolution (computing) and positioned us for another (energy)

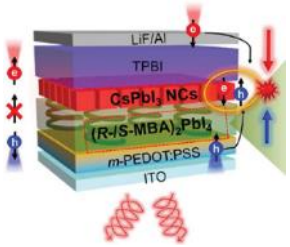
Microelectronics Everywhere

More people, more devices doing more work requiring more energy, with fewer atoms under more extreme environments



IBM 2 nm nanosheet technology

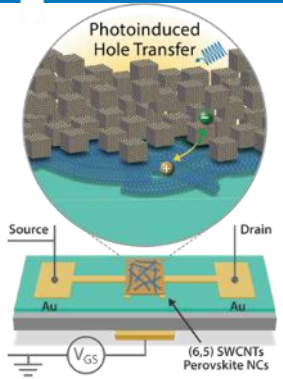
Microelectronics at the intersection



Degradation science at scale (large and small)

Information/ Computing

Energy



Quantum materials

Neuromorphic functionality

Power electronics

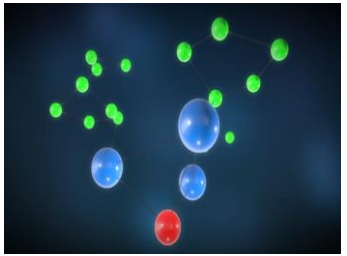
Circularity and critical materials

Micro electronics

Charge, spins and light-matter interactions

Ubiquitous sensing

Sensing and control

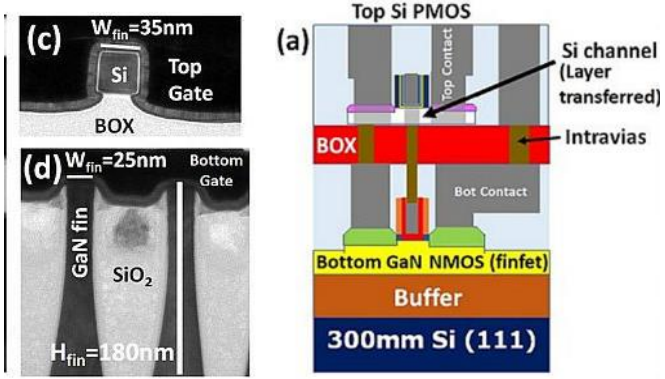


Power electronics: infrastructure for 2050

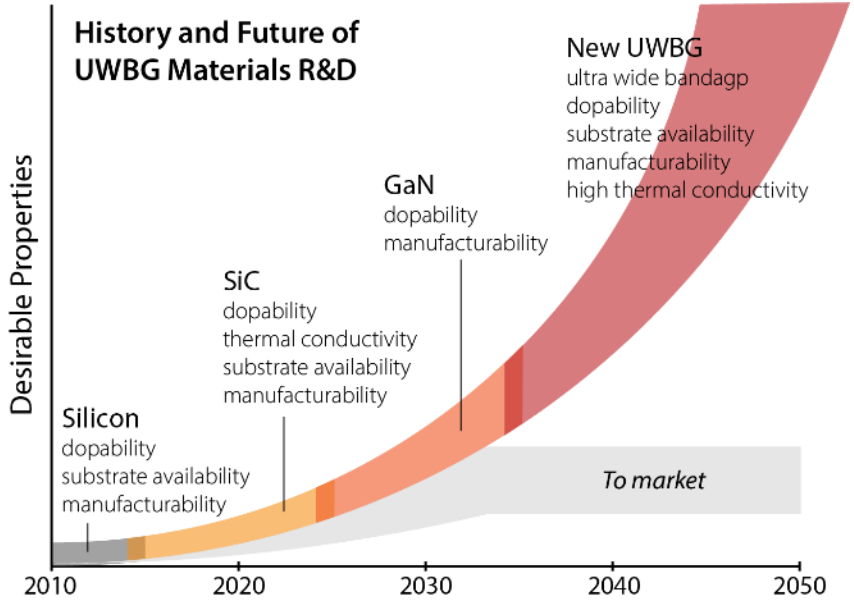
- Next generation power electronics are critical to the future grid and a sustainable energy system; smaller size, higher temperature, higher voltages
- New UWBG materials, heterogenous integration, interface and degradation science
- Power electronics will be the “BIL” of 2050; do the science and microelectronics now

Pittsburgh

Washington

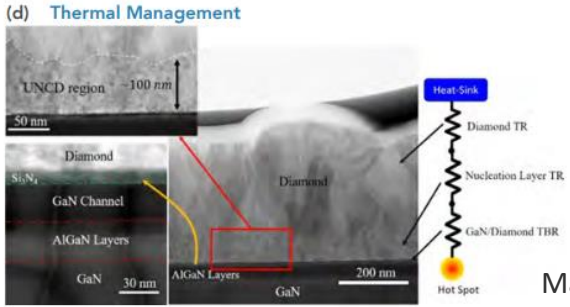


GaN FinFet on Si CMOS – low loss power inverter – Intel 2021



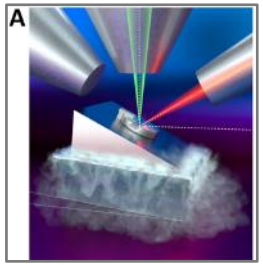
Degradation science: reliability and resilience

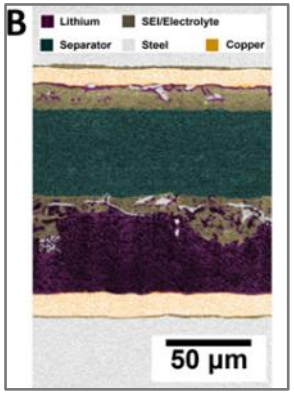
- What are the nanoscale/atomic scale “seeds” for hot spots and degradation?
- Understanding accelerated degradation and aging
- Combined accelerated testing (CAST)
  nm scale “CAST in the microscope”
- Developing the AI/ML enabled workflows to develop insight into heterogeneity

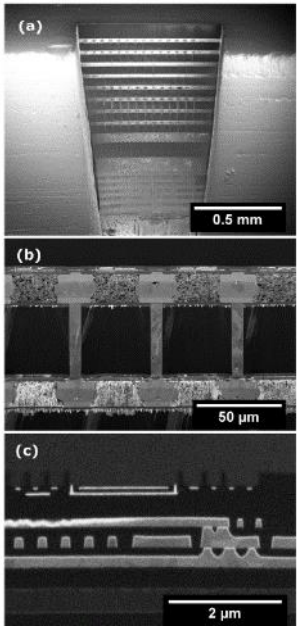


Malakoutian et.al., ACS Apply Mat. Inter. **13**, 60553 (2021)
Future Directions Workshop: Materials, Processes, and R&D Challenges in Microelectronics

“Eyes inside”
any microelectronics device, at any size, to understand real operating conditions



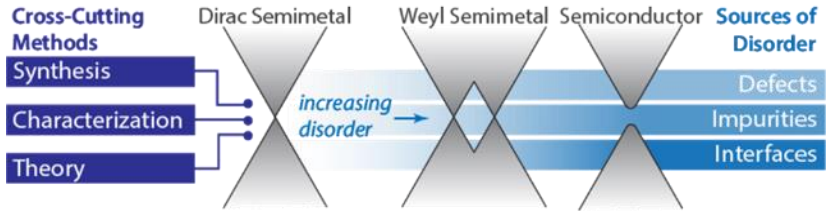


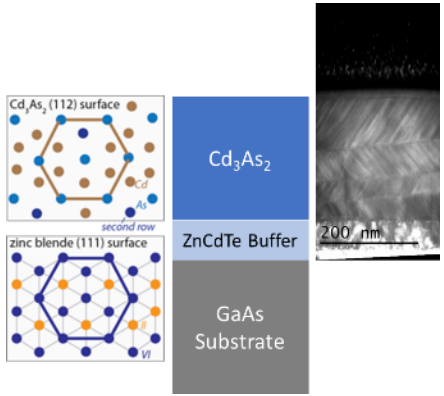


Randolph et. al., Vac. Sci. Tech. B 36, 06JB01 (2018);
Jungjohann et. al. ACS Energy Lett. **6**, 2138 (2021).

Topological Semimetals for New Energy Frontiers

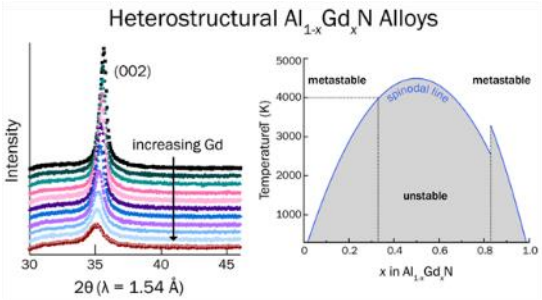
Probing epitaxy, native defects, alloying and doping for electronics, thermoelectrics, photodetectors and spintronics

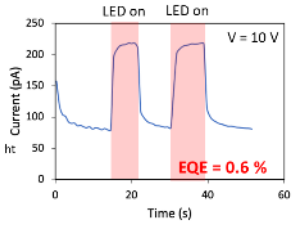


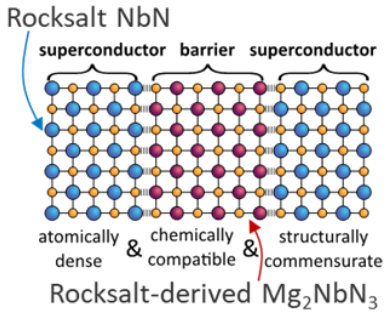


Nitrides for Microelectronics

Metastable thin film wurtzite AlGdN with up to 25% Gd for thermal neutron absorption

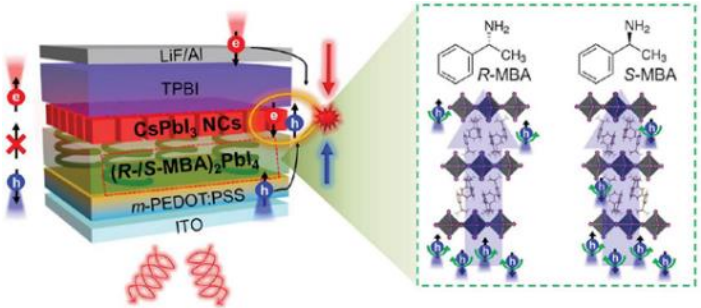






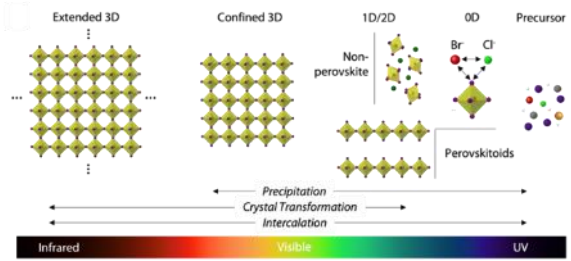
Sensors, actuators, qubits, magnets

Hybrid perovskites: spin and synapse control at room temperature



2D Perovskite Spin-LED (CHOISE)

Kim,…, Beard. Science 2021, 371, 1129



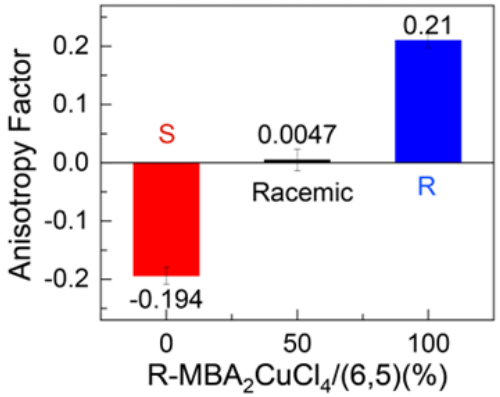
Perovskite Photonic Synapses (LDRD)

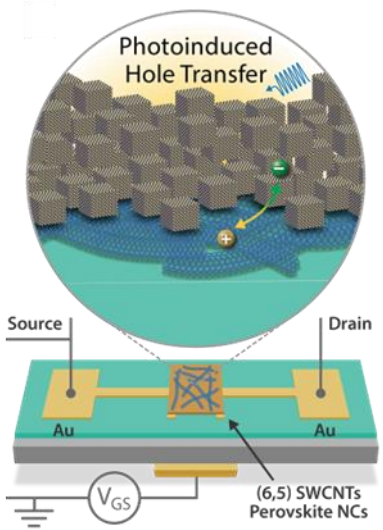
Vats, Ferguson, Wheeler, Blackburn

Adv. Mater. 2022, 10.1002/adma.202205459

Heterostructured CP Detector (CHOISE)

Hao,…Beard, Blackburn. *ACS Nano* **2021**, *15*, 7608





Low-power Optical Synapses (CHOISE)

Kim, Blackburn 2021, Sci. Adv., 7, eabf1959

Basic science

- **Understanding structure and properties at incommensurate interfaces**
  - Opens up materials and integration options – “tyranny of the substrate”
- **Spin-based room temperature information processing**
  - New degrees of freedom for functionality and energy efficiency
- **Replacing or reducing critical or expensive materials, circularity**
  - Redefining critical materials for 2050 – a “dynamic” list
    Abundant magnets, thin film conductors, materials that “unzip,” …
- **Fundamental conditions/mechanisms that initiate degradation**
  - Degradation science for the operation and control of the 2050 energy system
    “Eyes inside” coupled to AI/ML enabled workflows for assessing heterogeneity

Basic science needs: anticipating the alligators

Inability to exploit highest degree of material functionality due to integration limitations

Macroscale system degradation due to nanoscale Interface instability

Infrastructure limitations (a.k.a. power electronics) for the new energy economy

Material abundance/supply chain limitations

Energy consumption as a limitation to computing and information storage

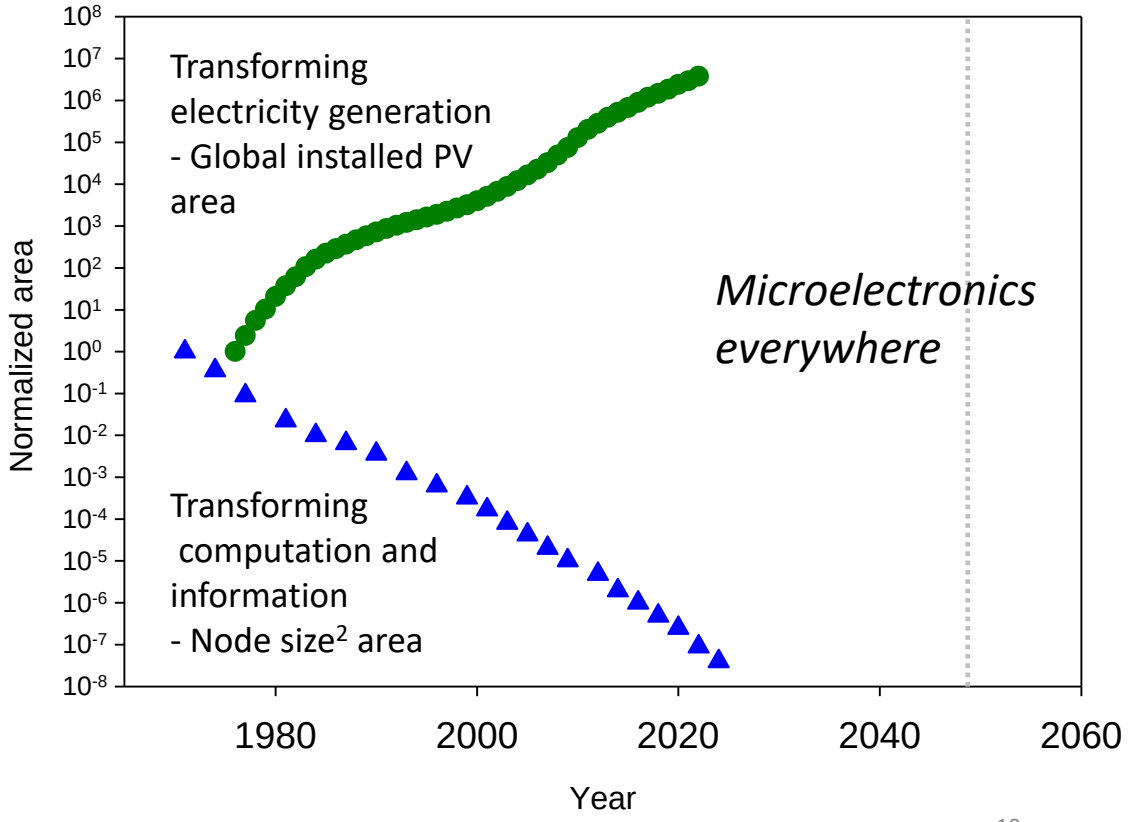
Microelectronics connecting work, heat and information

Putting Maxwell's demon to work

Coupling interaction of work, heat and information

The next three decades…

*How do we frame/reframe basic science questions and priorities for microelectronics to enable innovation **for** sustainability and equitable access to energy and information….*



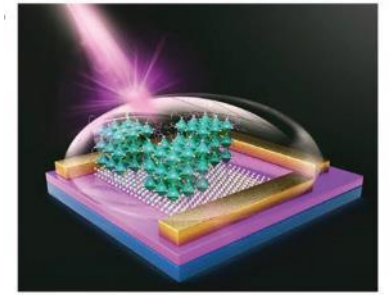
Thank you

Discussion

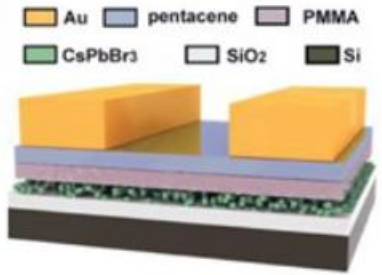
www.nrel.gov

Understand, exploit and enable co-design

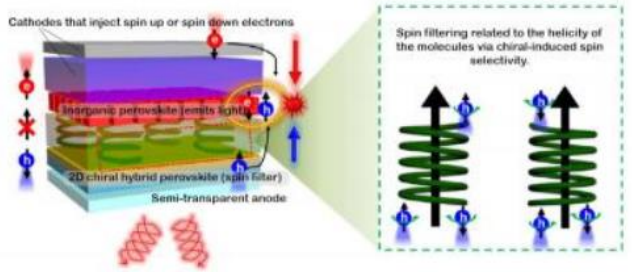
- Light-matter interactions in a new class of chiral semiconductors
- Spin-photon interfaces for interconverting electron spins and circularly polarized photons
- Structural impacts on insulator-metal transitions in correlated materials
- Coupling between electronic, ionic, and atomic motion in materials and heterostructures



Heterojunction phototransistor



Photonic flash memory



Spin polarized LED