Network for Computational Nanotechnology (NCN)

Purdue, Norfolk State, Northwestern, MIT, Molecular Foundry, UC Berkeley, Univ. of Illinois, UTEP

DESIGN GUIDELINES FOR LOW POWER TRANSISTORS AND HIGH EFFICIENCY PHOTOVOLTAICS

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Advisors:

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PURDUE UNIVERSITY

Outline

Energy Concerns

- Power consumption in Transistor Technology
- Efficiency of Photovoltaics

DESIGN IDEAS FOR LOW POWER TRANSISTORS

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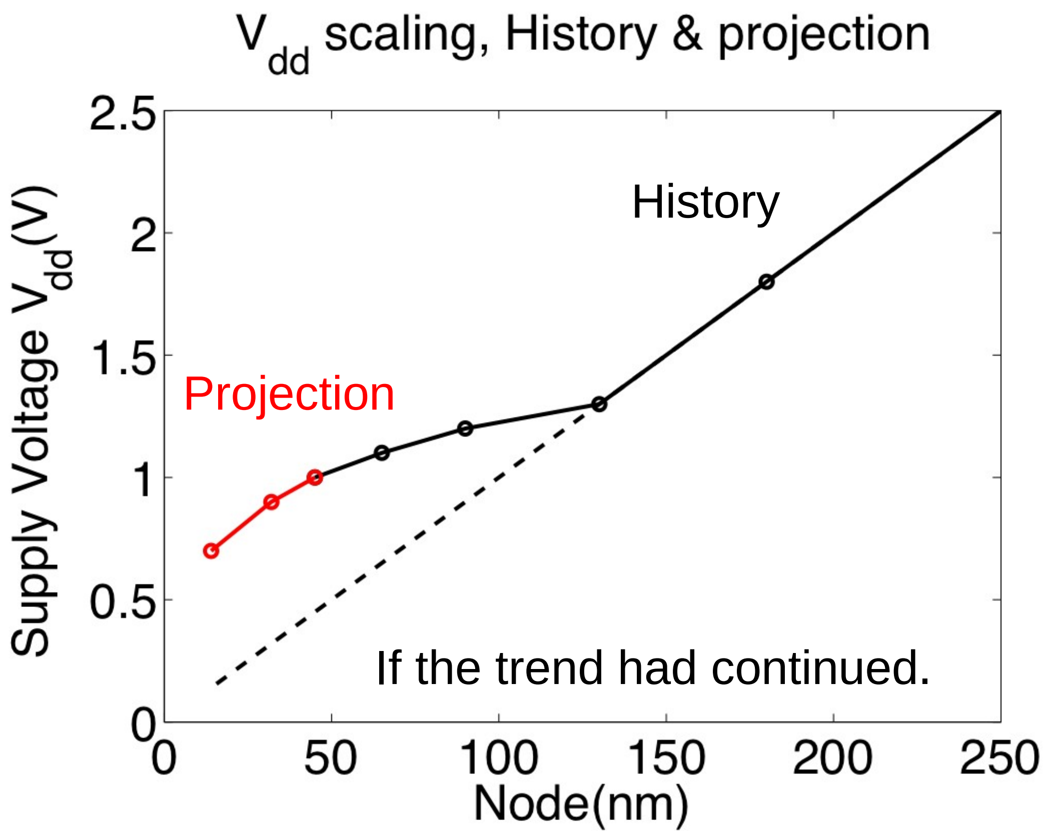
Motivation: Voltage Scaling in MOSFETs

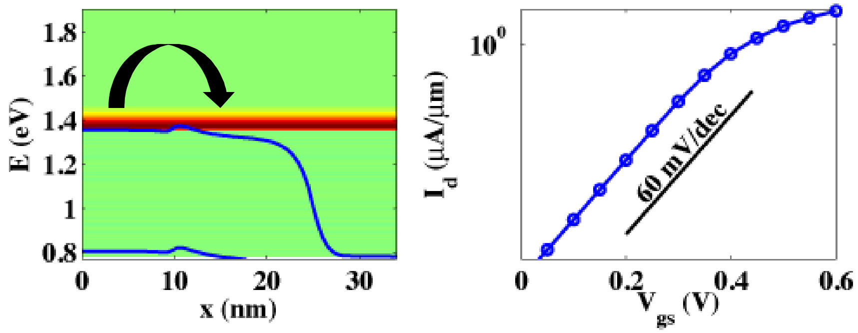


- Supply Voltage V_{DD} scaling keeps power consumption per chip under control.
- Heading for a crisis.

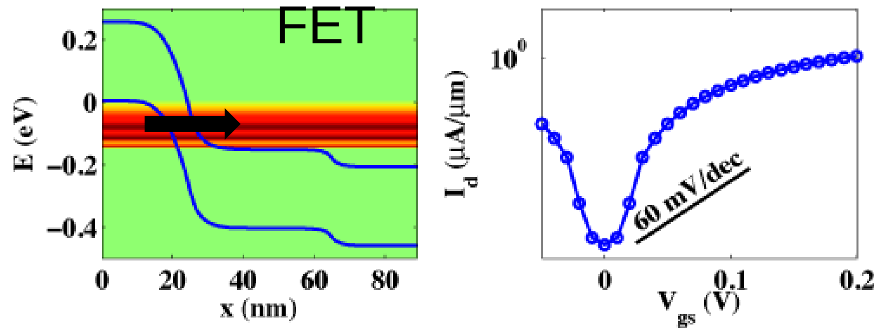
Source: ITRS(2007) & C. Hu, *Green Transistor as a solution to the IC power crisis.*

Can Tunnel-FETs replace MOSFETs?

MOSFET

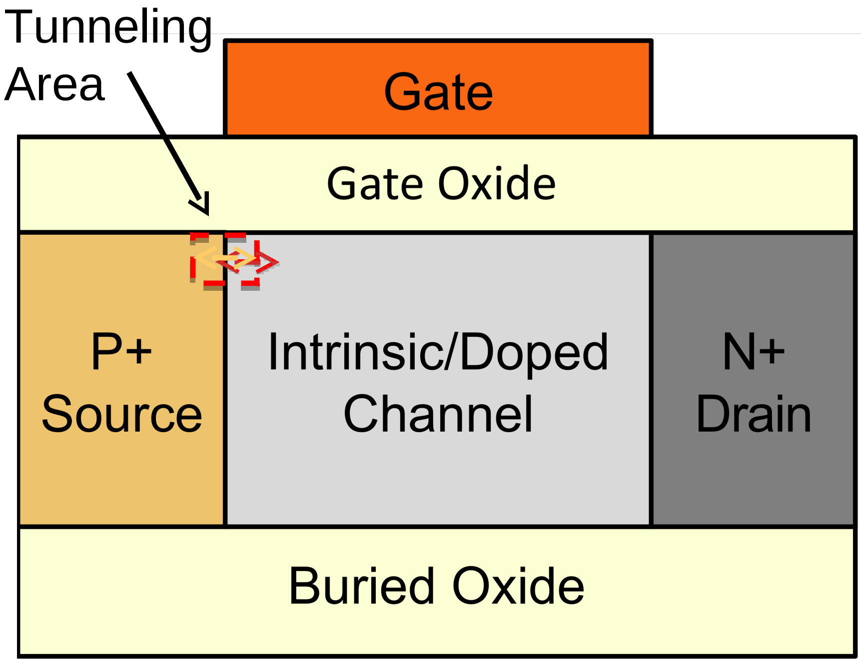


Tunnel-FET

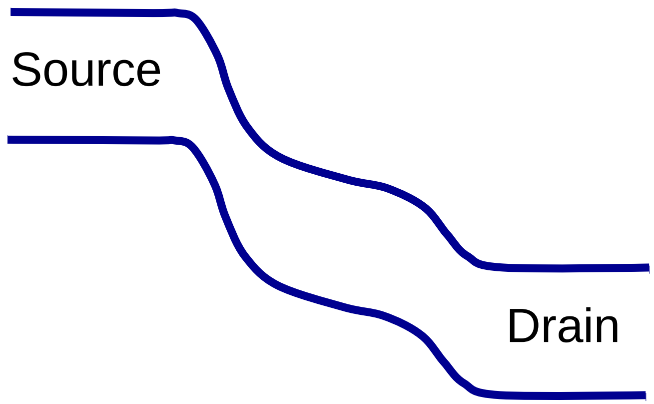


	MOSFET	Tunnel-FET
Subthreshold Swing	Fundamental 60mV/dec limit at room temperature.	Theoretically no lower limit.
Supply voltage (V_{DD}) scaling	Difficult since either increase of OFF-current or decrease of ON-current, both undesired	Possible, without any adverse affects.
ON-current	High, >1000 μA/μm	Very Low: BIG CHALLENGE!

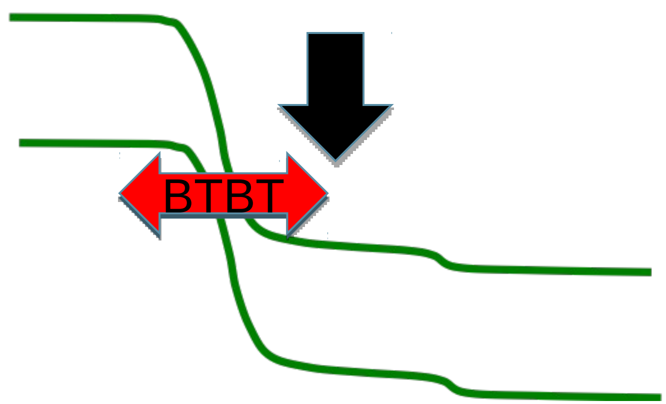
Tunnel-FET : PIN structure



Equilibrium : OFF STATE

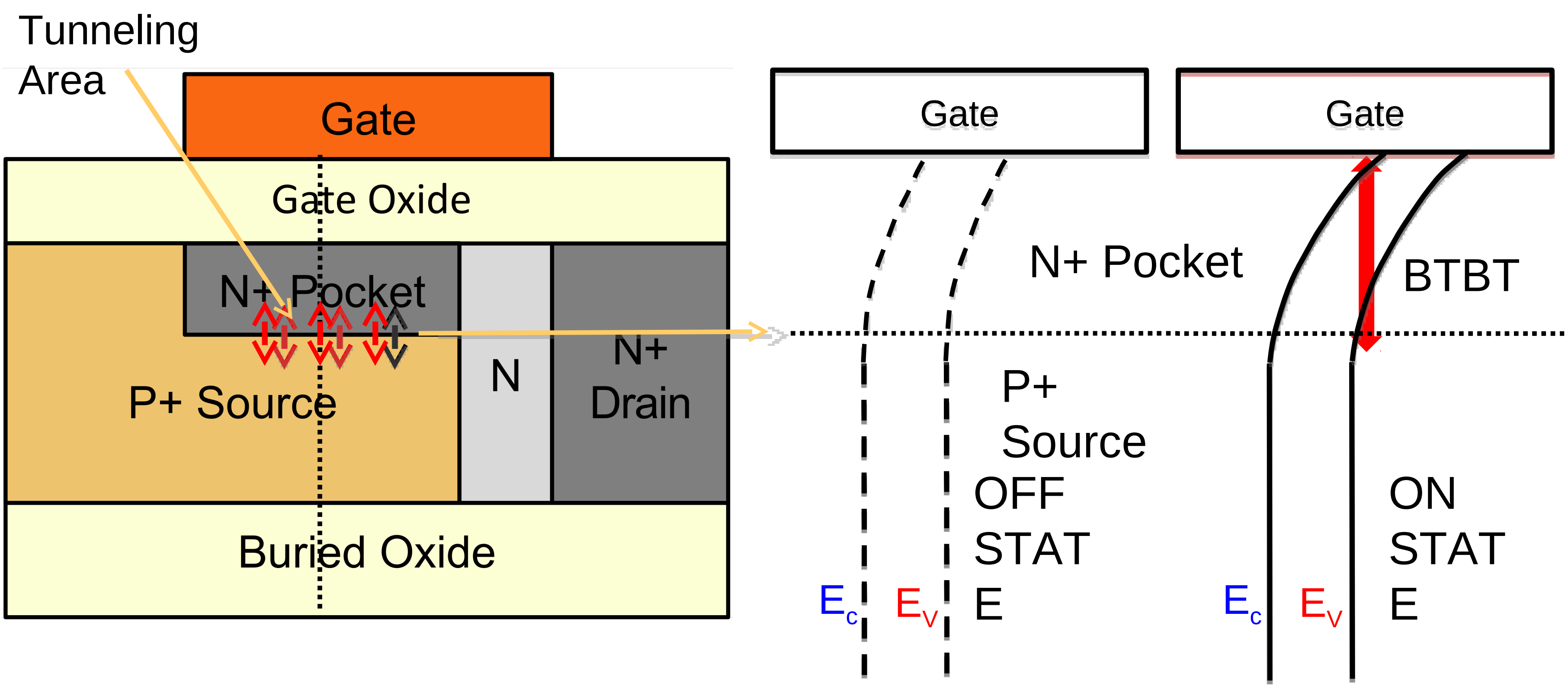


Positive gate bias: ON STATE



- Low ON current.
- Effect of gate not beyond 5nm.
- Small tunneling area.
- Electric field diminishes from top to bottom (gate to ground).

A special Tunnel-FET: Green-FET (gFET)



Source: Chenming Hu, *Green Transistor as a solution to the IC power crisis.*

- Large ON current: Large and uniform field over a substantial area. (Proportional to pocket length)
- Direct modulation of tunneling current through gate contact.
- Only commercial TCAD simulations, no Experimental results!

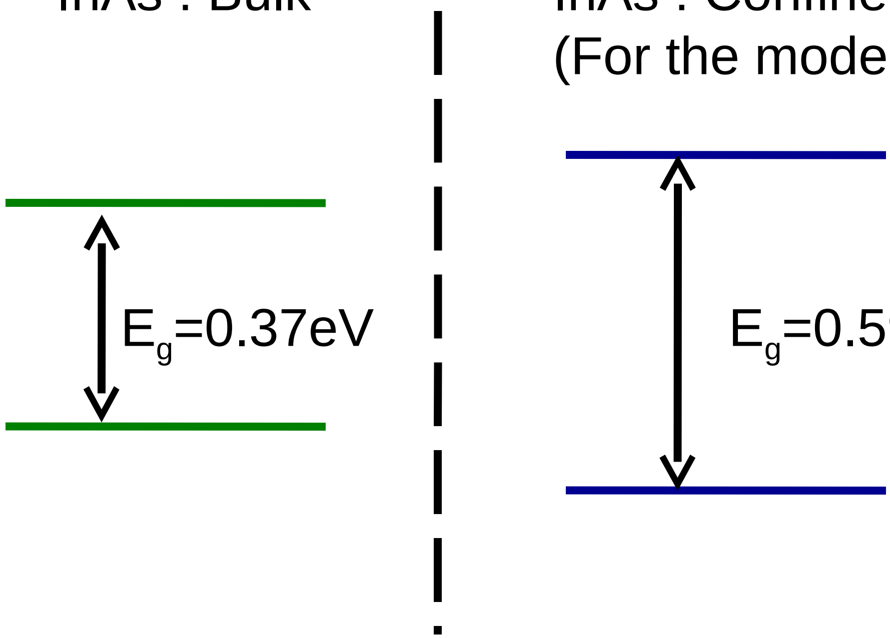
Method : Tight Binding

Why Tight-Binding?

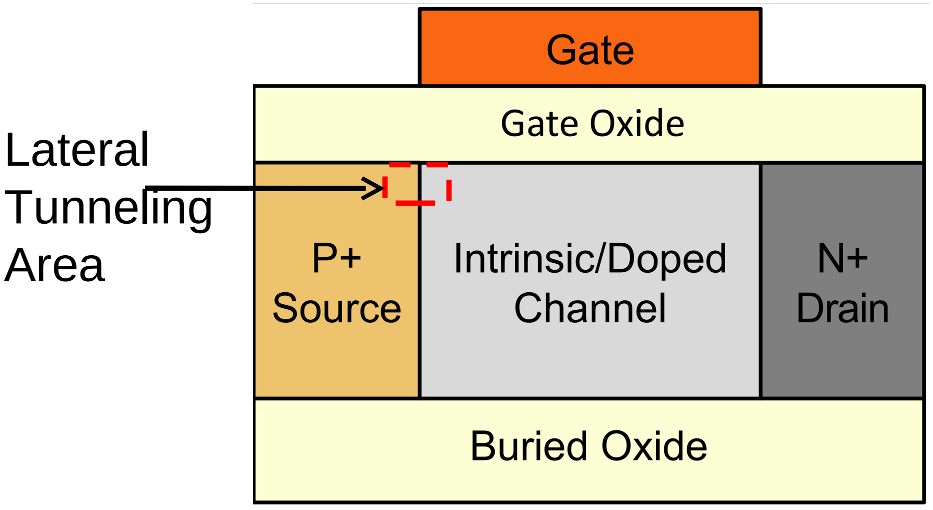
- Band Gap, effective mass: Bulk Vs Confinement
- Conduction and valence bands simultaneously.
- Tunneling probability in the forbidden gap.

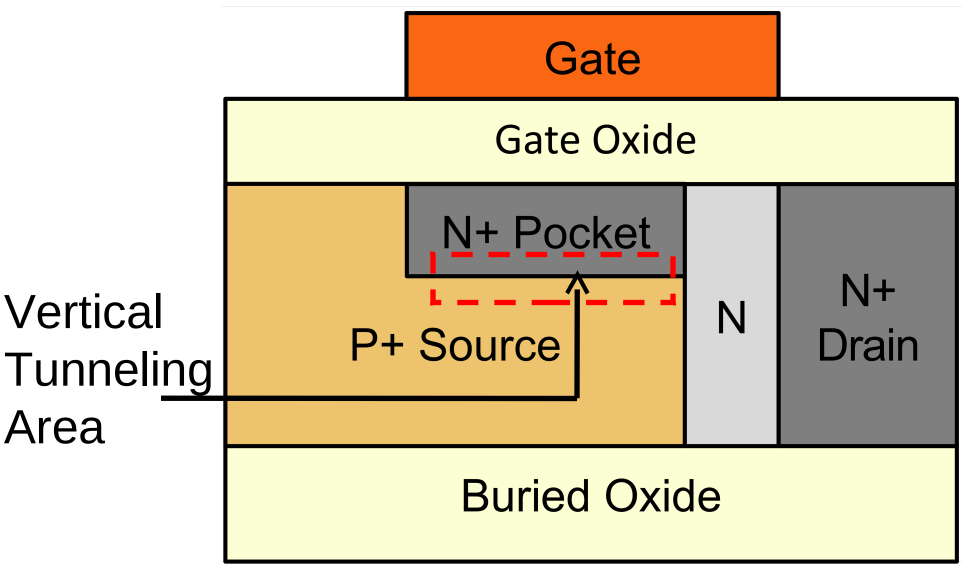
InAs : Bulk

InAs : Confinement
(For the modeled structure).

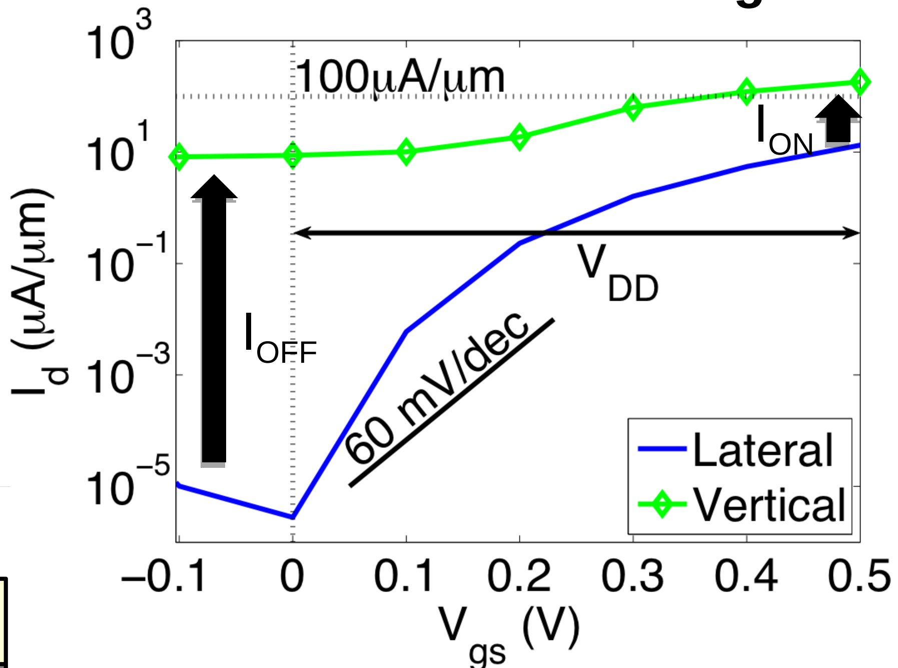


Lateral Vs Vertical





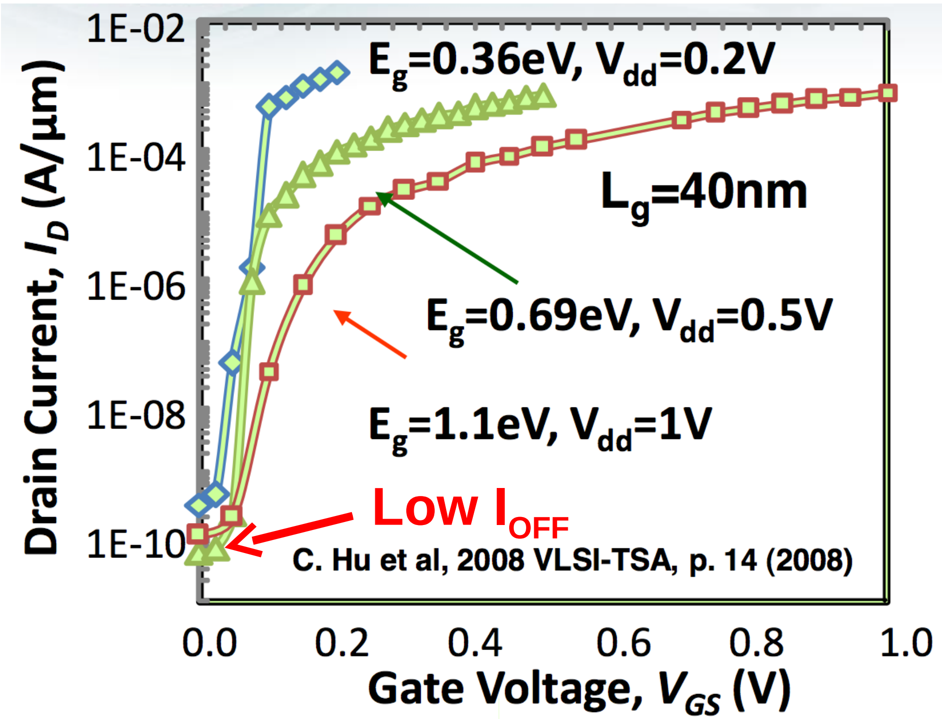
LATERAL: PIN VERTICAL: gFET



Increase in Tunneling area :
High I_{ON}

InAs gFET results: TCAD Vs OMEN

TCAD gFET I-Vs



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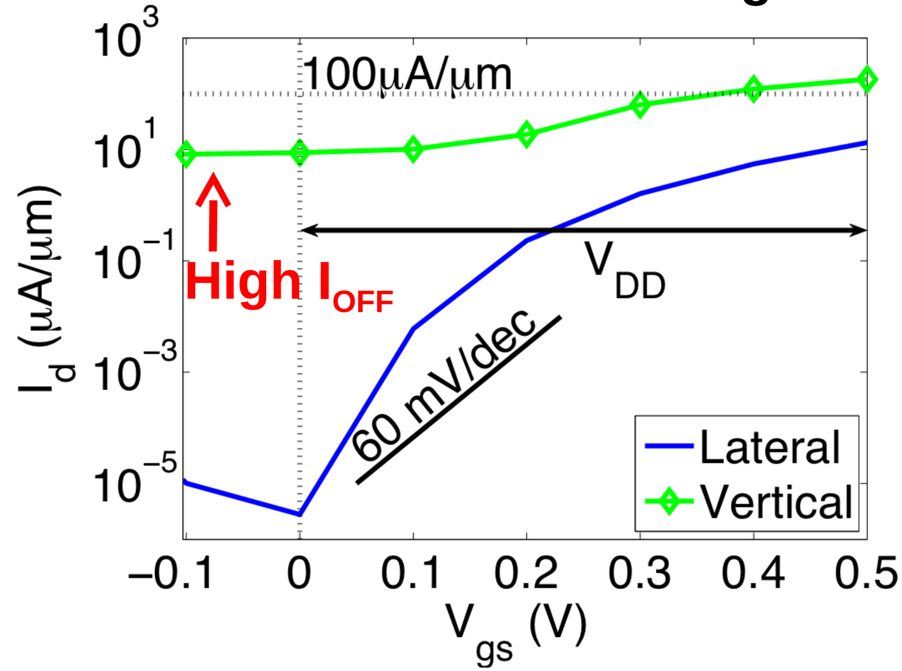


TCAD

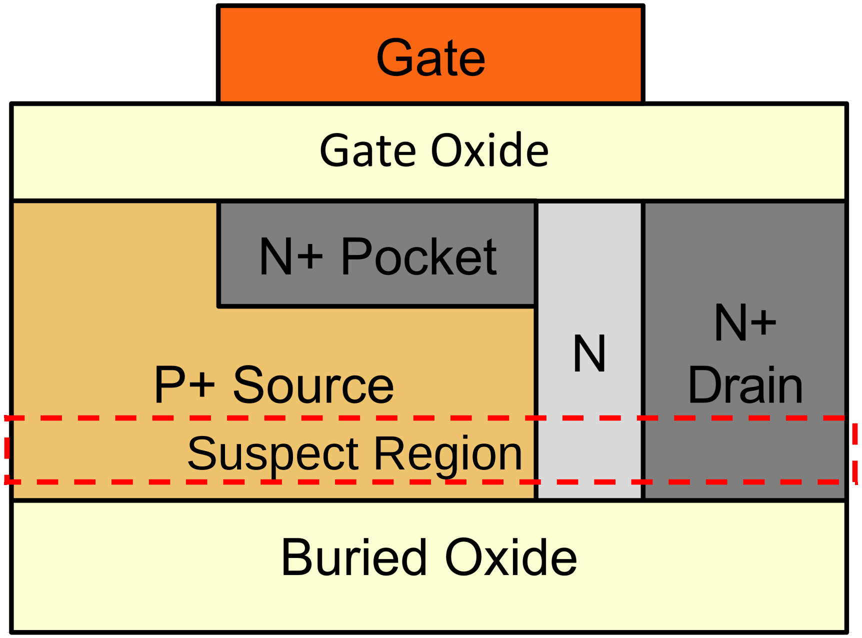
- Drift Diffusion & WKB (MEDICI, 2-band Kane model)
- Tunneling in specific regions only
- High I_{ON} and low I_{OFF}

OMEN

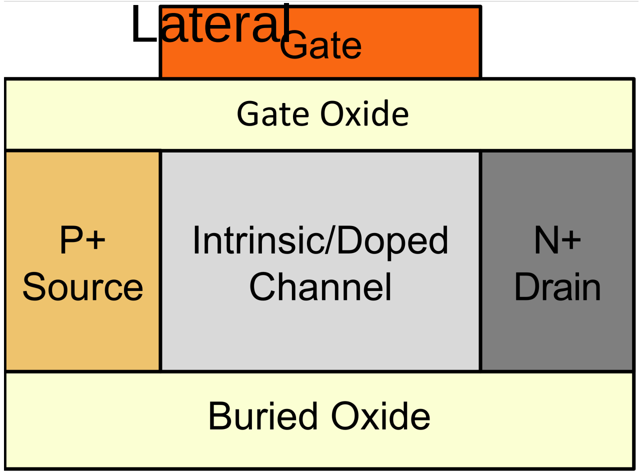
- Atomistic, Full Band, Non-equilibrium Quantum transport
- Tunneling present everywhere.
- High I_{ON} but high I_{OFF}

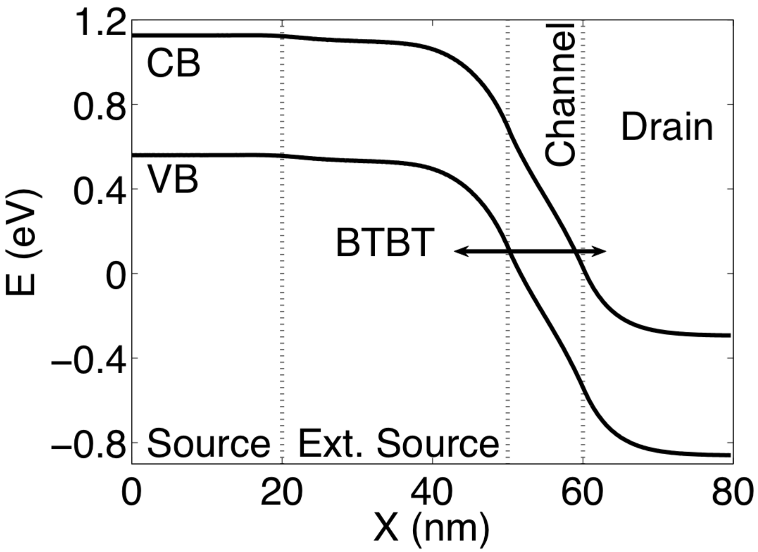
gFET OFF state current

gFET : Vertical



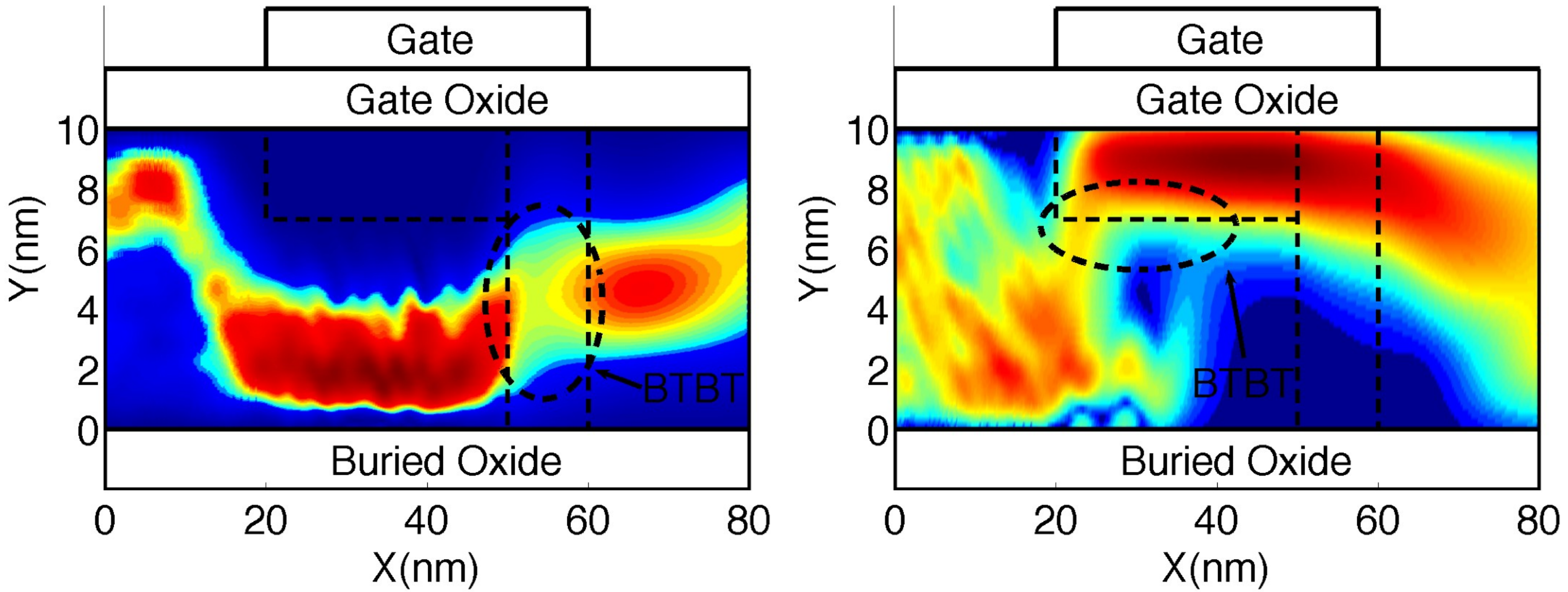
PIN TFET : Lateral





- Region below the pocket & PIN TFET, similar.
- Weak electrostatic control away from the gate.
- Possibility of a current pathway contributing to OFF state current.

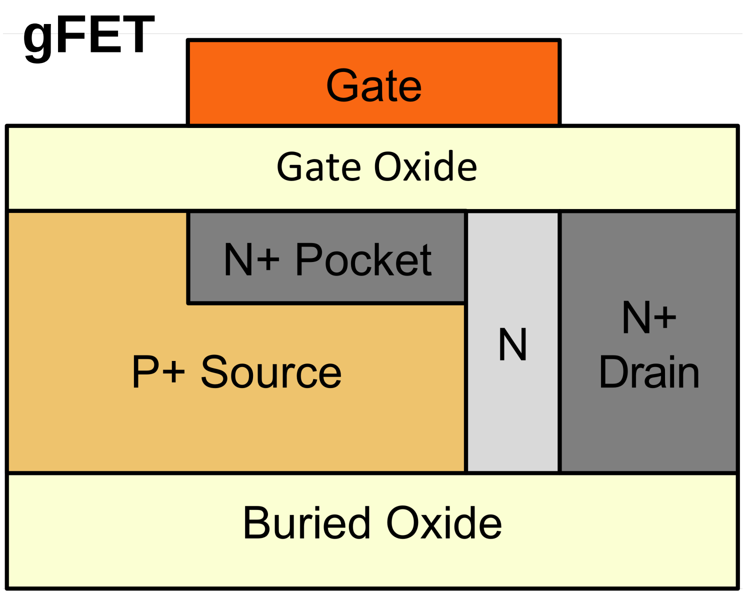
gFET spatial current distribution

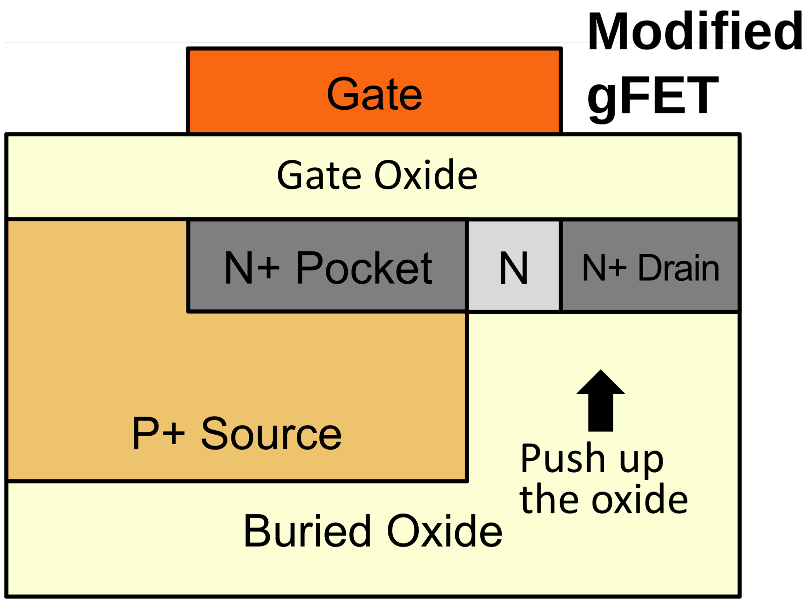


gFET-OFF STATE
Red denotes high current density.

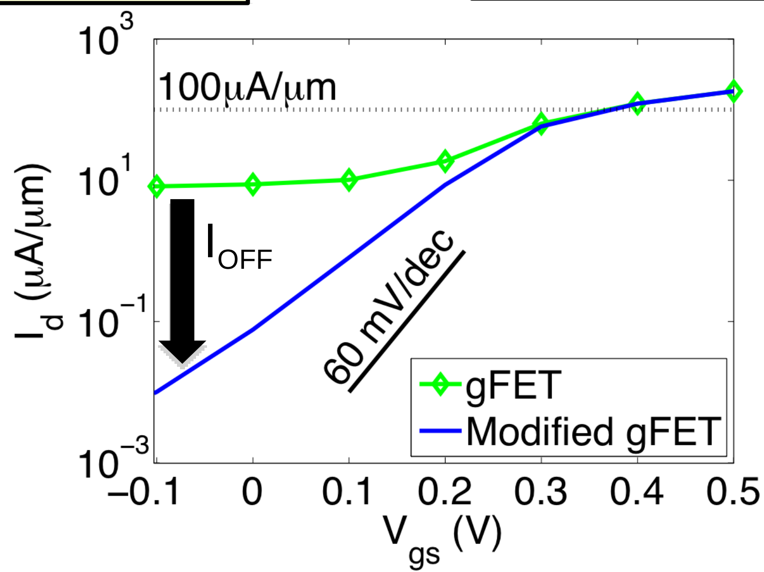
gFET-ON STATE
Different color-scale for clarity.

- OFF STATE: Lateral Tunneling
- ON STATE: Vertical Tunneling
- Unsuitable for low power logic applications: Necessitates a modification.



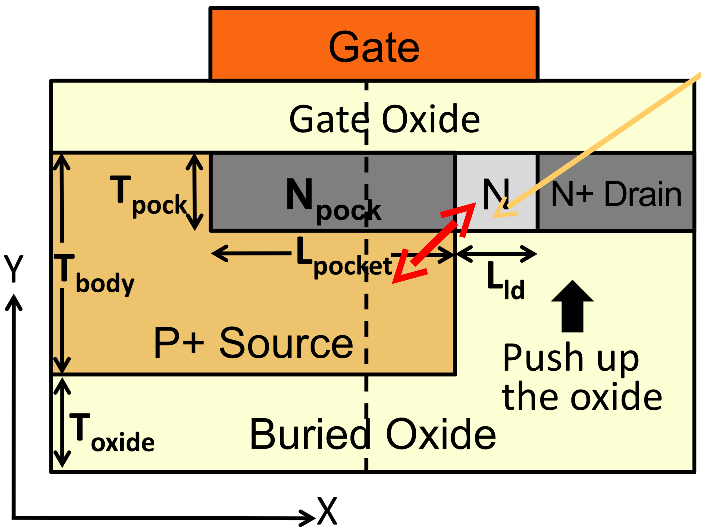


I_{OFF} reduces by several orders of magnitude, I_{ON} unaffected.



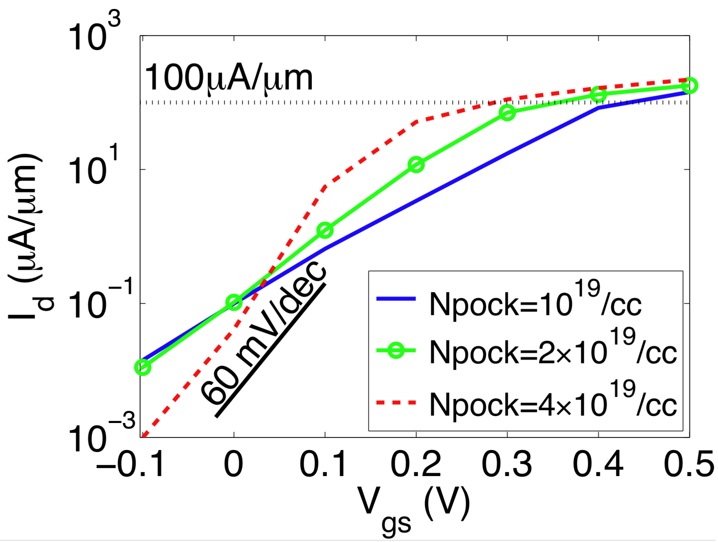
Introduction of an oxide/large band-gap material on the drain side.

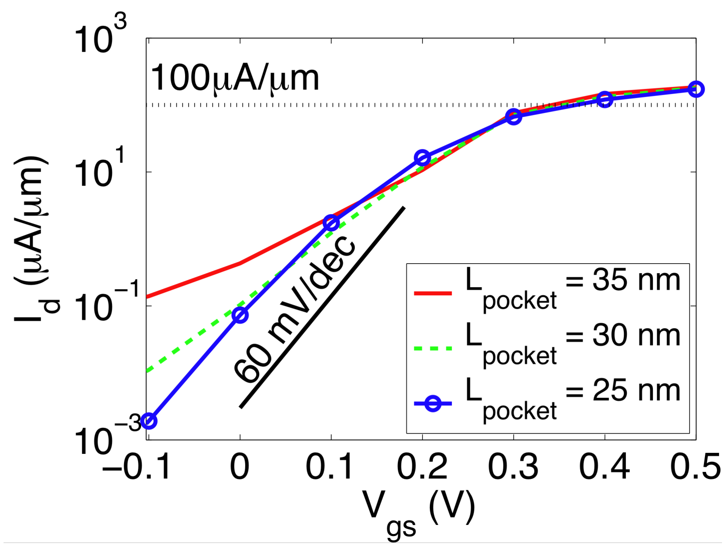
Effect of Pocket doping & Pocket length



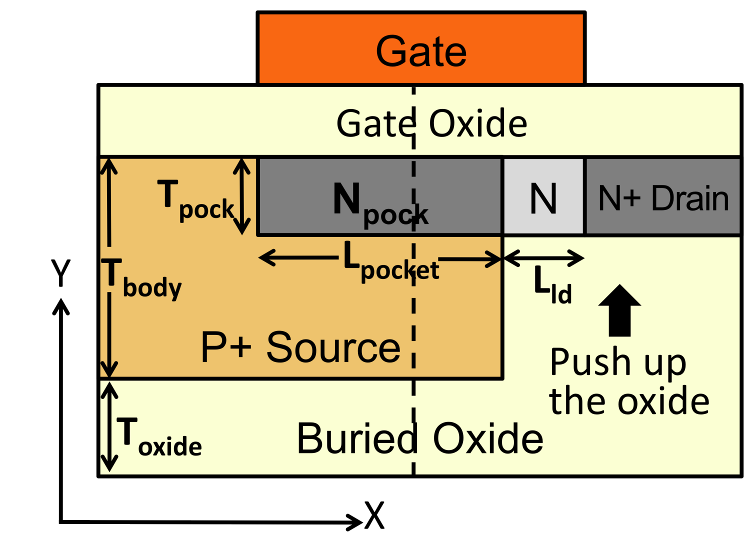
Diagonal current pathway

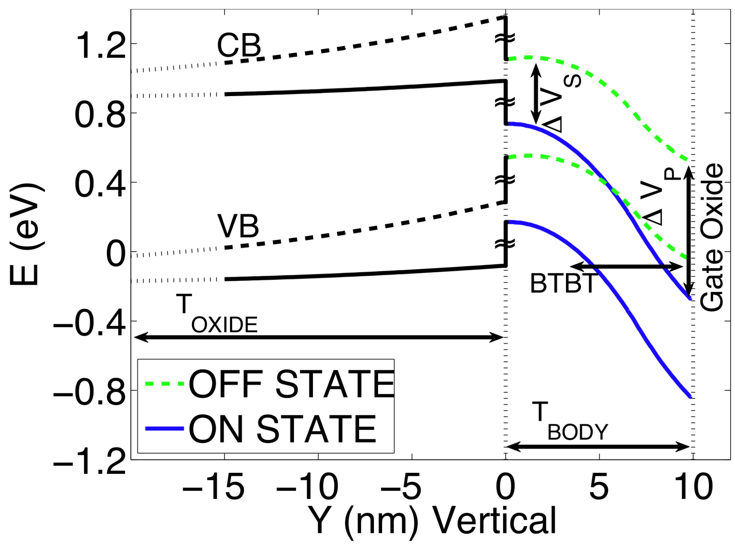
- Higher pocket doping gives higher electric fields.
- Shorter pocket length increases the length of diagonal current pathways.



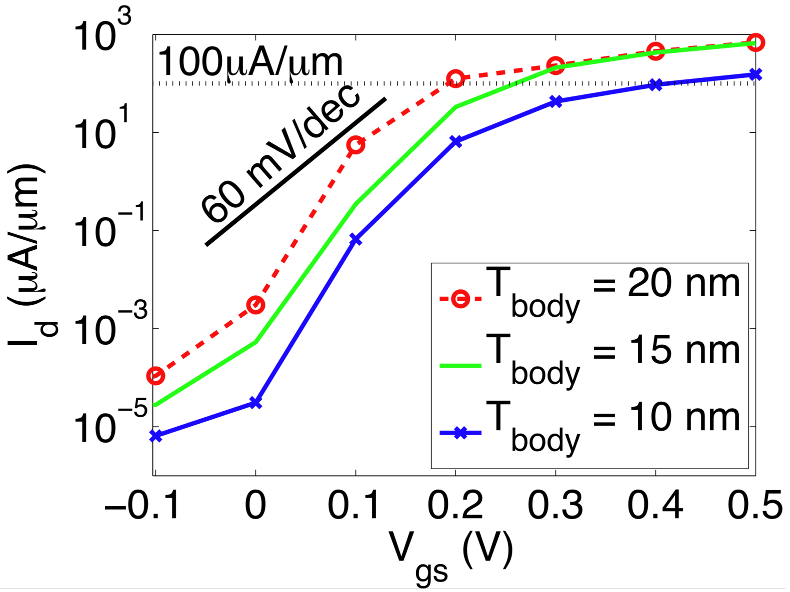


Effect of Body thickness

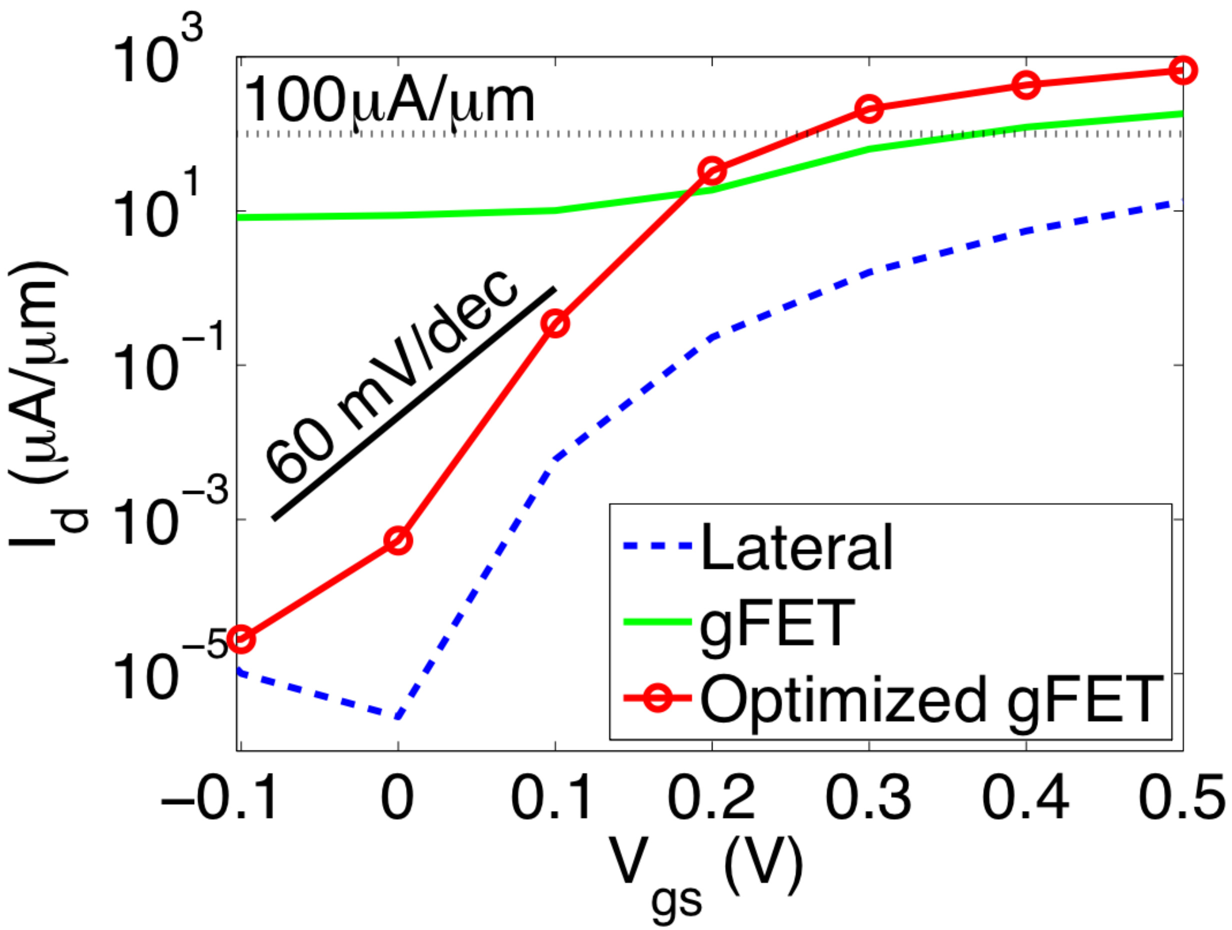




- Bands shift, away from the gate.
- Shifting of bands not good for BTBT.
- Shifting can be reduced by increasing body thickness (T_{BODY}).

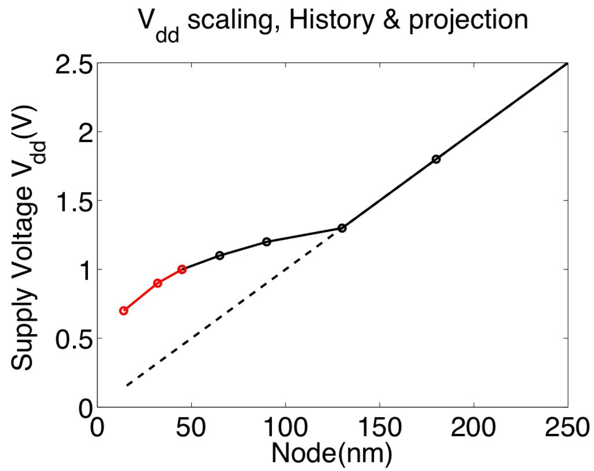


Comparison



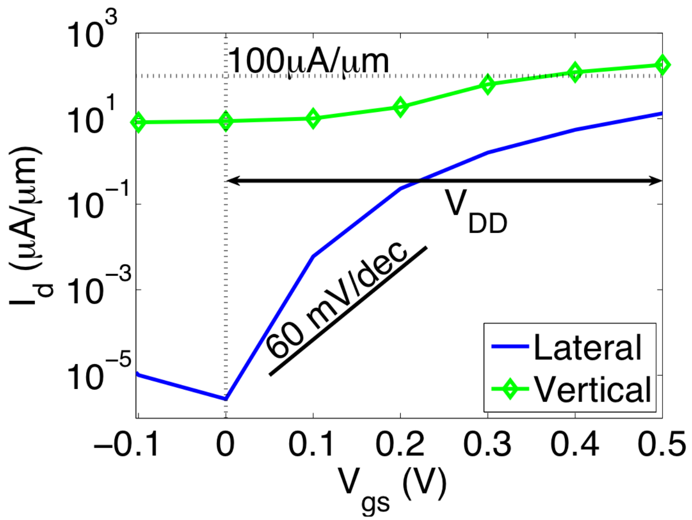
- Optimized gFET: Modified gFET + (optimized pocket doping/length and body thickness)

Power consumption an issue

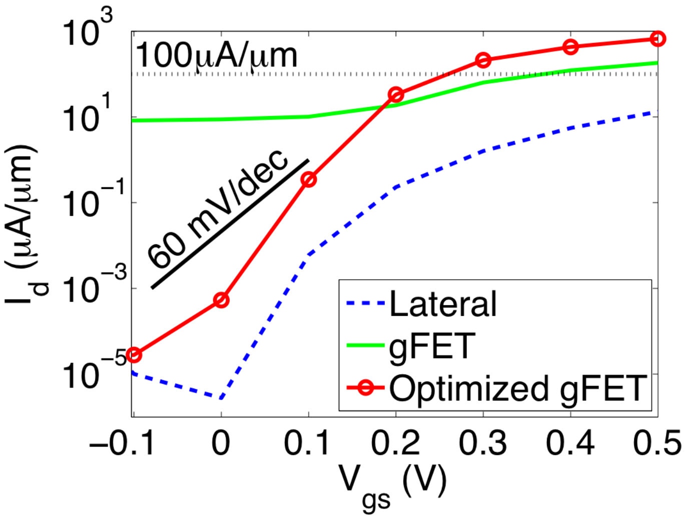


MOSFET : Voltage scaling difficult.
Tunnel-FET : Possible candidate.

Lateral Vs Vertical Tunnel-FET



Optimized gFET results



DESIGN GUIDELINES FOR HIGH EFFICIENCY PHOTOVOLTAICS

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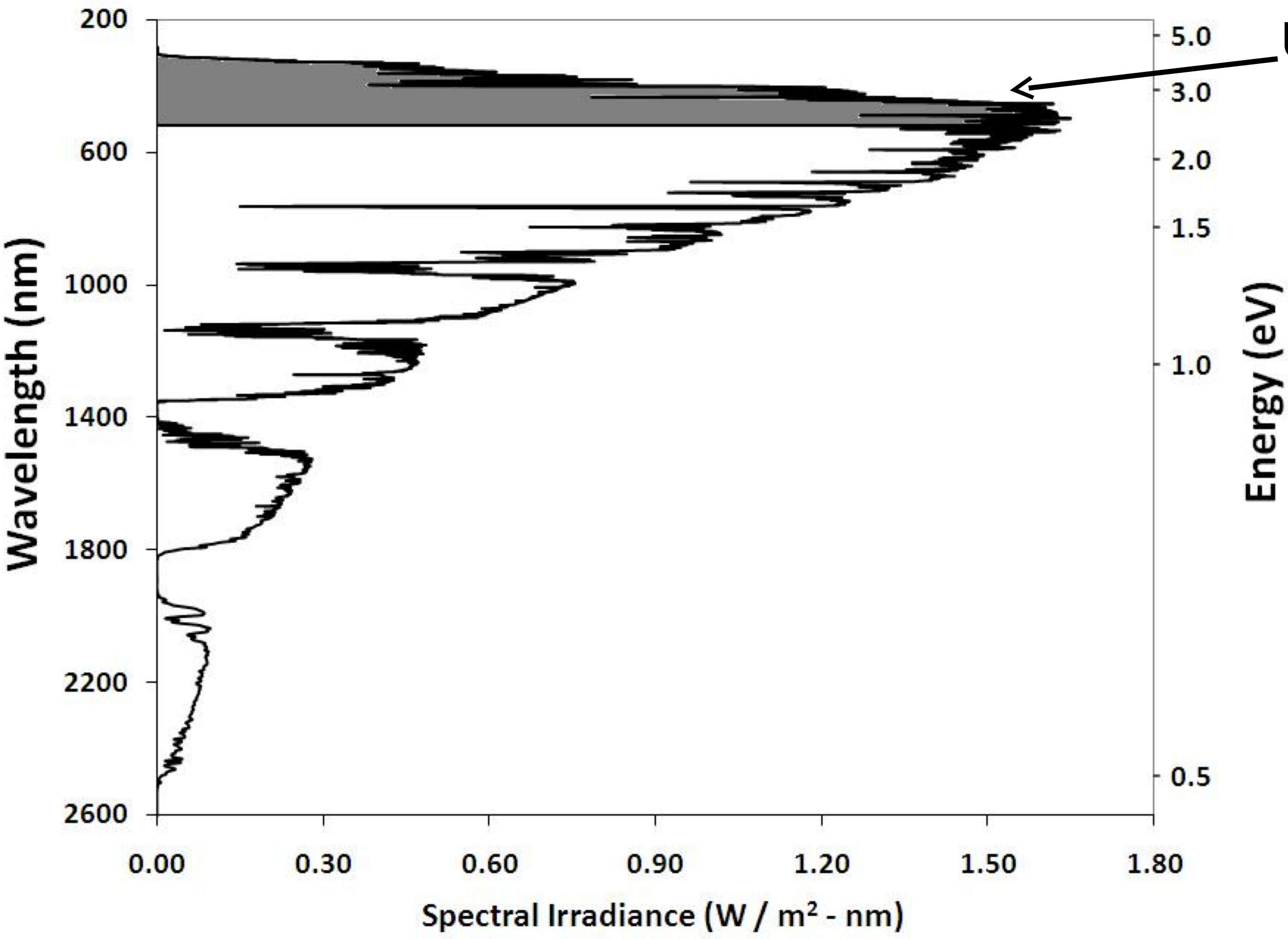
Limited efficiency of solar cells



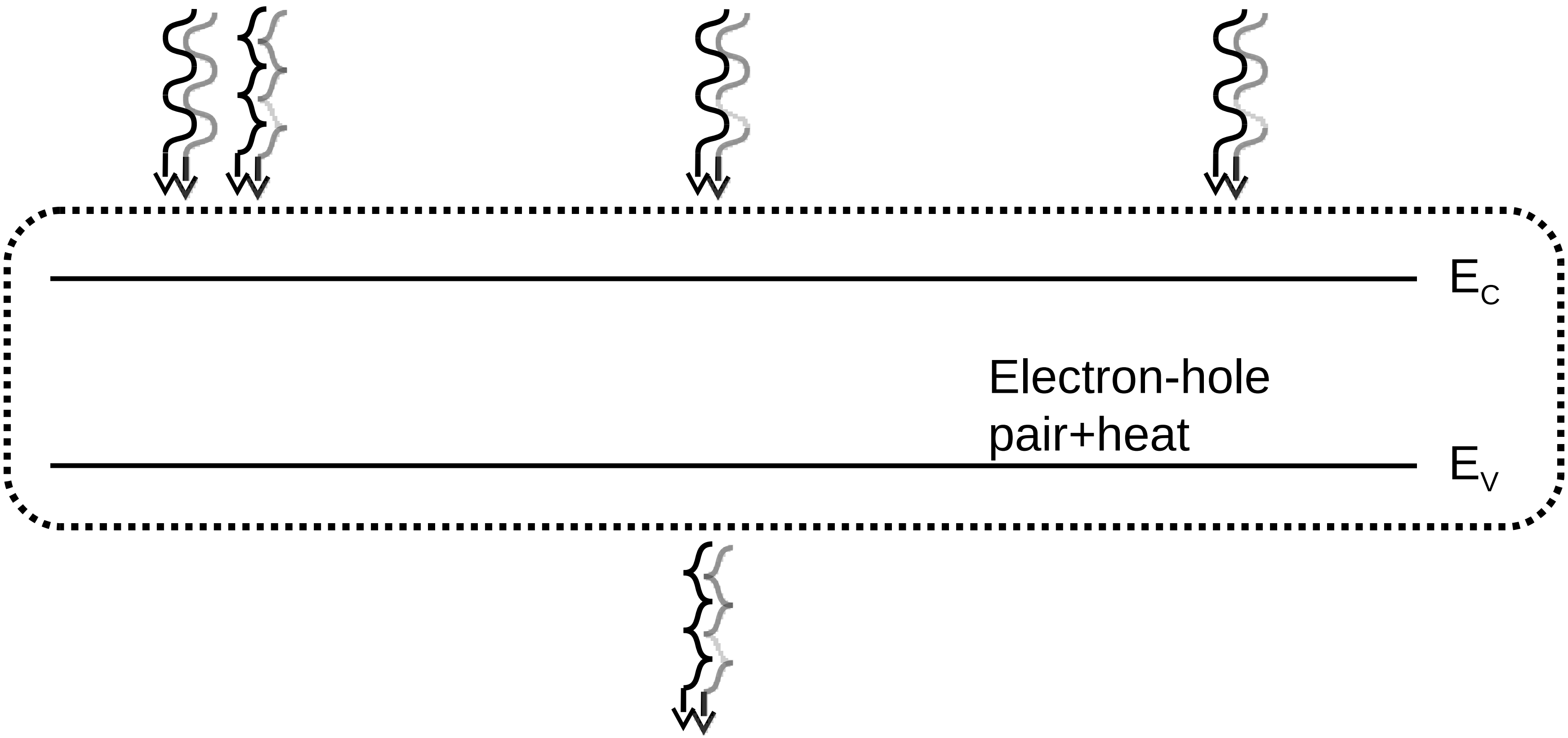
- Many types of Solar cells, but efficiency limited.
- 20% of solar spectrum untapped.
- Lack of material around 2.3-2.4eV.

AM 1.5 Solar spectrum: Shaded region corresponds to 21.1% of total irradiance. Fig. by Kyle Montgomery.

Reflected back

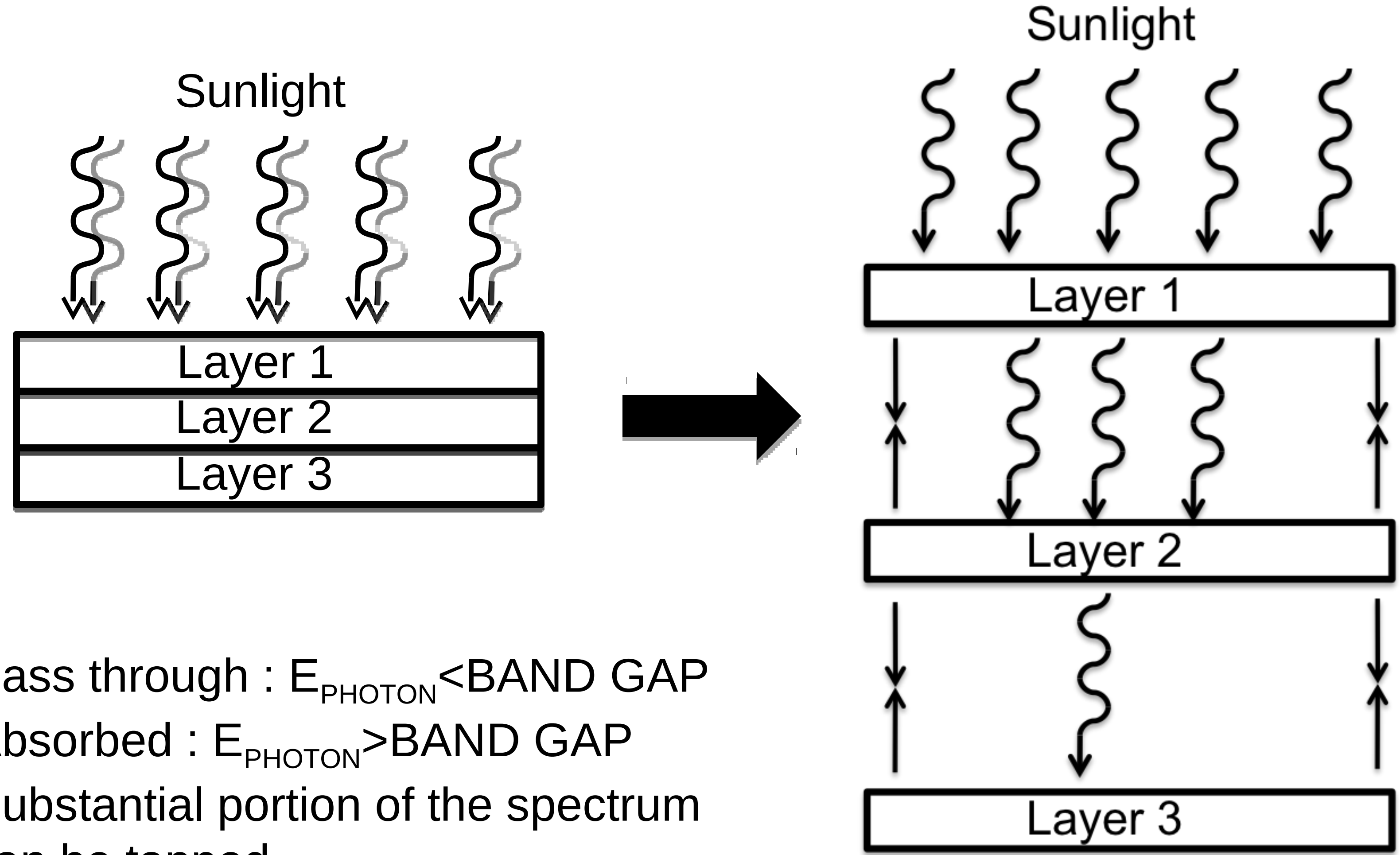
Pass through:
E_{PHOTON}<BAND GAP

Absorbed:
E_{PHOTON}>BAND GAP



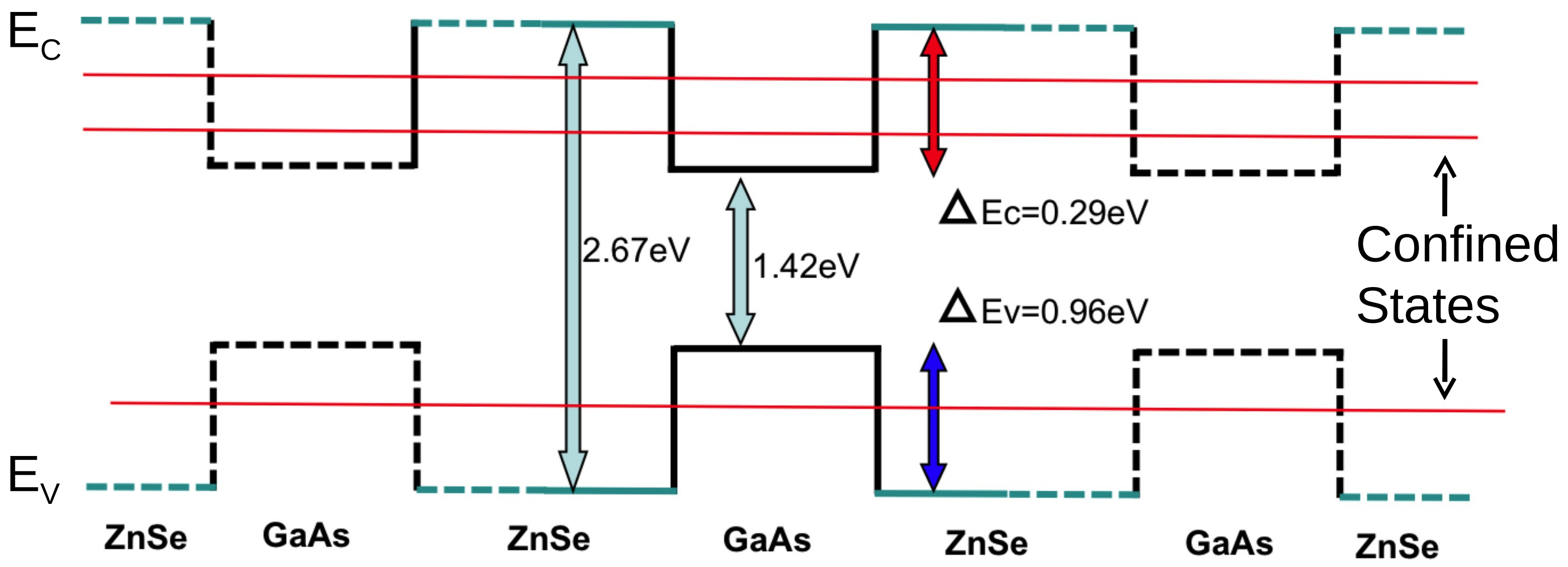
Multi-junction Solar cells

$E_{G1} > E_{G2} > E_{G3}$



- Pass through : E_{PHOTON}<BAND GAP
- Absorbed : E_{PHOTON}>BAND GAP
- Substantial portion of the spectrum can be tapped.

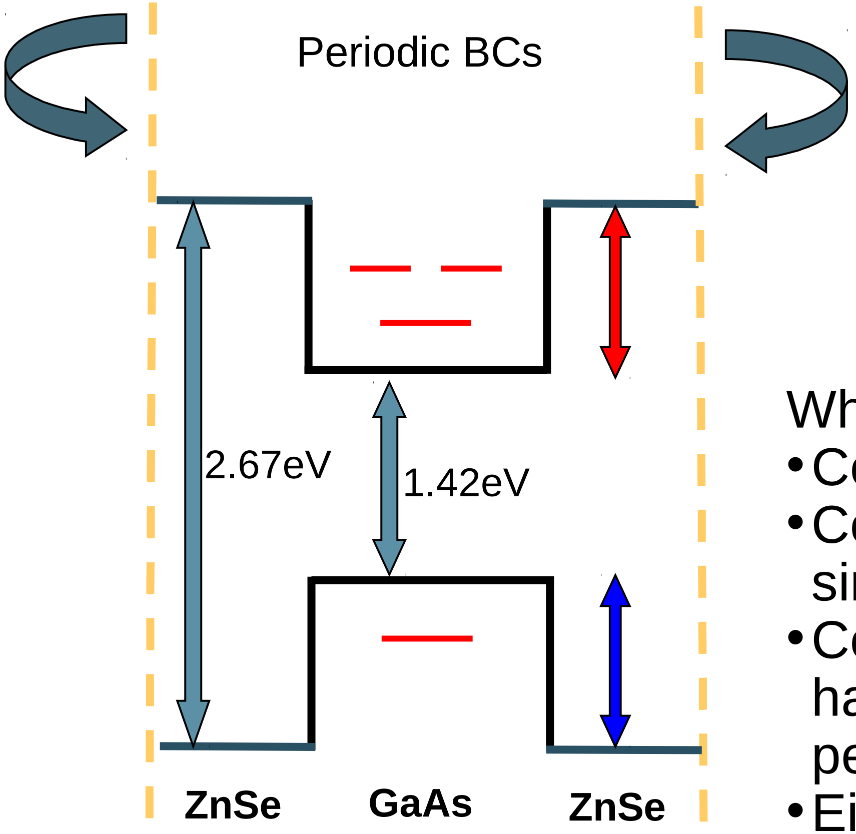
The ZnSe/GaAs system

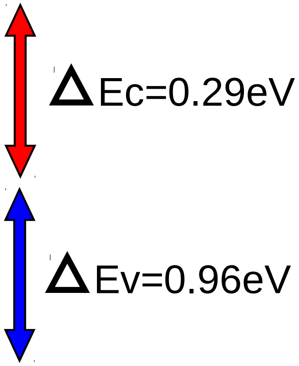


- Lattice matched : Can fabricate "Digital Alloys".
- Confined states dominate the band-edge. (Esaki & Tsu(1970), IBM).
- Super-lattice period determines the electronic properties.

Band offsets based on (A.J. Ekpunobi, Materials Science in Semiconductor Processing 8(4))

Method: Tight-binding





Why Tight-binding?

- Confinement effects.
- Conduction and valence bands simultaneously.
- Construct Periodic tight-binding hamiltonian for different super-lattice periods.
- Eigen-values used to estimate band-gap.

Re-parametrization of tight-binding parameters

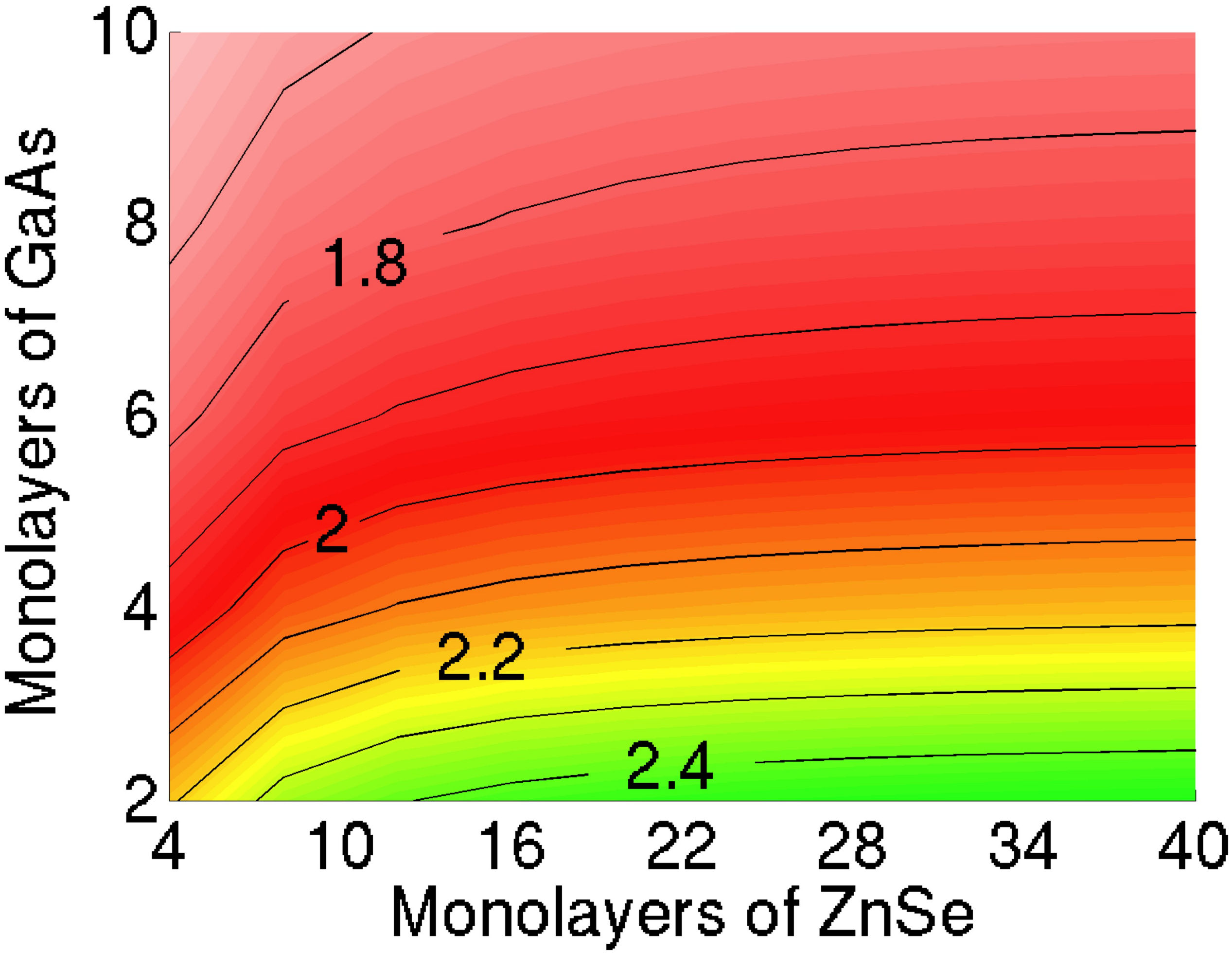
For ZnSe:

Parameters from Vogl et. al.	Need to re-parametrize
Inaccurate effective masses.	More accurate experimental data available. (Landolt–Börnstein tables)
Uses low temperature gaps	Device operates at room temperature.
Does not include spin-orbit coupling.	Spin-orbit interaction necessary to model the imaginary band linking the conduction and valence bands.

For GaAs: Source T. B. Boykin, G. Klimeck, R. C. Bowen, and R. Lake, PRB 56, 4102 (1997).

Band-gap Results: Guide for experiments

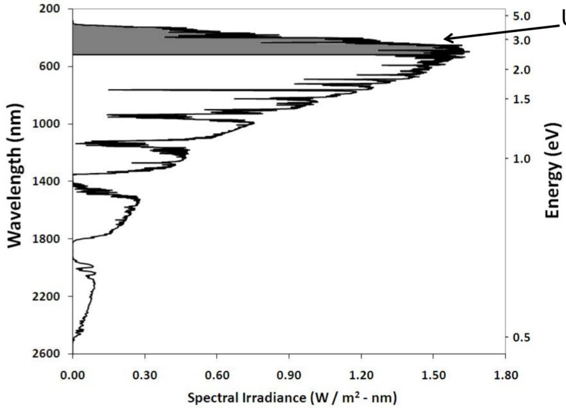
Band-gap (in eV) of the ZnSe/GaAs super-lattice.



- Difference of lowest conduction and highest valence band eigen-value.
- E_G = 2.4 eV : 20 ML ZnSe and 2 ML GaAs.
- Band-gap approaches bulk values at expected periods.
- Attempt to guide experiments.

Summary

Limited efficiency of solar cells



Untapped portion

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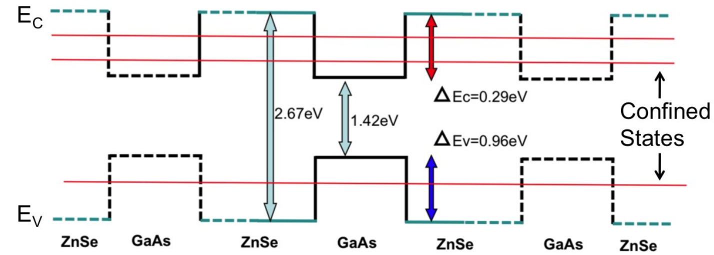

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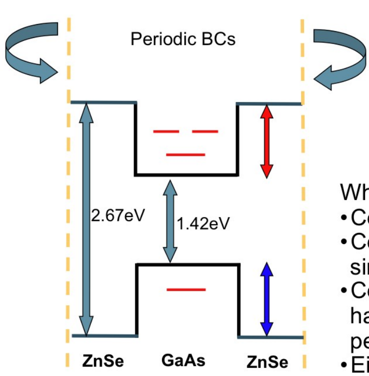

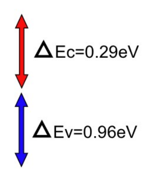

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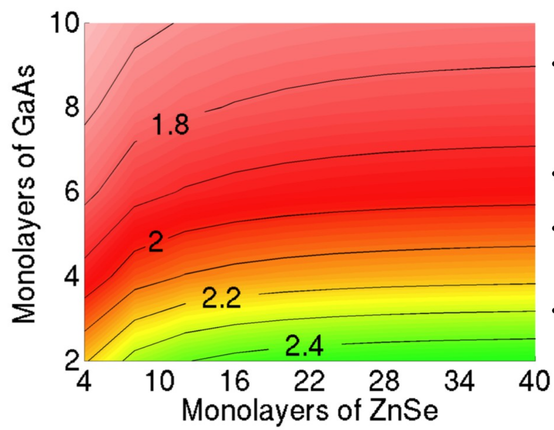

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Contributions

Patents: co-patentee on,

- Tunneling field effect transistor with Low Leakage Current.
- Solar Cell and LED with lattice matched super-lattice structure and fabrication method thereof.

Journal Publications:

- Agarwal, S.; Klimeck, G.; Luisier, M.; , "Leakage-Reduction Design Concepts for Low-Power Vertical Tunneling Field-Effect Transistors," Electron Device Letters, IEEE , vol.31, no.6, pp.621-623, June 2010.

- Samarth Agarwal, Kyle H. Montgomery, Timothy B. Boykin, Gerhard Klimeck, and Jerry M. Woodall, Design Guidelines for True Green LEDs and High Efficiency Photovoltaics Using ZnSe/GaAs Digital Alloys, Electrochem. Solid-State Lett. 13, H5 (2010).

- Samarth Agarwal, Michael Povolotskyi, Tillmann Kubis and Gerhard Klimeck, Adaptive quadrature for sharply spiked integrands, Journal of Computational Electronics, vol 9, no.3-4, 252-255.

Contributions cont'd.

Other publications:

- S. Agarwal, G. Klimeck, 1D hetero-structure tool for atomistic simulation of nano-devices, Proceedings of TECHCON 2008, Austin, TX, Nov. 3-4, 2008.

- Kyle Montgomery, Samarth Agarwal, Gerhard Klimeck, and Jerry Woodall, Proposal of ZnSe/GaAs Digital Alloys for High Band Gap Solar Cells and True Green LEDs, IEEE Nanotechnology Materials and Devices Conference (NMDC 2009), June 2-5, 2009, Traverse City, Michigan, USA .

Simulation tools on the nanoHUB:

- Transport in 1D heterostructures.
- Poisson Schrödinger Solver for 1D heterostructures.
- Transfer matrix and tight-binding tool for 1D Heterostructures.

Supporting documents and chapters for a book by World Scientific.

Acknowledgements

Prof. Klimeck & Prof. Reifenberger

Prof. Datta & Prof. Savikhin

Prof. Vasileska, Prof. Boykin & Prof. Woodall

Dr. Mathieu Luisier

All NCN students and group members

Thank You!