The Influence Of Carrier Thermalization On The Performance Of Nitride Tunneling Hetero-FETs

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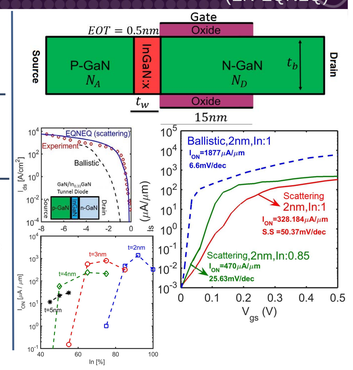
E-K Equilibrium-NonEquilibrium Model (EK-EQNEQ)

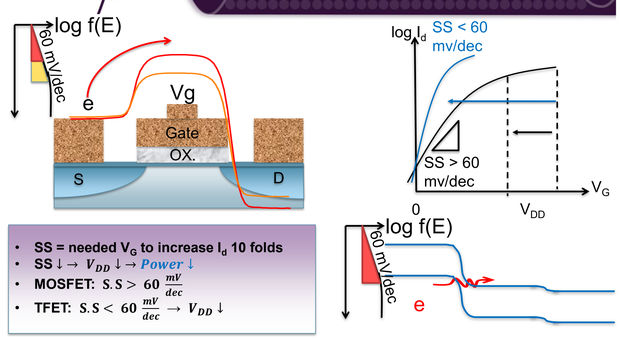
Devices: Nitride Tunnel Hetero-structures
Problem:
- Barrier is too long to transport ballistic
- Quasi-bound states are not filled ballistic

Approach:
- Divide device into two Equil. and one Non-equil. regions (E-K dependent).
- Self consistent with 3D Poisson

Results / Impact:
- Newly developed E-K EQ-NEQ model matches well with measurements of Nitride diodes (Succeeded where ballistic has failed).
- The new model is being used to optimize and design Nitride TFETs



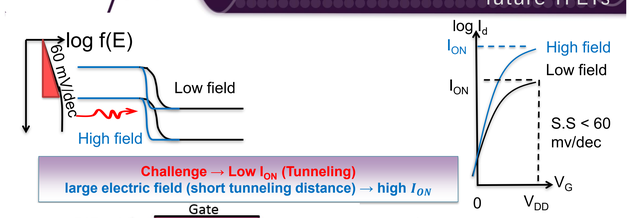
TFETs can provide steeper transistors!



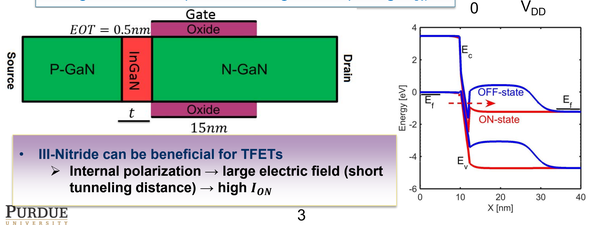
- SS = needed V_G to increase I_d 10 folds
- SS↓ → V_{DD}↓ → *Power*↓
- MOSFET: $S.S > 60\ \frac{mV}{dec}$
- TFET: $S.S < 60\ \frac{mV}{dec} \rightarrow V_{DD}\downarrow$

Challenge → Low I_{ON} (Tunneling)

III-Nitrides are promising candidates for future TFETs

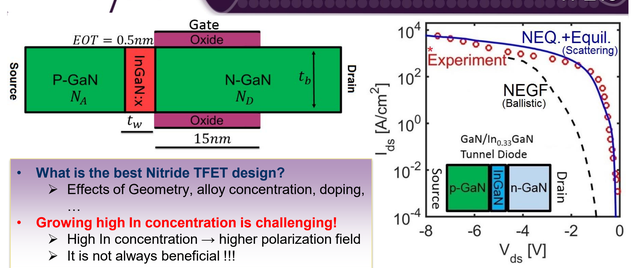


Challenge → Low I_{ON} (Tunneling)
large electric field (short tunneling distance) → high I_{ON}



- **III-Nitride can be beneficial for TFETs**
  - **Internal polarization → large electric field (short tunneling distance) → high I_{ON}**

A rigorous model is needed to design Nitride TFETs

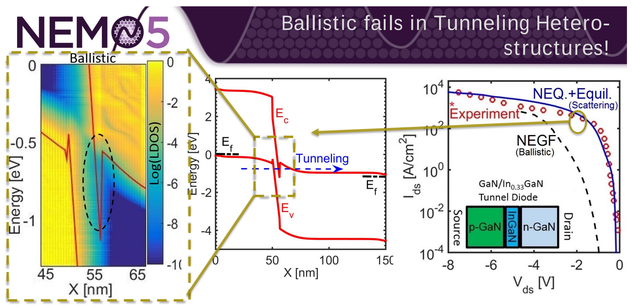


- **What is the best Nitride TFET design?**
  - Effects of Geometry, alloy concentration, doping, …
- **Growing high In concentration is challenging!**
  - High In concentration → higher polarization field
  - It is not always beneficial !!!

- **A rigorous Multiphysics model (NEQ.+Equil.) is needed to answer those questions!**
  - Newly developed EQ-NEQ model matches well with measurements of Nitride diodes (Succeeds where ballistic fails).
  - The new model is being used to optimize and design Nitride TFETs

* Krishnamoorthy, Sriram, et al. "Polarization-engineered GaN/InGaN/GaN tunnel diodes." *Applied Physics Letters* 97.20 (2010): 203502.
[+Yan, Xiaodong, et al. "Polarization-induced Zener tunnel diodes in GaN/InGaN/GaN heterojunctions." Applied Physics Letters 107.16 (2015)]

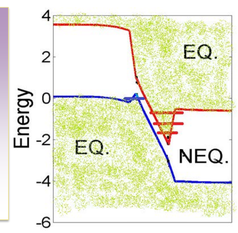
Ballistic fails in Tunneling Hetero-structures!



- **Ballistic transport:**
  - No inelastic scattering.
  - Particle's total energy doesn't change in the device.
- **Why does ballistic (coherent) transport fail?**
  - No scattering → Quasi bound states are neither broadened nor filled.

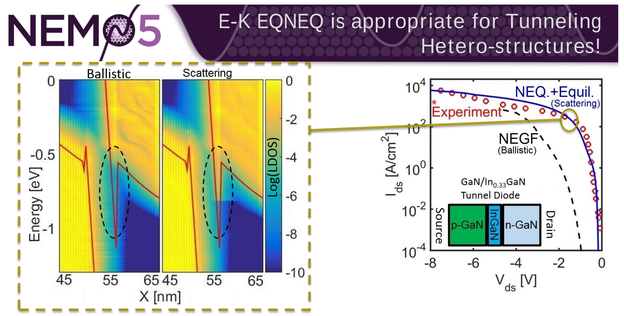
E-K Equil+NEQ model (EQNEQ)

- **A new EQNEQ Model:**
  - Three regions;
    - Two equilibrium (EQ.) with a defined quasi fermi level
    - One non-equilibrium (NEQ.)
  - Ballistic calculations in NEQ. region
  - Strong scattering in EQ. regions
  - Phenomenological Scattering self energy (in~6meV) is included through experimental relaxation time in EQ regions.
  - Region boundaries depend on E-K band diagram.*



***This is a new model that has been implemented in NEMO5**

E-K EQNEQ is appropriate for Tunneling Hetero-structures!



- **E-K EQNEQ succeeds , matches well with experiments.**
  - "Contribution of quasi-bound states to transport are captured in Eq-NEQ simulations.

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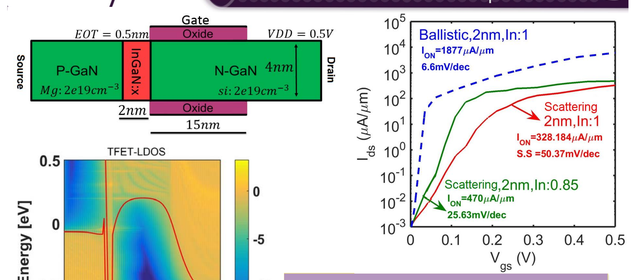
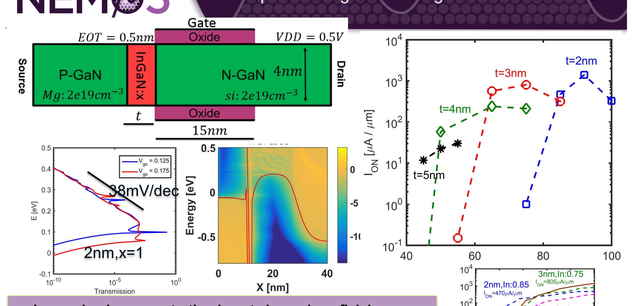
TFET Scattering degrades Subthreshold performance



- **Scattering degrades the S.S significantly**
- **85% In is better than 100% for 0.5V node.**
- **Performance can be improved by optimizing the design**
- **Simulation is self-consistent, includes thermal ionization, strain, ..**

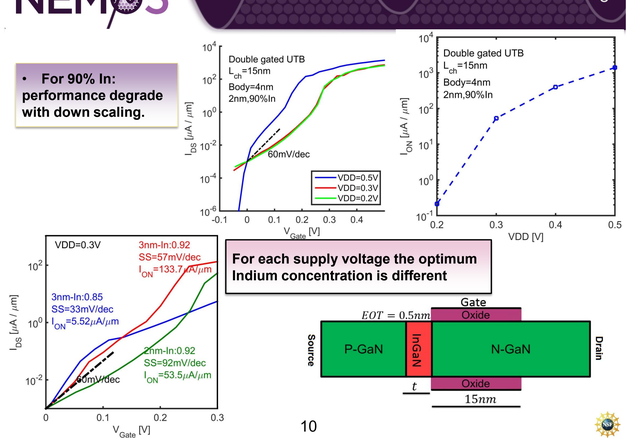
Optimizing the design of Nitride TFET



- **Increasing In concentration is not always beneficial.**
- **S.S lower limit is dominated by DOS in the quantum wells.**
- **Trade-off between polarization and density of notch states.**
- **Higher In concentration with thinner wells provides higher ON current**
- **ON/OFF > 1e4 possible with In as low as 40%**

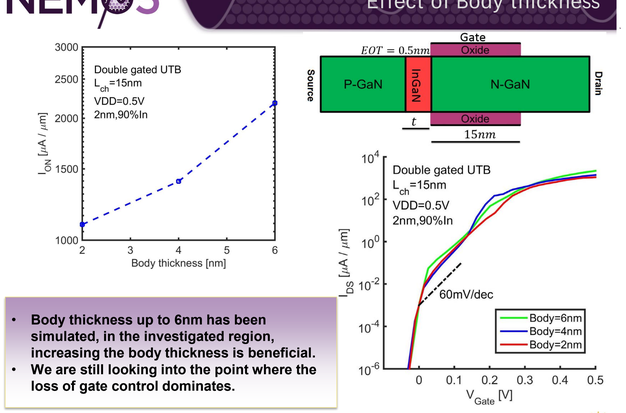
VDD down scaling

- **For 90% In: performance degrade with down scaling.**



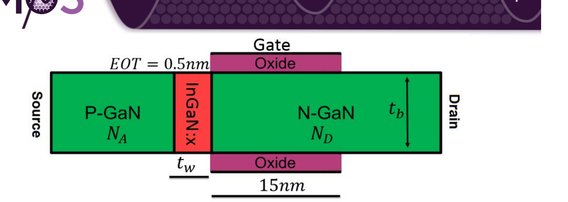
For each supply voltage the optimum Indium concentration is different

Effect of Body thickness



- **Body thickness up to 6nm has been simulated, in the investigated region, increasing the body thickness is beneficial.**
- **We are still looking into the point where the loss of gate control dominates.**

Next Steps



- **Optimize the TFET Design to maximize ON-current**
  - InN/InGaN
  - A wire has stronger confinement and has less quasi-bound states
  - Continue Low VDD optimization
- **Study:**
  - Continue Body thickness effect
  - Effect of alloy grading on performance
  - Channel scaling limit.
  - Influence of Defects

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*** These authors have contributed equally**

Theme 2383.002: Quantum Engineered Steep Transistor
Task D.2.4: Atomistic Carrier Transport Modeling for Steep Devices

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