Center for Energy Efficient Electronics Science

Replacing the Transistor with a Lower Voltage Switch: What are the Prospects?

Green Photonics Symposium at Technion

Haifa, Israel, April 23, 2014

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UC Berkeley-Florida International-MIT-Stanford-U Texas El Paso
Contra Costa-LA Trade Tech

A Science & Technology Center

Research Team

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Theme Leaders


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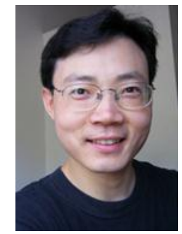
J. Wu

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Antoniadis


Bulovic


Del Alamo


Fitzgerald


Hoyt


Lang


Swager

Stanford University


Wong

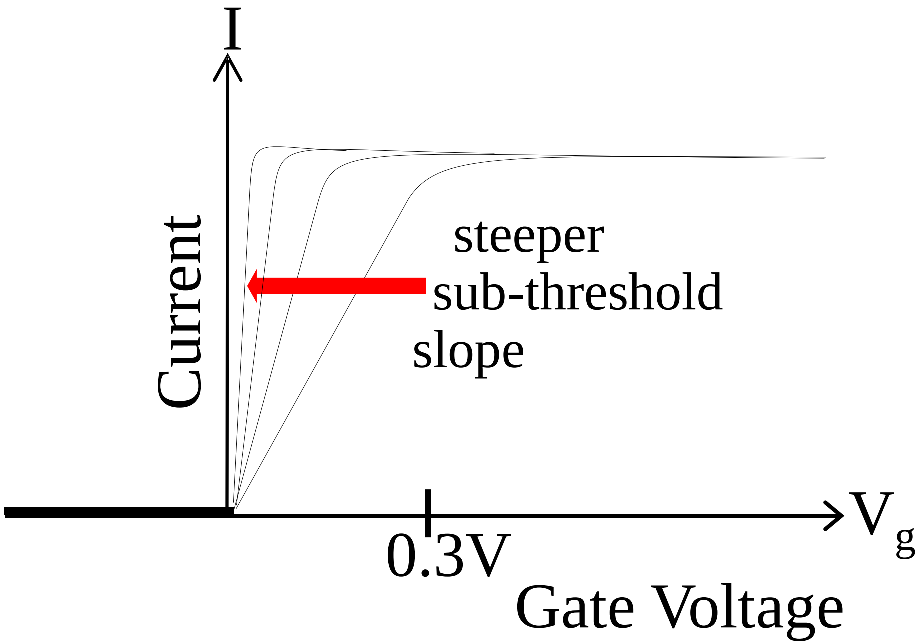
The University of Texas at El Paso


Zubia

Florida International University


Khizroev

A New More Sensitive Electronic Switch



Take the powering voltage from ~1Volt down to milli-Volts
(noise is in μVolts)

The New Switch has to Satisfy Three Specifications:

1. Steepness (or sensitivity)

switches with only a few milli-volts

60mV/decade ⇒ **1mV/decade**

2. On/Off ratio. $10^6 : 1$

3. Current Density or Conductance Density

(for miniaturization)

old spec at 1Volt: 1 mAmp/micron

our spec: **1 milli-Siemen/micron**

A 1 micron device should conduct at 1KΩ in the on-state.

This Center will address the Electronics Energy Efficiency by Four Interconnected Approaches:

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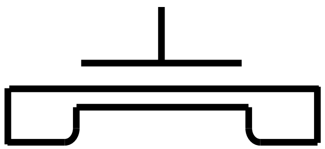
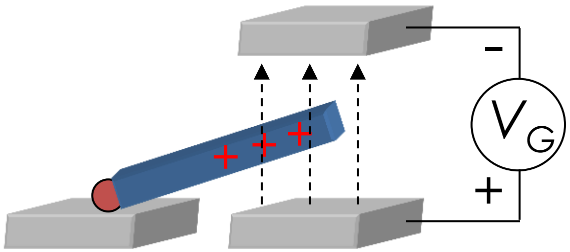


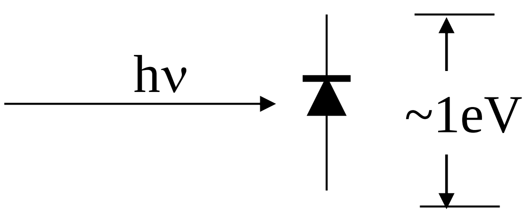
Nanoelectronics:
Solid-State Milli-Volt Switching

Theme 2:



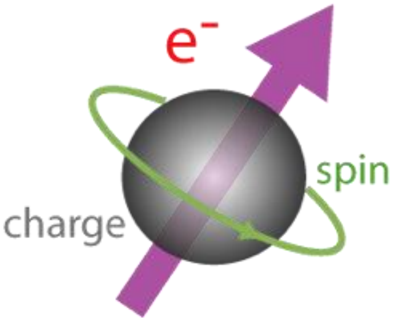
Nanomechanics:
Zero-Leakage Switching

Theme 3:



Nanophotonics for Ultra-Low Energy Communication

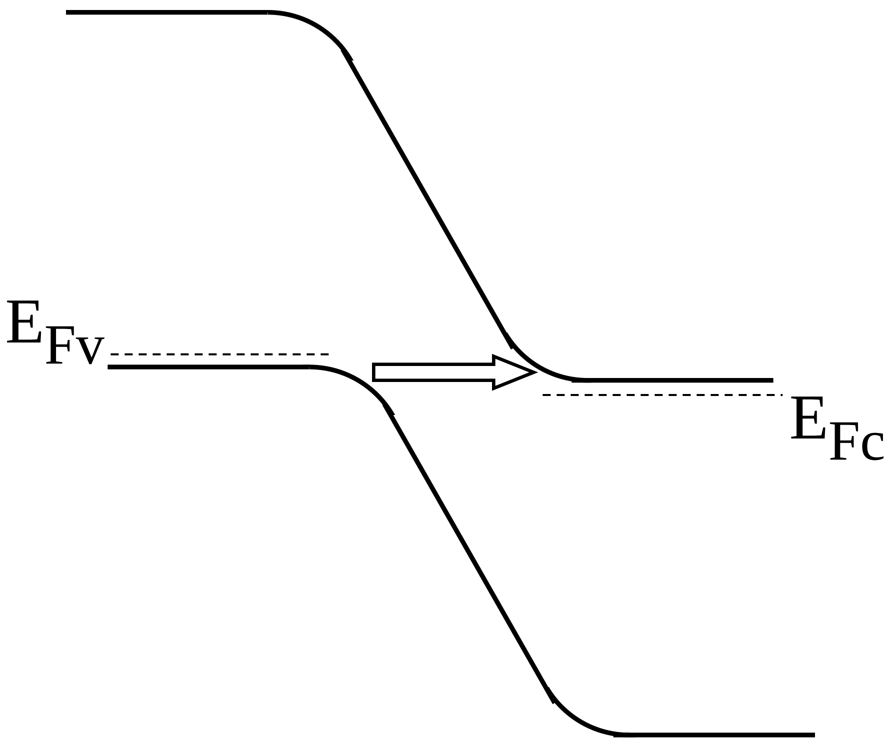
Theme 4:



Nanomagnetics:
A Low Energy Magnetic Switch

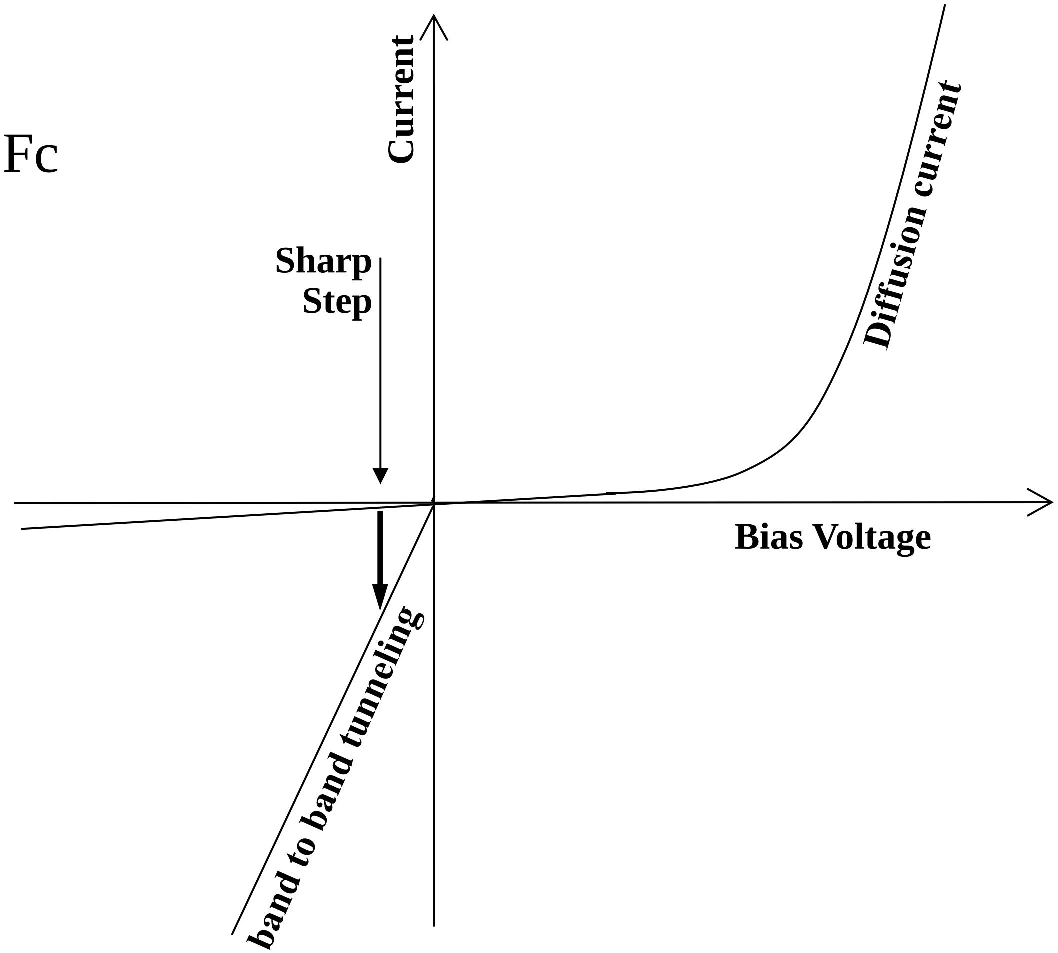
Theme 1 - Nanoelectronics: Solid-State Milli-Volt Switching

The Backward Diode as a Switch:

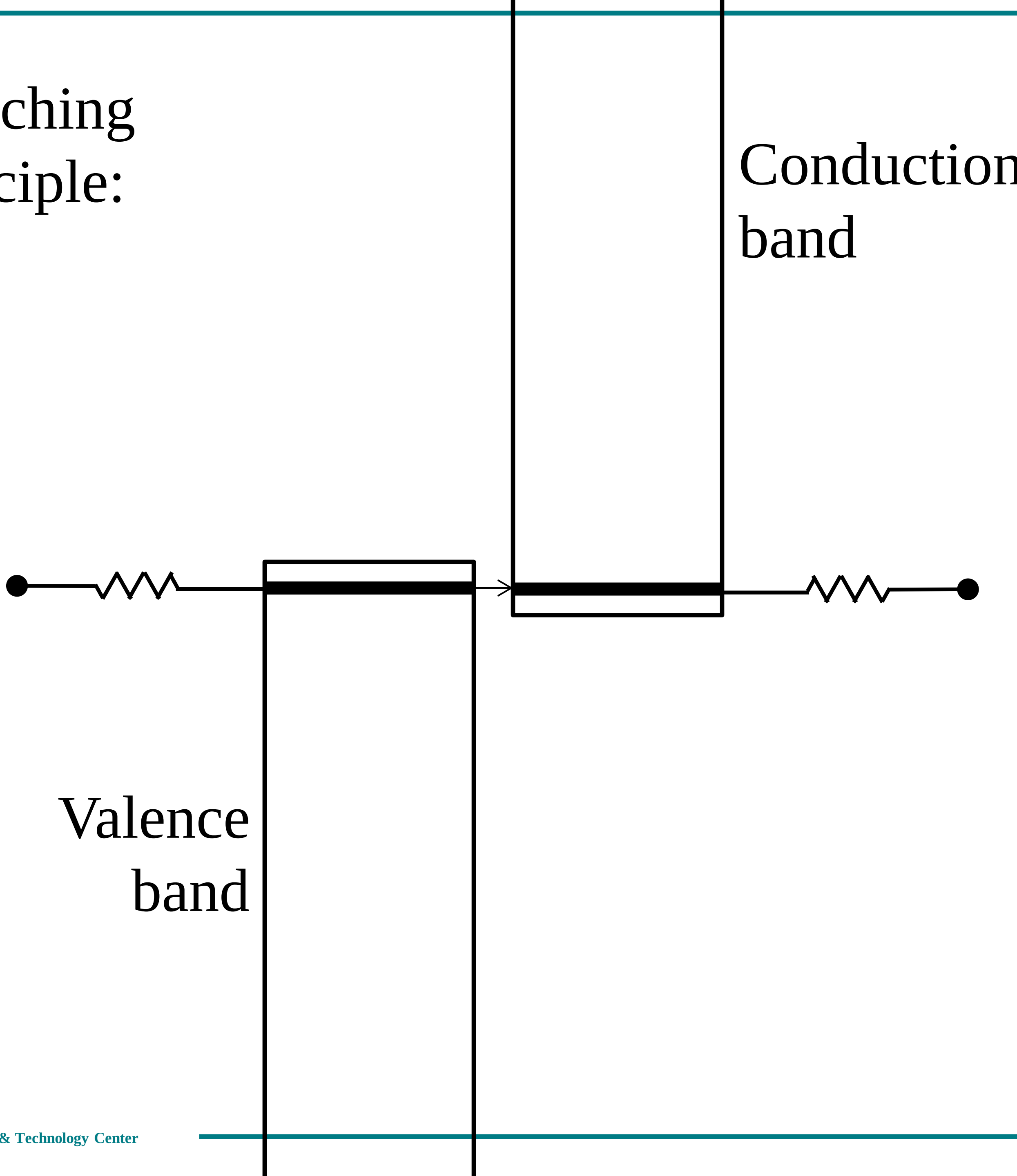


<u>The Backward Diode:</u>

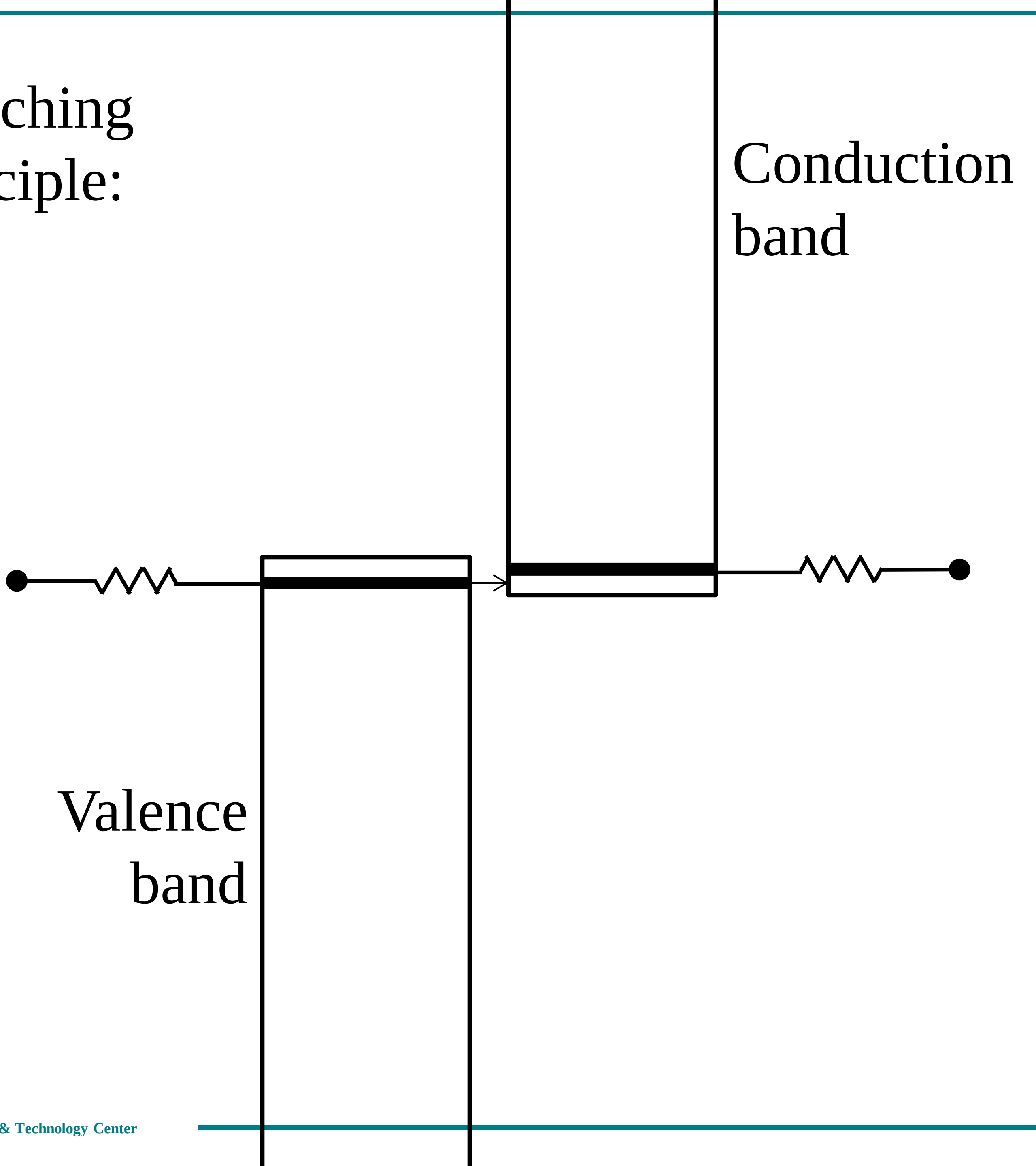
These have been routinely made in Ge homo-junctions, since the 1960's.



Switching Principle:

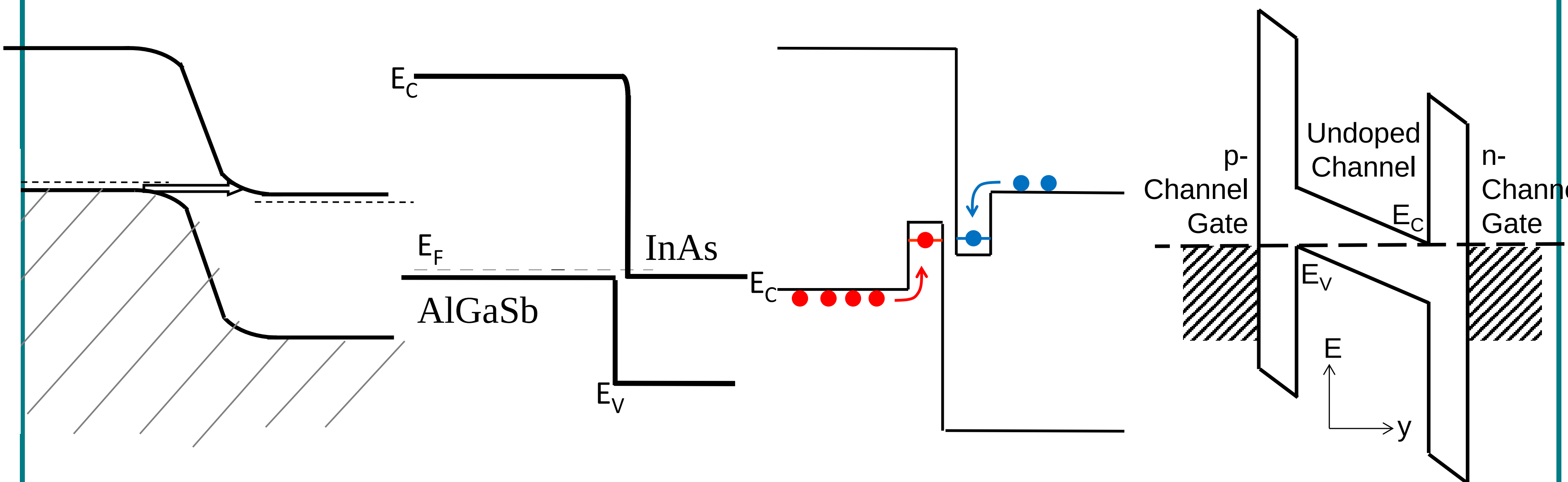


Switching Principle:



The evolution of the tunnel transistor concept:

2000 | 2007 | 2010 | 2012



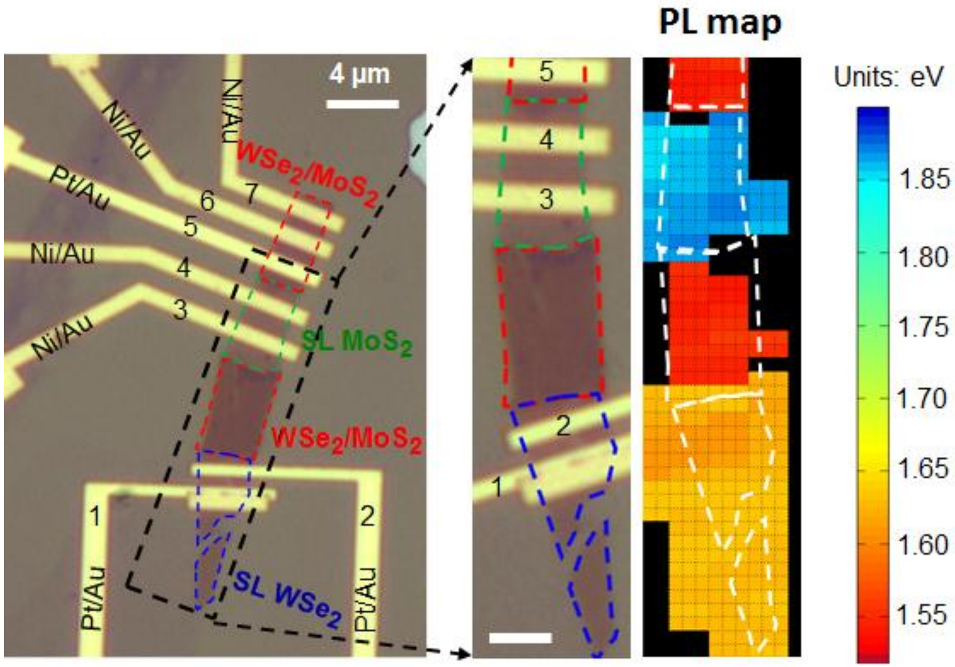
homojunction tunneling

Type III heterojunction

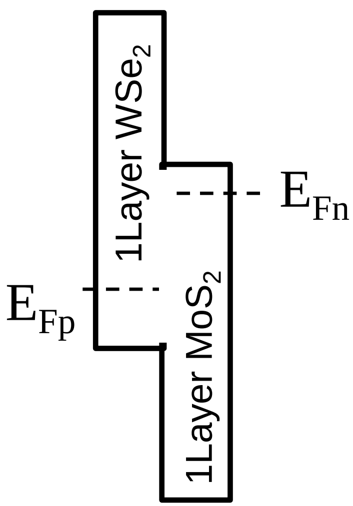
2d-2d quantum well heterojunction

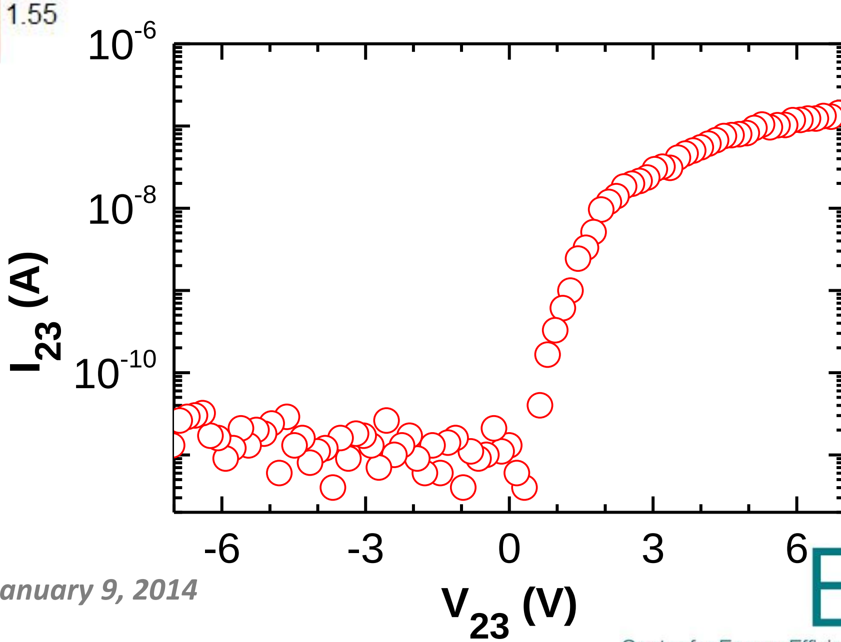
the Bilayer switch

Electrical transport through the heterobilayer WSe_2/MoS_2



- The van der Waals junction is electrically active
- As expected rectifying behavior is observed given the type II band offset





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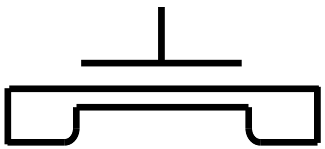

Nanoelectronics:
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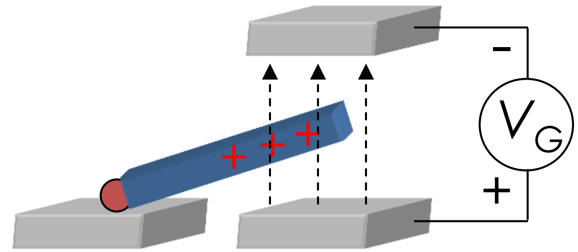
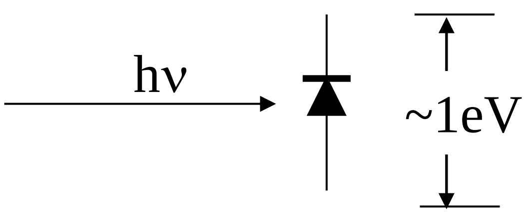


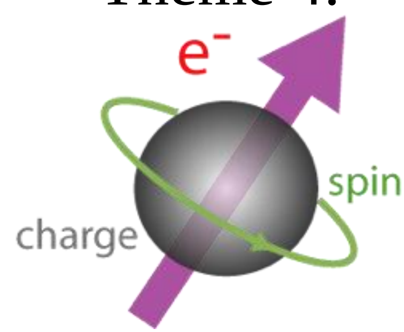
Nanomechanics:
Zero-Leakage Switching

Theme 3:



Nanophotonics for Ultra-Low Energy Communication

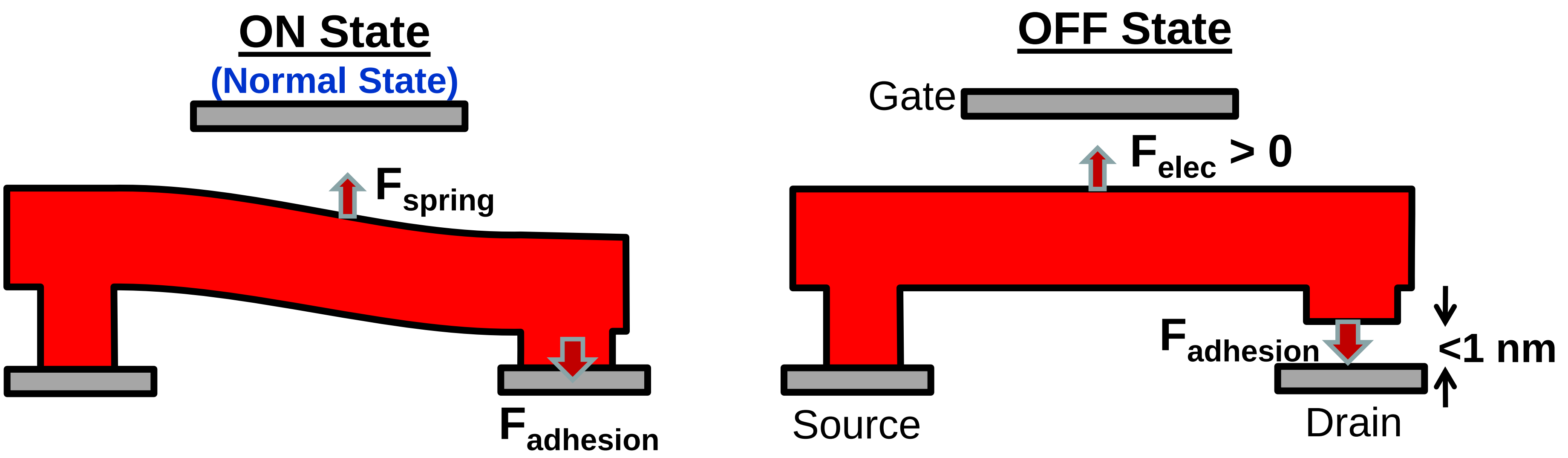
Theme 4:



Nanomagnetics:
A Low Energy Magnetic Switch

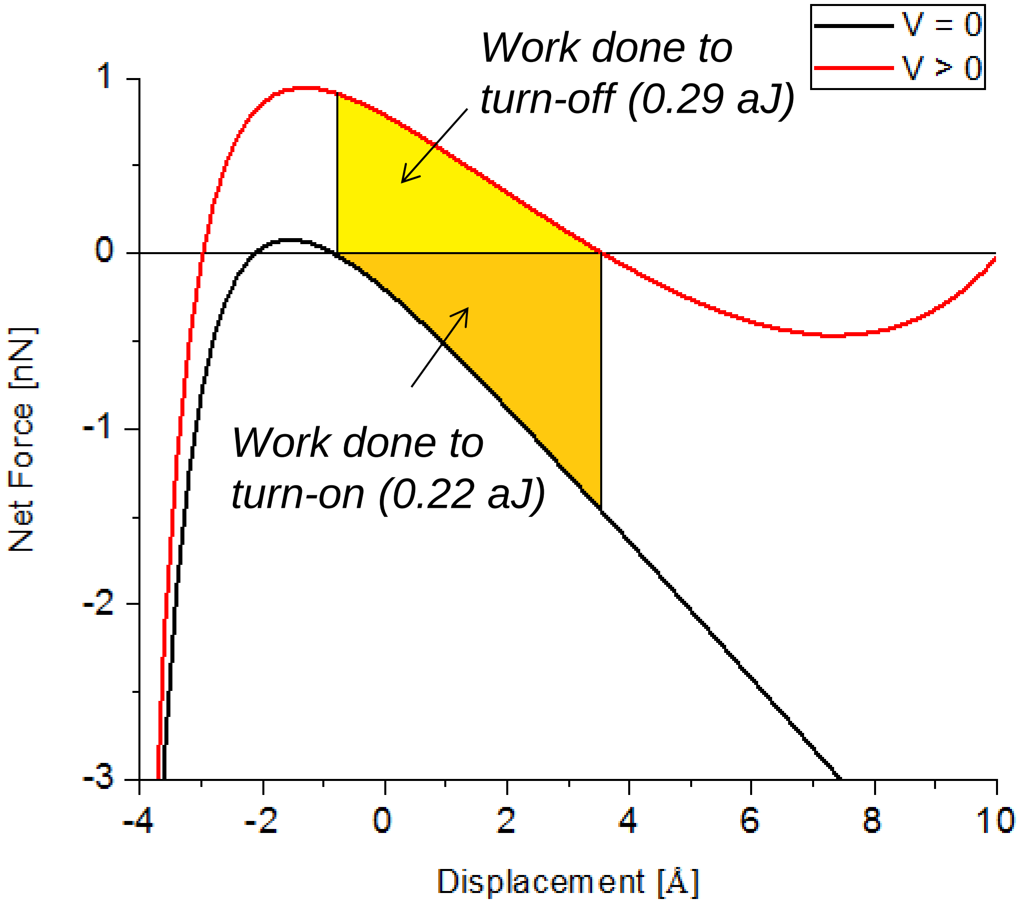
Theme 2 – Nano-Mechanical Switching

Balance the Spring Constant versus Surface Adhesion



- Contact gap is very small ➔ pull-in upon release
  - A normally-on switch
- Build a gate to turn the switch off electrostatically
  - F_{spring} helps overcoming $F_{adhesion}$ ➔ voltage reduction!

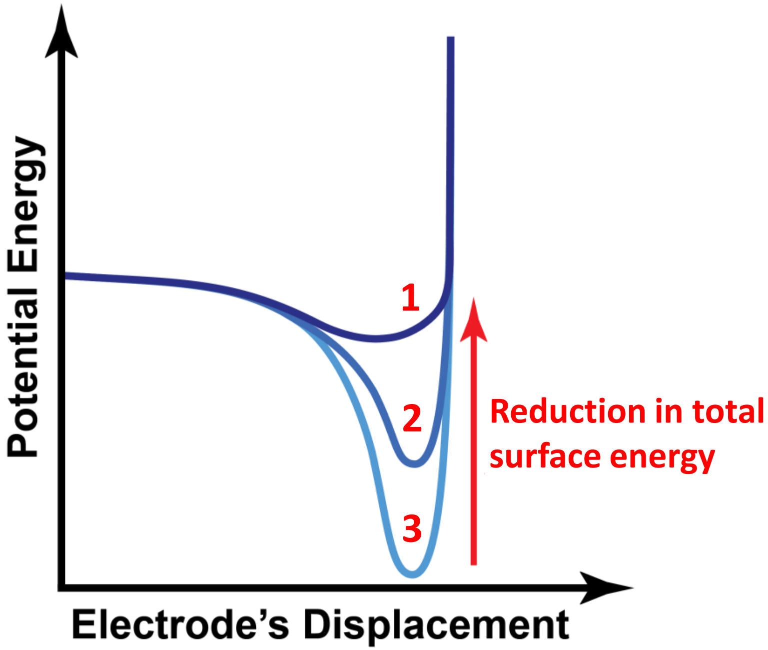
Balance the Spring Constant versus Surface Adhesion

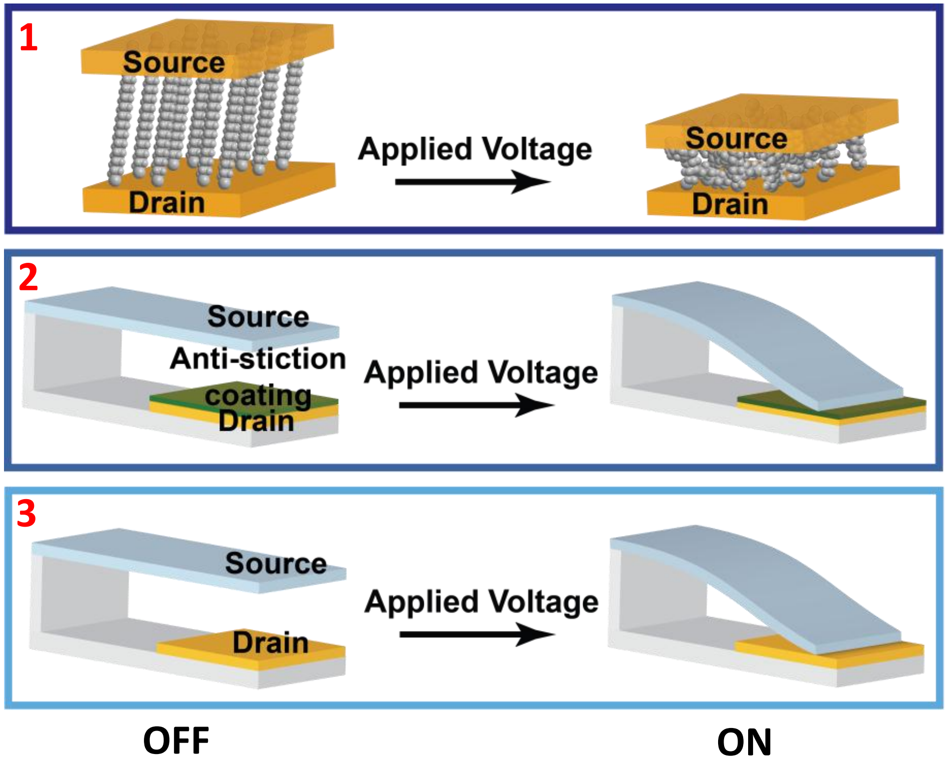


- g_{cont} = 4 Å
- g_{act} = 2 nm
- k_{spring} = 3.5 N/m
- $H = 7\times10^{-20}$ J
  - Assuming SiO_2
- A_c = 10 nm^2
  - Can be scaled further
  - $E_{adhesion}$ ~ 0.7 aJ
- A = 0.08 µm^2
  - C = 0.41 fF
  - Tradeoff *vs.* g_{act}

I-R. Chen et al., *to be published*

Insert a thin molecular layer to control stiction





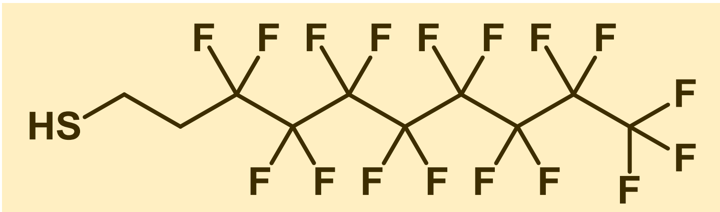
$\Delta E_S \sim A\, \Delta\gamma$

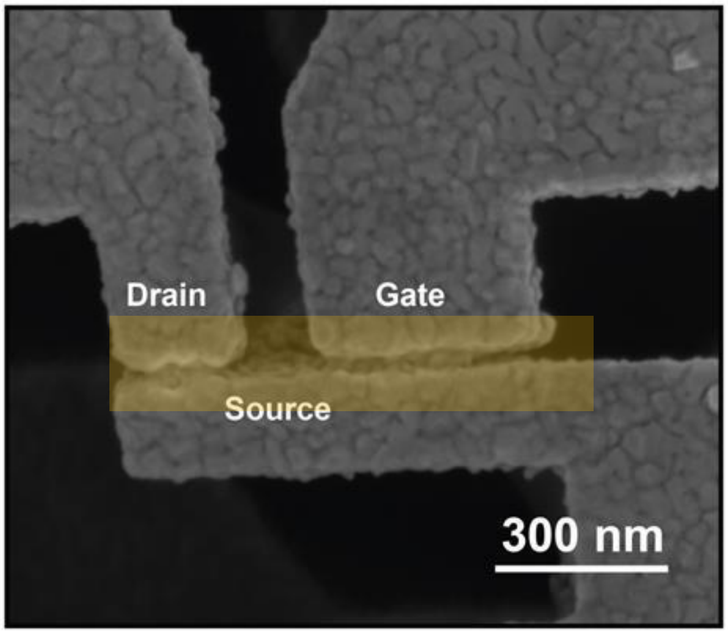
ΔE_S : Surface Energy A : Contact Area $\Delta\gamma$: Work of Cohesion

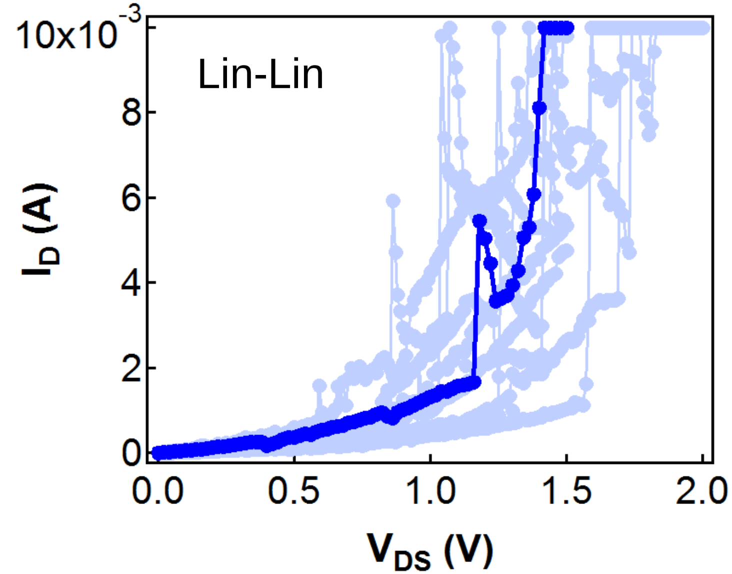
Physical and chemical interactions causing solid-solid surface adhesion (cohesion)

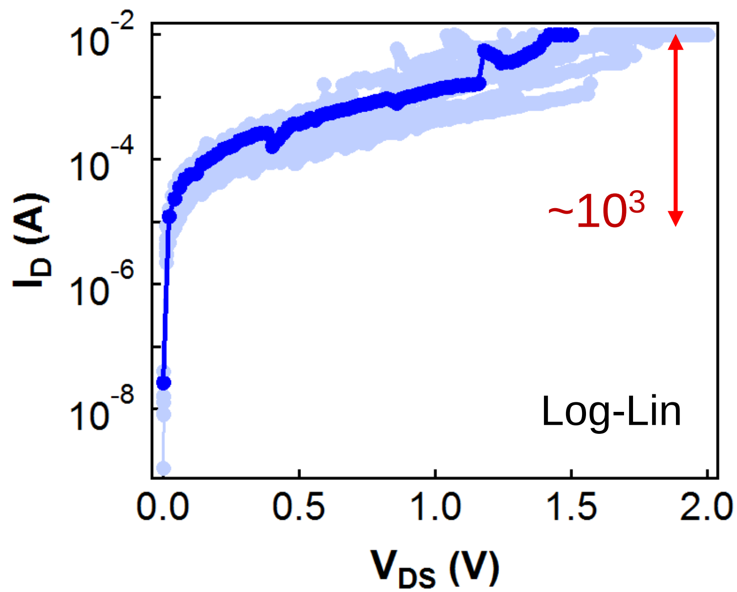
- Covalent
- Ionic
- Electrostatic
- Metallic
- Hydrogen
- van der Waals

Overcoming Stiction using Organic Thin Film









Organic thin film **prevents stiction** allowing **repeatable operation**

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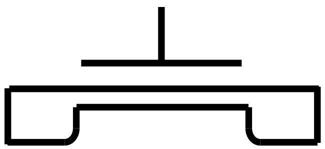

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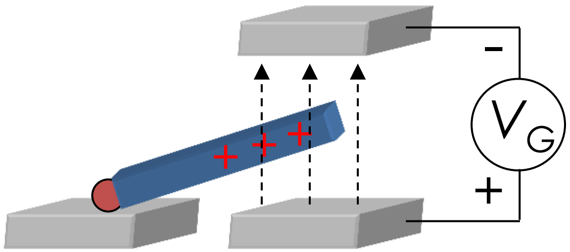

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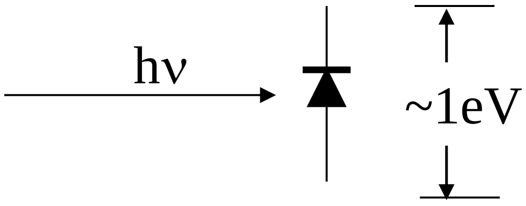
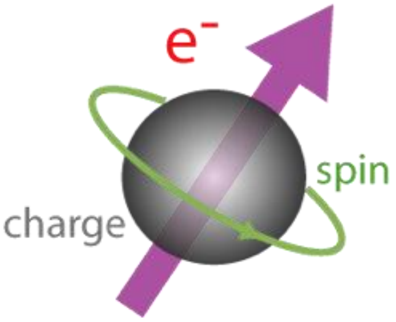


Nanophotonics for Ultra-Low Energy Communication

Theme 4:



Nanomagnetics:
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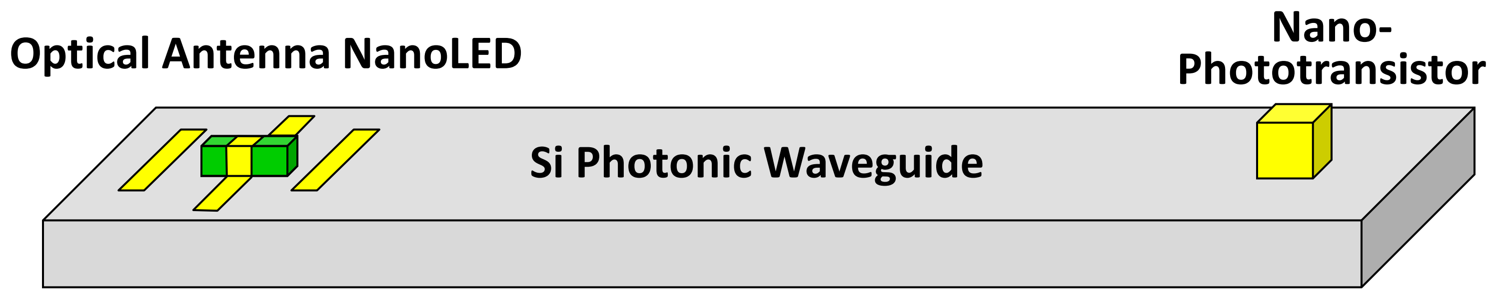
Theme 4 – NanoPhotonic Switching

Theme 3

Optical Inter-Connect

Main Goal:

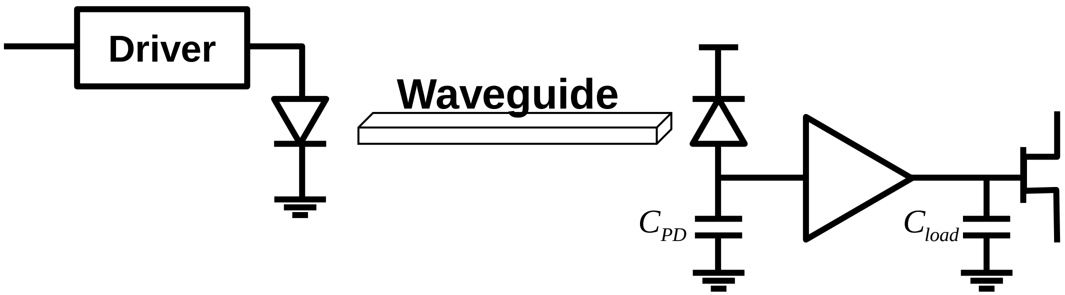
- **Dramatically improve the interconnect energy efficiency: 20,000photons/bit $\Rightarrow$ 20 photons/bit**

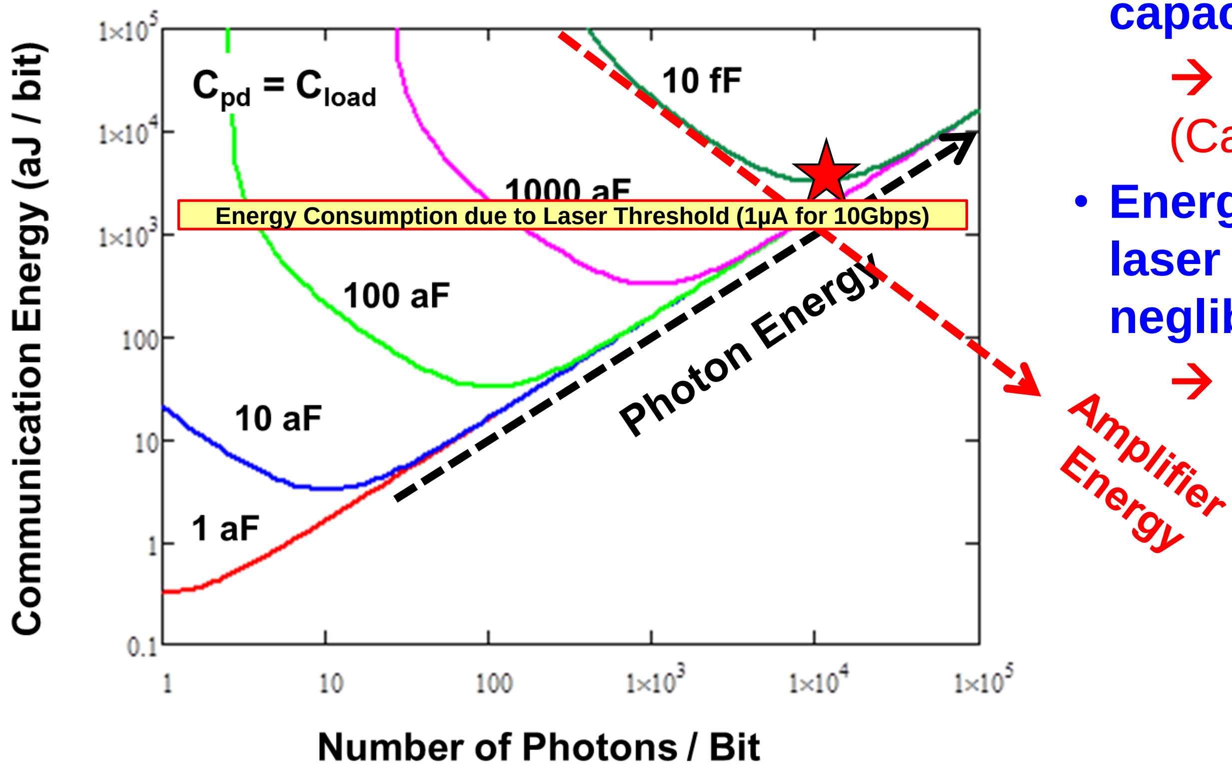


Key scientific challenges

- **sub-wavelength-scale nanophotonic devices**
- **An integrated optical antenna**
- **Heterogeneous integration of III-V on Si**

Interconnect Energy



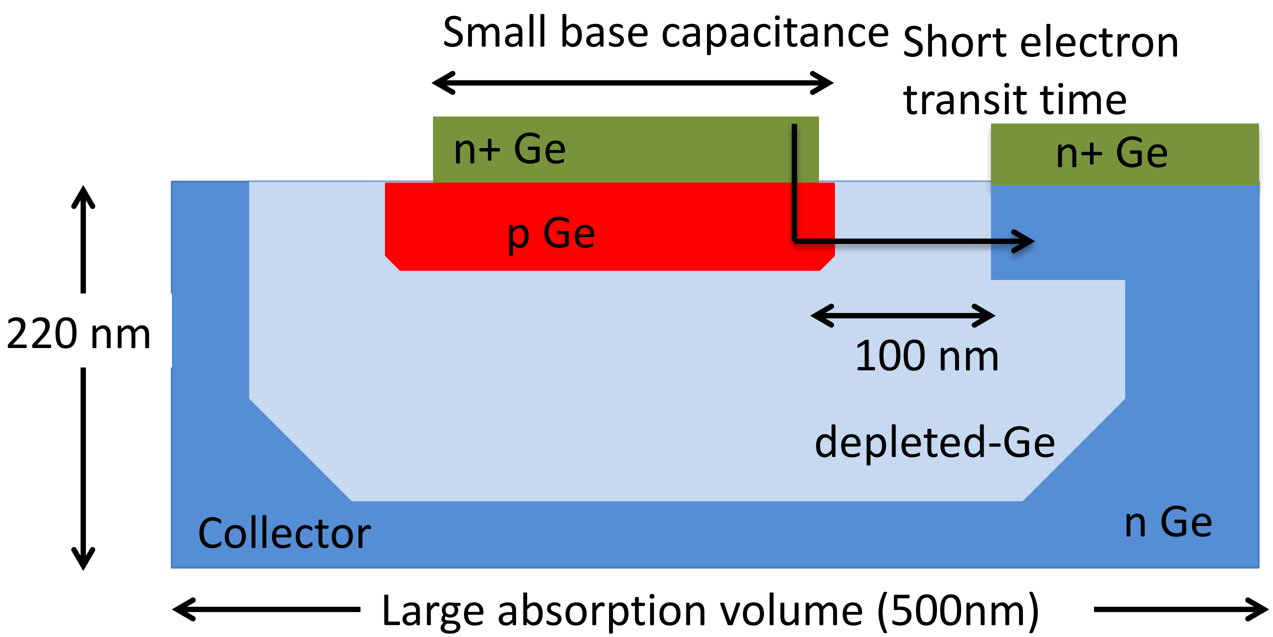


- **Energy consumption minimized when transmitter (photon) energy equals receiver (amplifier) energy**
- **Minimum energy is proportional to detector capacitance**
  - **→ Nanophotodetectors**
    (Capacitance ∝ device size)
- **Energy consumption due to laser threshold is non-neglibible**
  - **→ NanoLED**

Silicon Photonics: Replace Photodiode with Bipolar Phototransistor

Chris Keraly

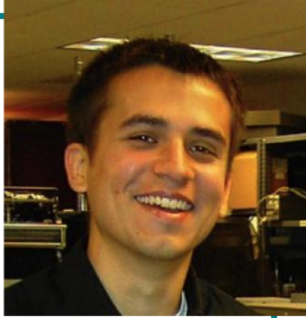
- **Decoupling light absorption and transit time**
- **This allows for a large device for light absorption, while enabling a small transistor area for low capacitance, large gain and speed**



Estimated base capacitance ~ 60 aF $C_{Self} + C_{EB} + C_{EC}$

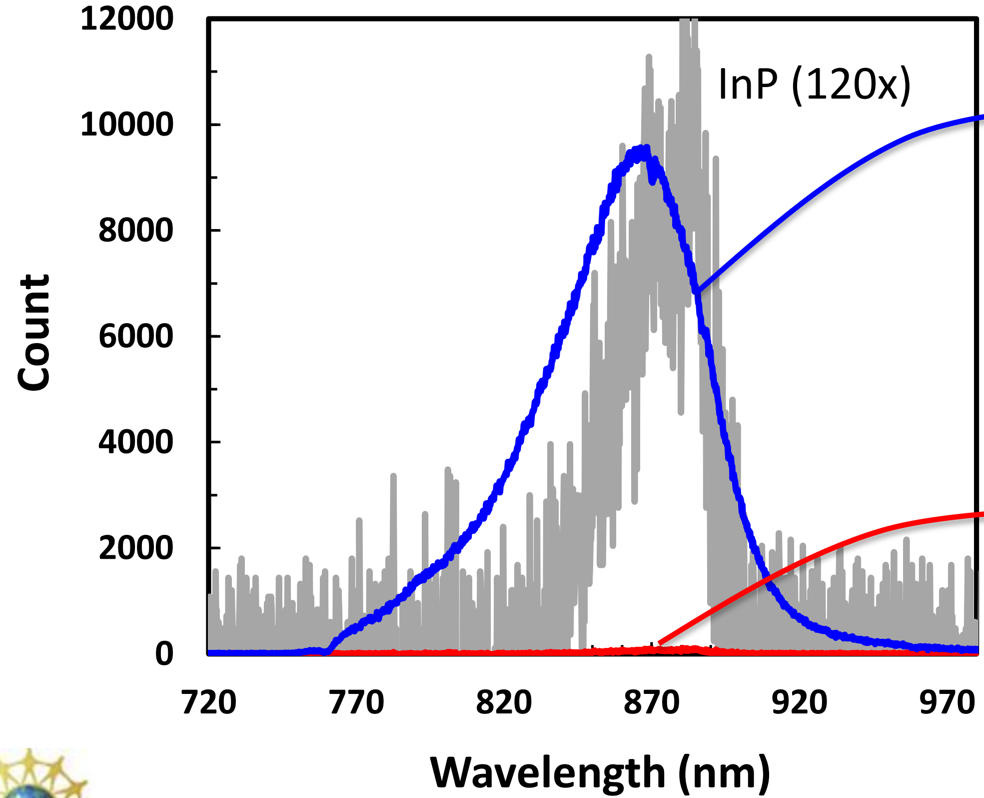
Electron transit time: 2.5 ps $\tau = \frac{W_B{}^2}{2D_{nb}} + \frac{W_B}{v_{sat}} + \frac{W_{CBD}}{2v_{sat}}$

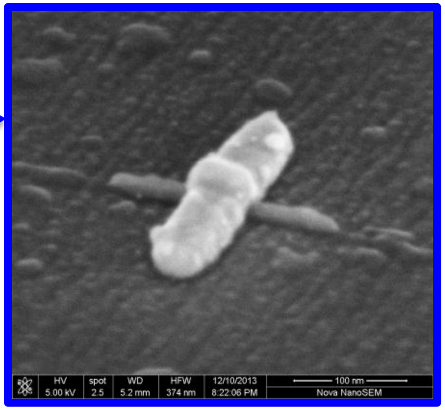
Optical Antenna Based InP NanoLED



Kevin Messer

- InP has low surface recombination velocity
- Higher photon energy allows direct speed characterization
- 120x enhancement with 17nm wide ridge





InP NanoLED

InP

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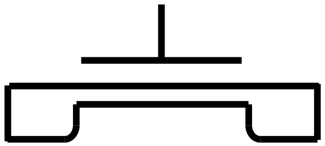

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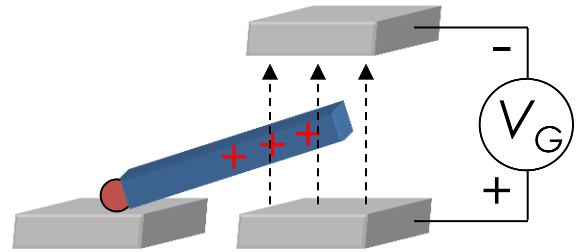

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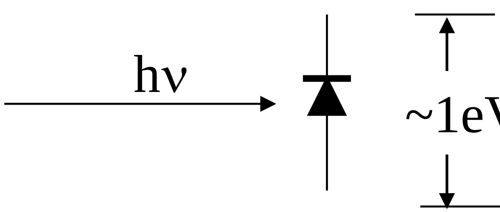

Nanophotonics for Ultra-Low Energy Communication

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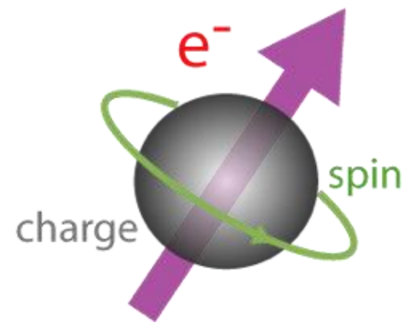
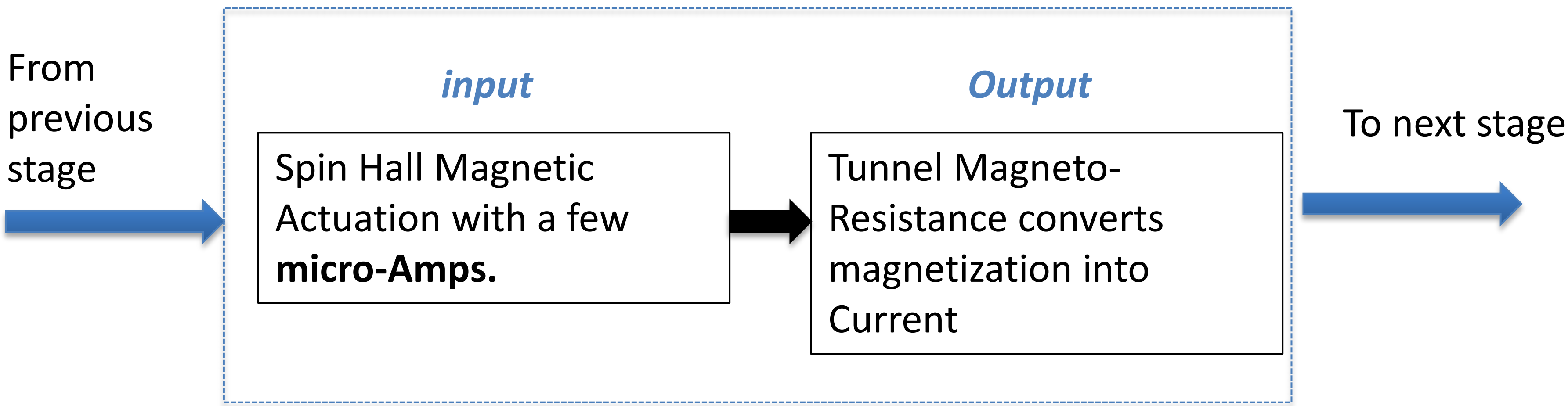


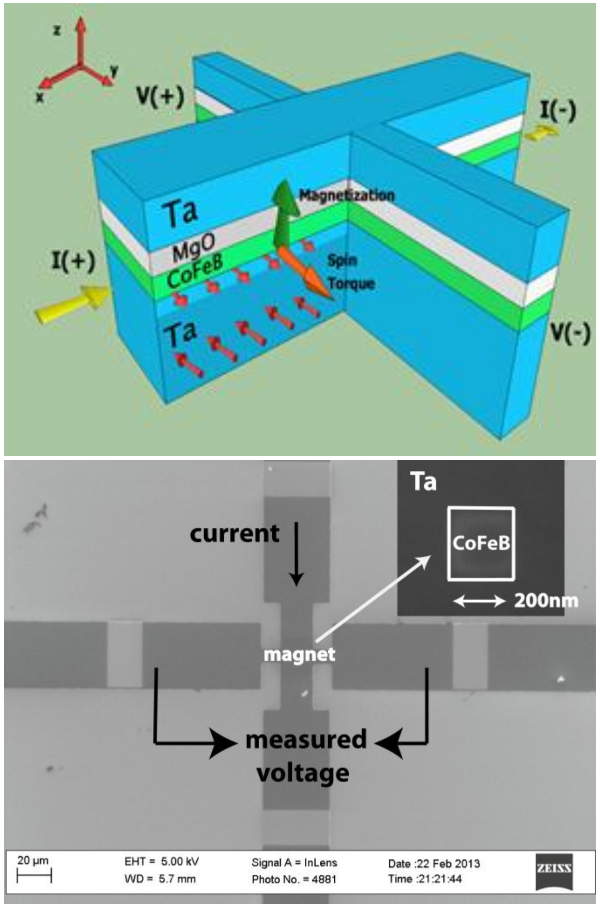
Nanomagnetics:
A Low Energy Magnetic Switch

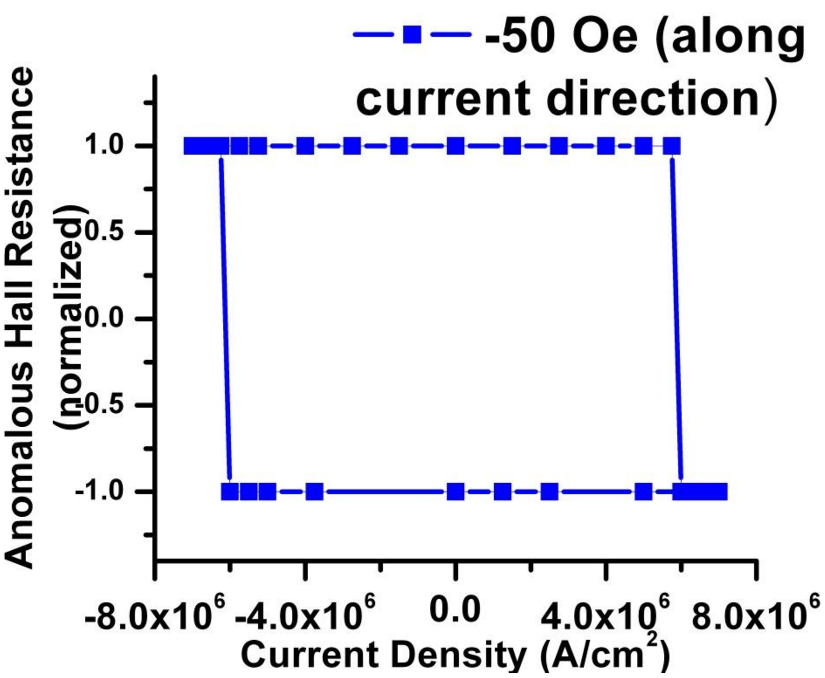
Theme 4 – NanoMagnetic Switching

Nano-Magnetic Switching:
Gain & Fan-out



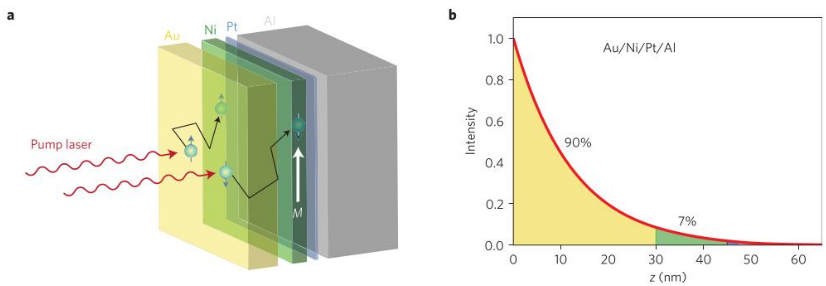
Spin Hall Effect observed by Salahuddin et al prior to Cornell publication



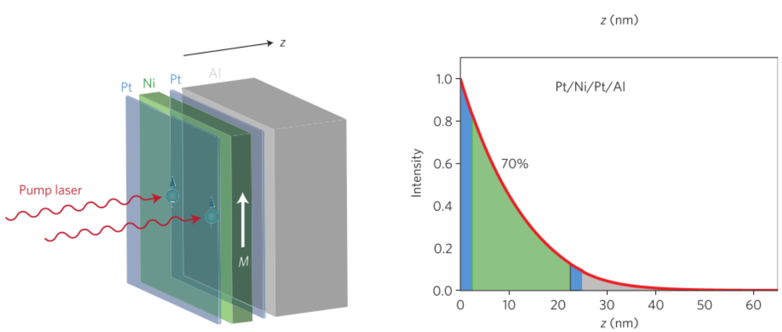


Bhowmik, You and Salahuddin, IEDM, 2012, MMM, 2013; Also Liu et. al. Science (2012)

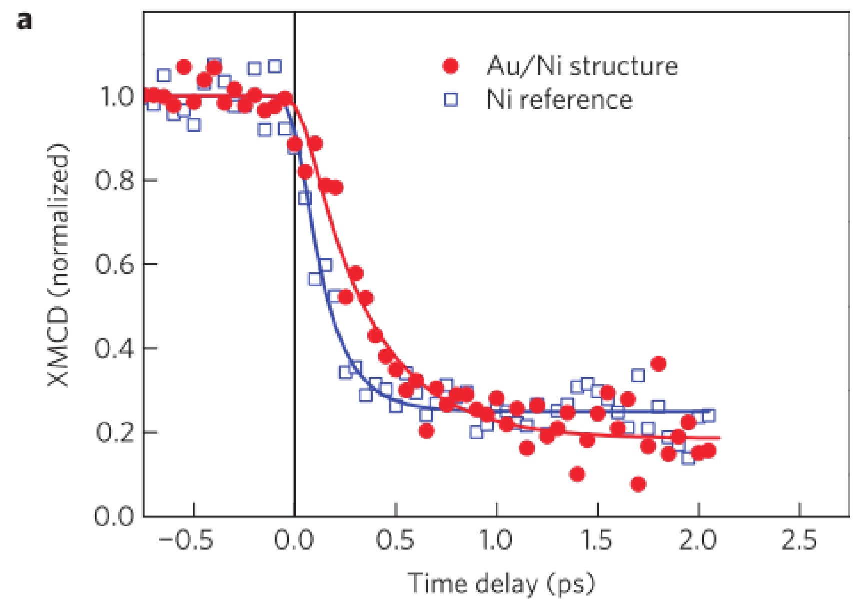
High Speed Magnetic Switching: Demagnetization by Electrical Hot Electron Injection OR by Rapid Electrical Thermal Heating



Laser absorbed in Au layer
Hot electrons “super” diffuse into Ni



Laser absorbed directly in Ni

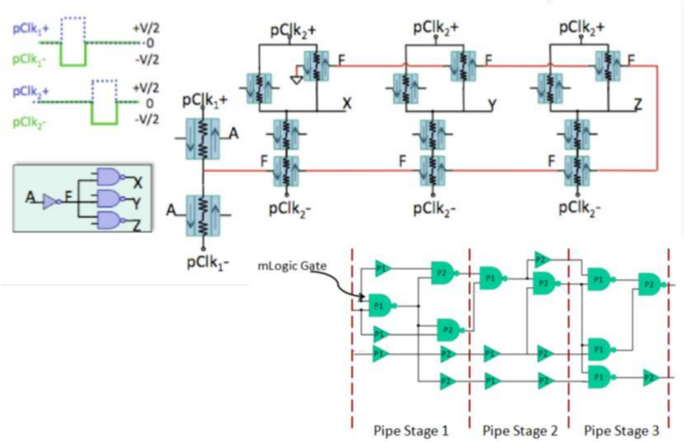


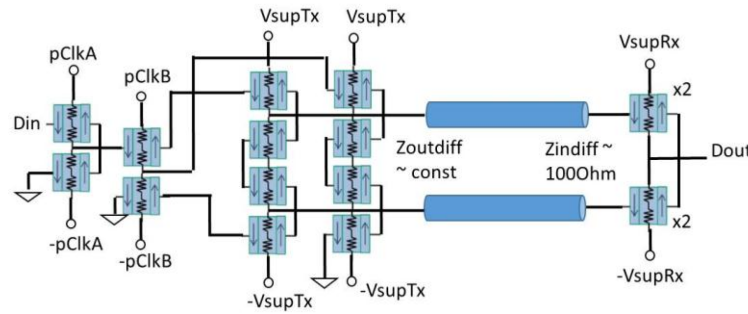
Ni magnetization dynamics

Circuits/Systems Design with Modest On/Off Ratio Magnetic Devices

New Investigator: Vladimir Stojanovic, UCB

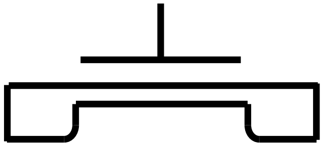
Morris et al, DAC 12





- Pulse gates to save on leakage – pipelining a useful side benefit
  - Need to evaluate savings with detailed study of pulsing costs (CMOS chip)
- Instead – use multi-phase clocks/pulses for stage-gating

A low-voltage technology, or an impedance matching device, needs to be invented/discovered at the Nano-scale:



transistor amplifier with steeper sub-threshold slope

- •TFET's
- •Negative Capacitance Gates

--V_2O_5 metal-insulator transition

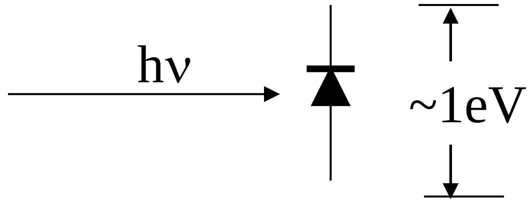
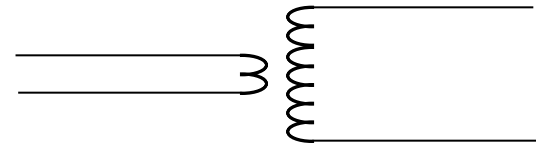
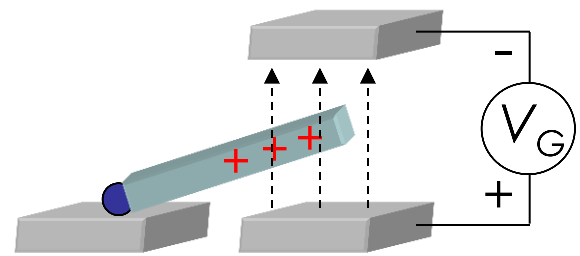


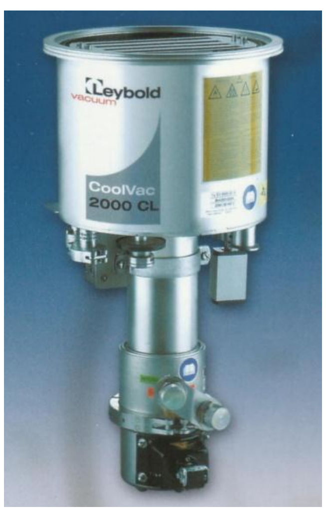
photo-diode



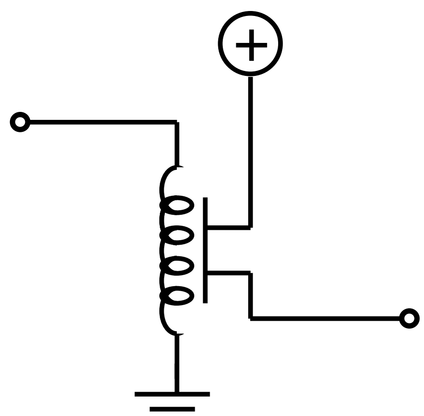
nano-transformer



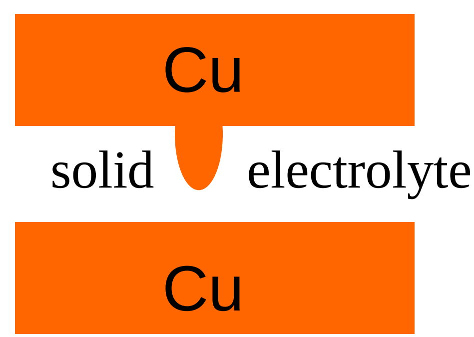
MEM's switch



Cryo-Electronics
kT/q~q/C



giant magneto-resistance
spintronics



Electro-Chemical Switch

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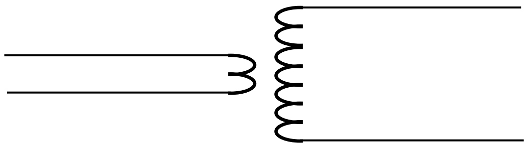
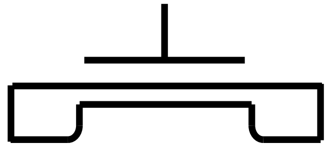
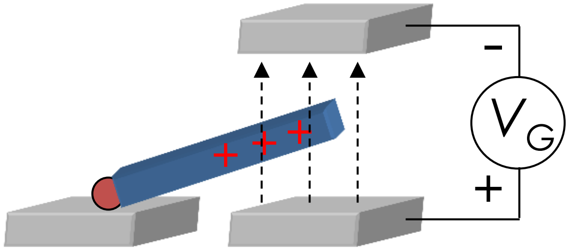


nano-transformer



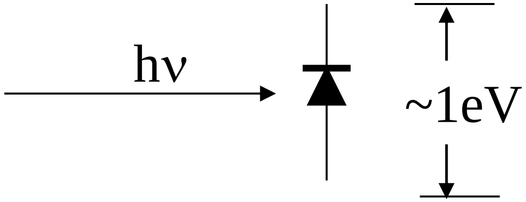
Nanoelectronics:
Solid-State Milli-Volt Switching

Theme 2:



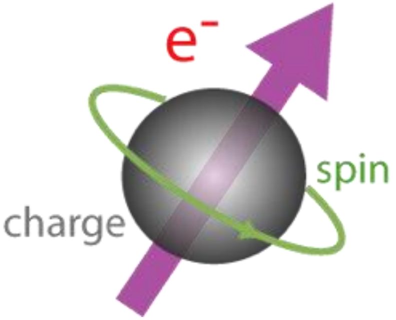
Nanomechanics:
Zero-Leakage Switching

Theme 3:



Nanophotonics for Ultra-Low Energy Communication

Theme 4:



Nanomagnetics:
A Low Energy Magnetic Switch