SELF-HEATING EFFECTS IN SOI DEVICES AND GAN HEMTS

Dragica Vasileska, ASU

Thanks to …

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Outline

- Motivation
- Thermal Effects
- Previous Work Done in Thermal Modeling
- The ASU Model for Addressing Self-Heating
- Conclusions

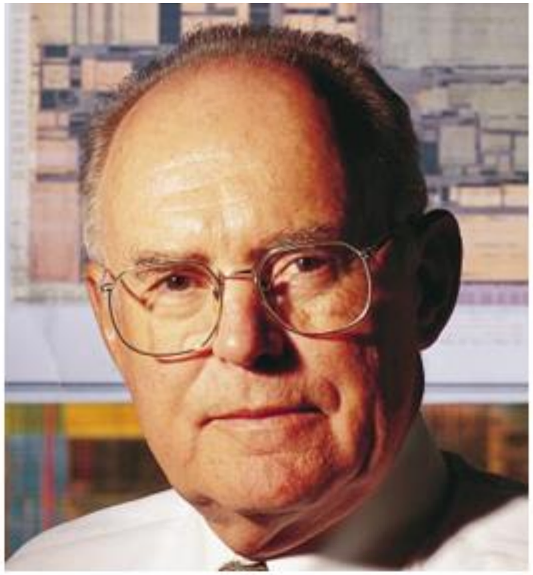
‘Painted Mosque’ In Tetovo, Republic of Macedonia

Motivation

Transistor Scaling

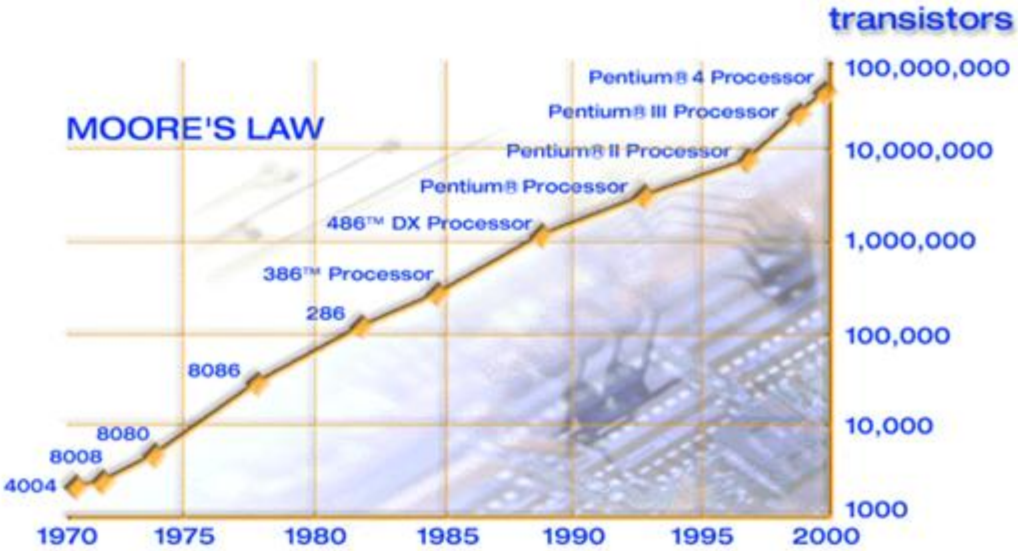
Thermal Effects and Scaling

Transistor Scaling: Moore's Law



Gordon Moore

"every 1.5 years complexity doubles"



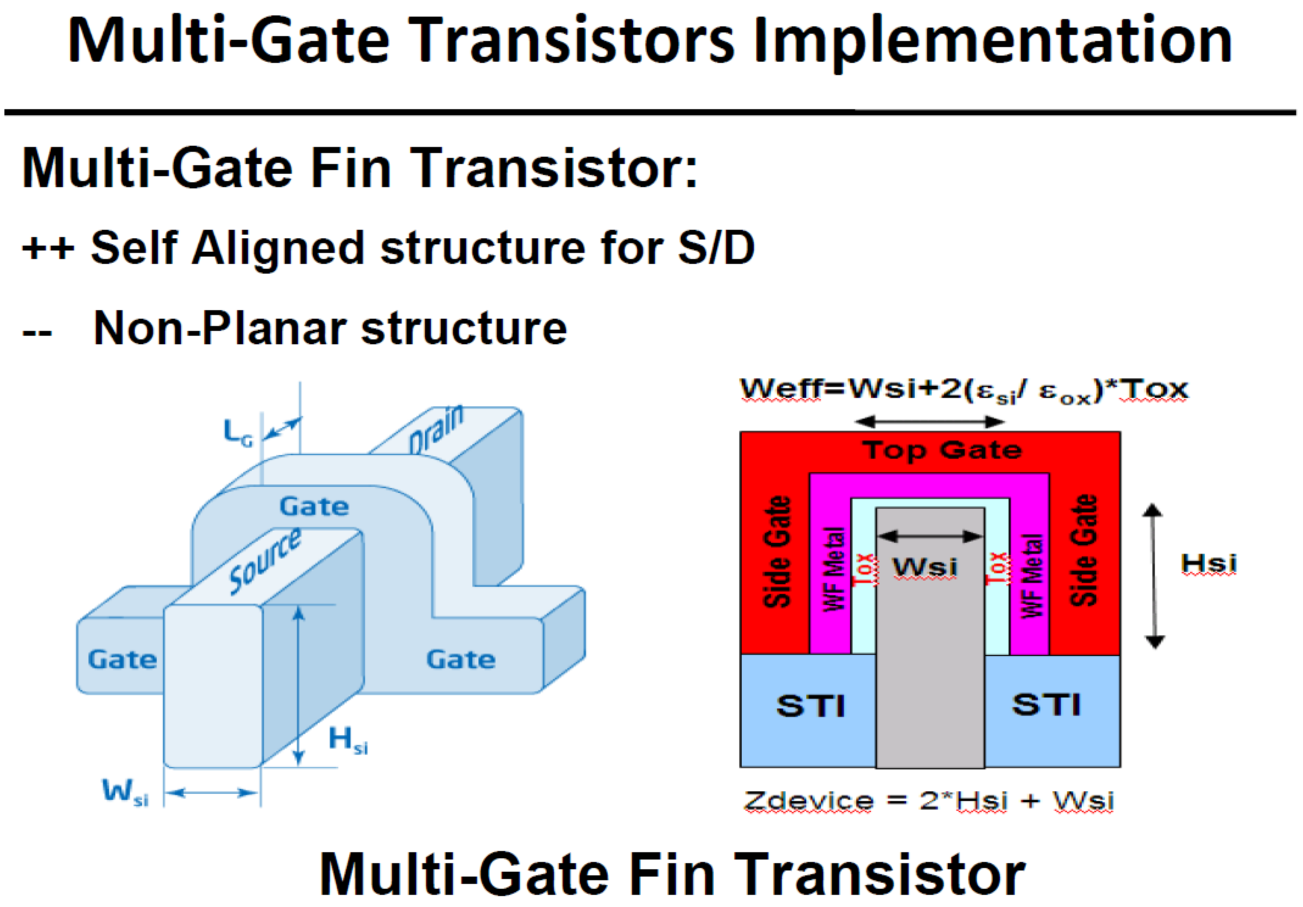
www.intel.com

Transistor Scaling: Dennard's Law

Geometry & Supply voltage	L_g, W_g T_{ox}, V_{dd}	K	**Scaling K : K=0.7 for example**
Drive current in saturation	I_d	K	$I_d = v_{sat} W_g C_o (V_g - V_{th})$ C_o: gate C per unit area $\rightarrow W_g (t_{ox}^{-1})(V_g - V_{th}) = W_g t_{ox}^{-1}(V_g - V_{th}) = KK^{-1}K = K$
I_d per unit W_g	$I_d/\mu m$	1	I_d per unit $W_g = I_d / W_g = 1$
Gate capacitance	C_g	K	$C_g = \varepsilon_o \varepsilon_{ox} L_g W_g / t_{ox} \rightarrow KK/K = K$
Switching speed	τ	K	$\tau = C_g V_{dd} / I_d \rightarrow KK/K = K$
Clock frequency	f	1/K	$f = 1/\tau = 1/K$
Chip area	A_{chip}	α	α: Scaling factor → **In the past, $\alpha > 1$ for most cases**
Integration (# of Tr)	N	α/K^2	$N \rightarrow \alpha/K^2$ **$= 1/K^2$, when $\alpha = 1$**
Power per chip	P	α	$fNCV^2/2 \rightarrow K^{-1}(\alpha K^{-2})K(K^1)^2 = \alpha$ **$= 1$, when $\alpha = 1$**

R. **Dennard**, et al., *IEEE Journal of Solid State Circuits*, vol. SC-9, no. 5, pp. 256-268, Oct. 1974.

More Moore …



Multi-Gate Transistors Implementation

Multi-Gate Fin Transistor:

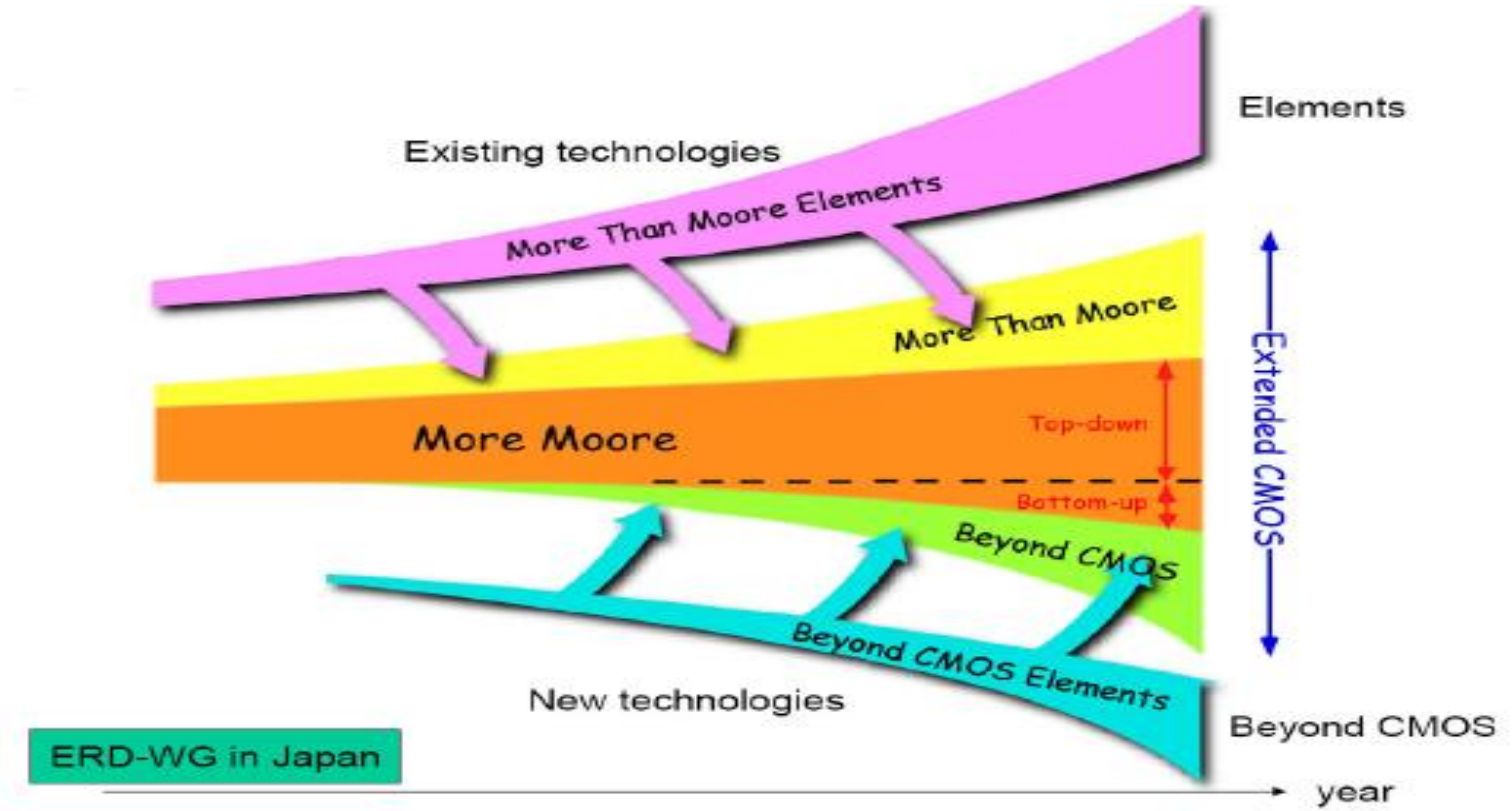
++ Self Aligned structure for S/D

-- Non-Planar structure

Multi-Gate Fin Transistor

www.intel.com

More Than Moore and Beyond CMOS

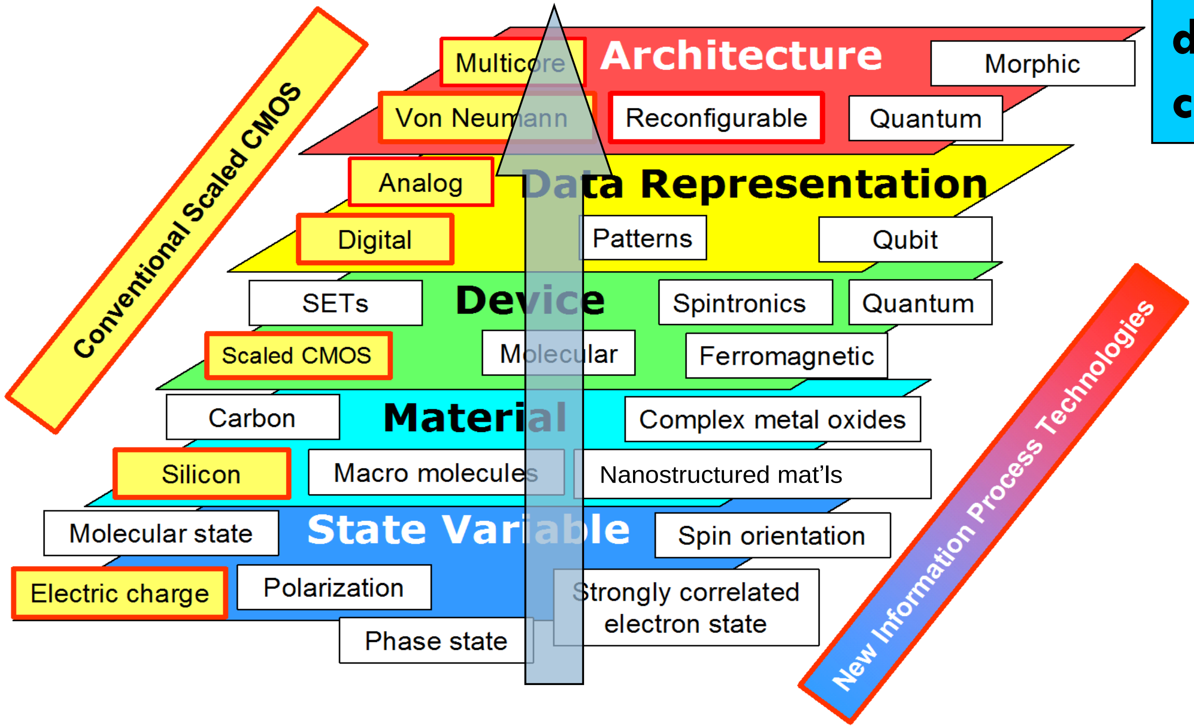


ITRS-ERD vision of the role of Beyond CMOS and More than Moore elements to form future extended CMOS platforms (2010).

www.itrs.com

2020 and Beyond …

Transversal Research Projects



Conventional Scaled CMOS

Architecture

Multicore

Von Neumann

Reconfigurable

Quantum

Morphic

Data Representation

Analog

Digital

Patterns

Qubit

Device

SETs

Scaled CMOS

Molecular

Spintronics

Quantum

Ferromagnetic

Material

Carbon

Silicon

Macro molecules

Complex metal oxides

Nanostructured mat'ls

State Variable

Molecular state

Electric charge

Polarization

Phase state

Strongly correlated electron state

Spin orientation

New Information Process Technologies

Multi-disciplinary cooperation

- **-System-technology interaction**
- **-Nanofabrication**
- **-Energy efficiency**
- **-Next switch**
- **-Universal memory**
- **-3D integration**
- **-Novel architectures**

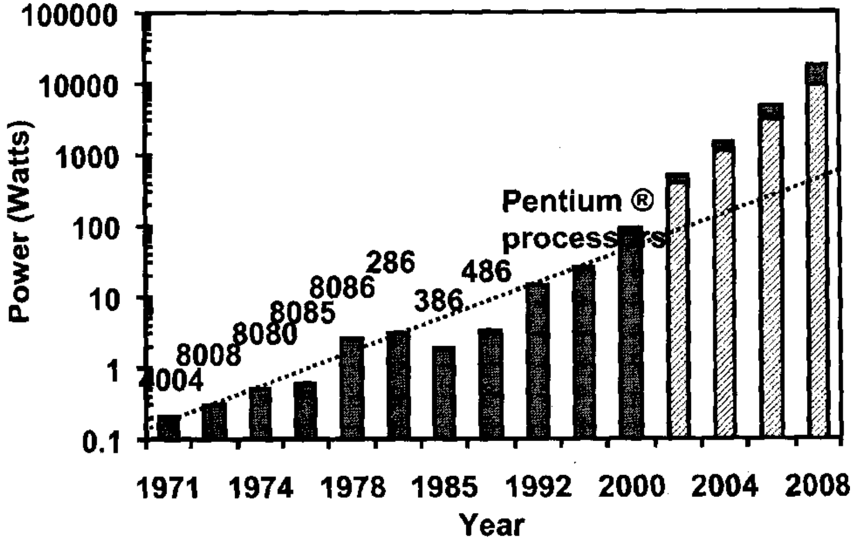
- Advanced component technology + advanced system design

- Beyond CMOS + advanced More than Moore integration with More Moore

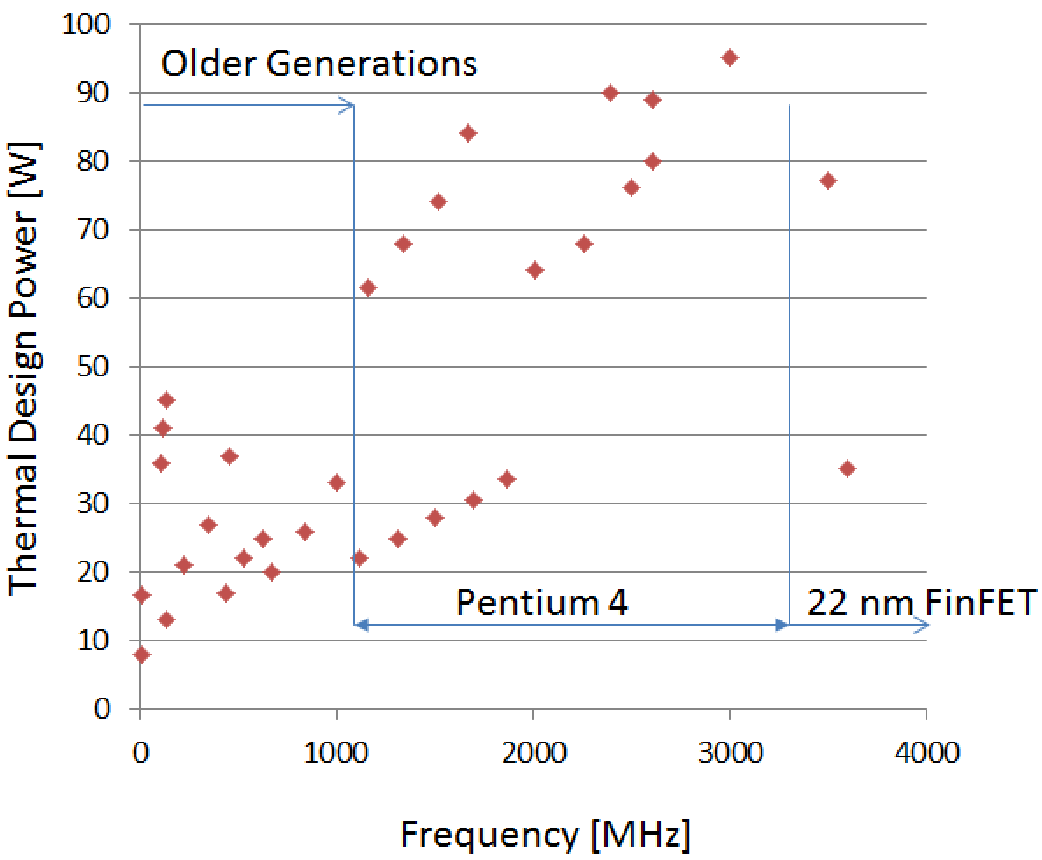
For systems 2020 and beyond

Thermal Effects and Scaling

- Intel VP Patrick Gelsinger (ISSCC 2001)
  - If scaling continues at present pace, by 2005, high speed processors would have power density of nuclear reactor, by 2010, a rocket nozzle, and by 2015, surface of sun.
  - “Business as usual will not work in the future.”
- Intel stock dropped 8% on the next day
- But attention to power is increasing



Thermal Design Power



- The **thermal design power (TDP)**, sometimes called **thermal design point**, refers to the maximum amount of power the cooling system in a computer is required to dissipate.

- For example, a laptop's CPU cooling system may be designed for a 20 watt TDP, which means that it can dissipate up to 20 watts of heat without exceeding the maximum junction temperature for the computer chip.

‘Church of St. Pantelejmon’, Skopje, Republic of Macedonia (12th century Byzantine church)

Thermal Effects

Electro-Thermal Effects

Thermo-Electric Effects

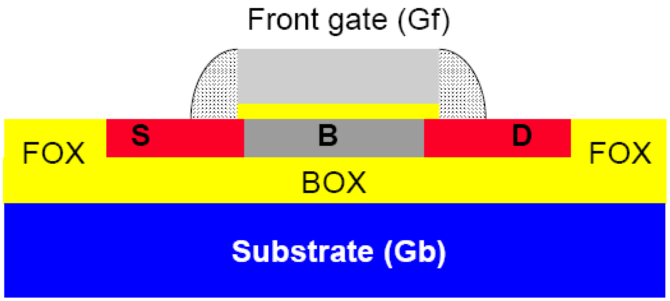
Analogy Between Electrical and Thermal Variables

Electro-Thermal Effects

- Joule Heating:
  - When an electric current flows through a solid or liquid with finite conductivity, electric energy is converted to heat through resistive losses in the material.
  - The heat is generated on the microscale when the conduction electrons transfer energy to the conductors atoms through collisions.
  - Joule heating is in some cases unwanted, and efforts are made to reduce it.
    - However, many applications rely on Joule heating;
      - some of these use the effect directly, such as cooking plates,
      - while other applications, such as microvalves for fluid control, use the effect indirectly through thermal expansion.

Why Electro-Thermal Effects in Devices?

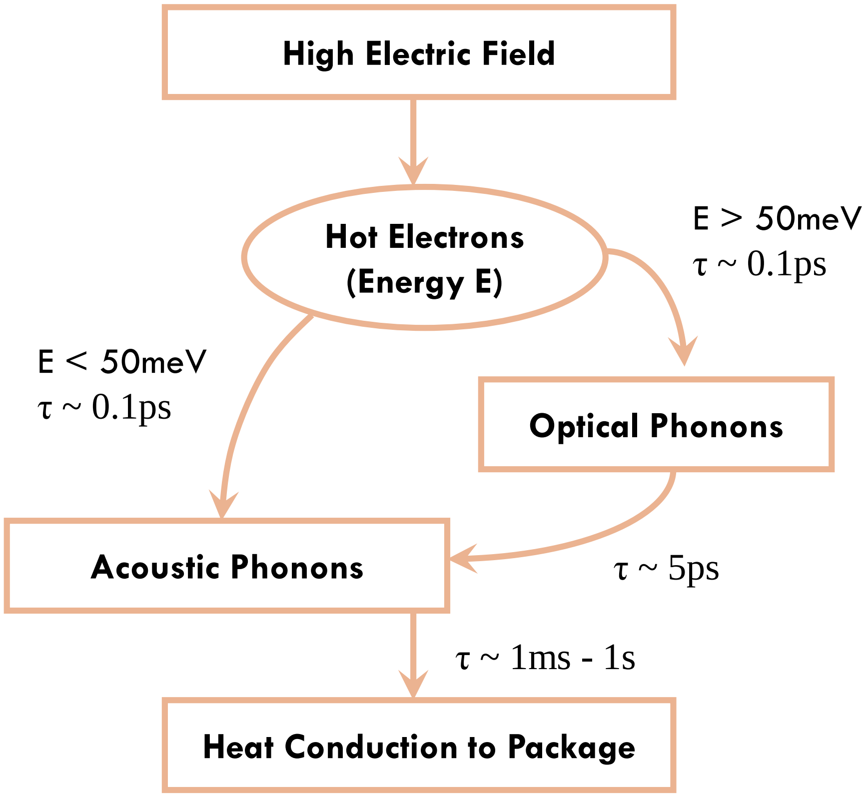
Reason for Observation of Self-Heating



Fully depleted (FD) body

Material	k_{th} (W/mK)
Si	148
Ge	60
Silicides	40
★ Si (10 nm)	13
★ SiO_2	1.4

MUSTs in the Theoretical Model



High Electric Field

Hot Electrons (Energy E)

E > 50meV $\tau \sim 0.1$ps

E < 50meV $\tau \sim 0.1$ps

Optical Phonons

$\tau \sim 5$ps

Acoustic Phonons

$\tau \sim 1$ms - 1s

Heat Conduction to Package

E. Pop, R.W Dutton, K.E. Goodson, "Analytic Band Monte Carlo Model for Electron Transport in Si Including Acoustic and Optical Phonon Dispersion," *J. Appl. Phys.* **96**, 4998 (2004)

Implementation of Electro-Thermal Effects in Commercial Simulators

- Silvaco ATLAS implements **Wachutka** model for lattice heating which accounts for:
  - Joule heating
  - Cooling due to carrier generation and recombination
  - Peltier and Thomson effects

$$C\frac{\partial T_L}{\partial t} = \nabla \bullet \left(\kappa \nabla T_L\right) + H$$

Heat capacitance per unit volume

Thermal conductivity

Heat generation

Wachutka, G.K., "Rigorous Thermodynamic Treatment of Heat Generation in Semiconductor Device Modeling", *IEEE Trans., Computer-Aided Design* Vol. 9, No. 11 (1990): 1141-1149.

Heat Generation Model

- In the past, the heat generation model was simply:

$$H = (J_n + J_p) \bullet E$$

- Presently:

$$H = \frac{|J_n|^2}{q\mu_n n} + \frac{|J_p|^2}{q\mu_p p} - \longrightarrow$$

Joule heating term

$$-T_L\left(J_n \nabla P_n\right) - T_L\left(J_p \nabla P_p\right) + \longrightarrow$$

Peltier and Joule-Thomson effects

$$+q(R-G)\left[T_L\left(\frac{\partial \phi_n}{\partial T_{n,p}}\right) - \phi_n - T_L\left(\frac{\partial \phi_p}{\partial T_{n,p}}\right) + \phi_p\right] - \longrightarrow$$

$$-T_L\left[\left(\frac{\partial \phi_n}{\partial T_{n,p}}\right) + P_n\right]\nabla \bullet J_n - T_L\left[\left(\frac{\partial \phi_p}{\partial T_{n,p}}\right) + P_p\right]\nabla \bullet J_p$$

Recombination and Generation heating and cooling terms

Wachutka, G.K., "Rigorous Thermodynamic Treatment of Heat Generation in Semiconductor Device Modeling", *IEEE Trans., Computer-Aided Design* Vol. 9, No. 11 (1990): 1141-1149.

Non-Isothermal Current Densities

- When SILVACO GIGA module is being invoked, the electron and hole current densities are modified to account for spatially varying lattice temperatures:

$$J_n = -q\mu_n n\left(\nabla\phi_n + P_n \nabla T_L\right)$$

$$J_p = -q\mu_p p\left(\nabla\phi_p + P_p \nabla T_L\right)$$

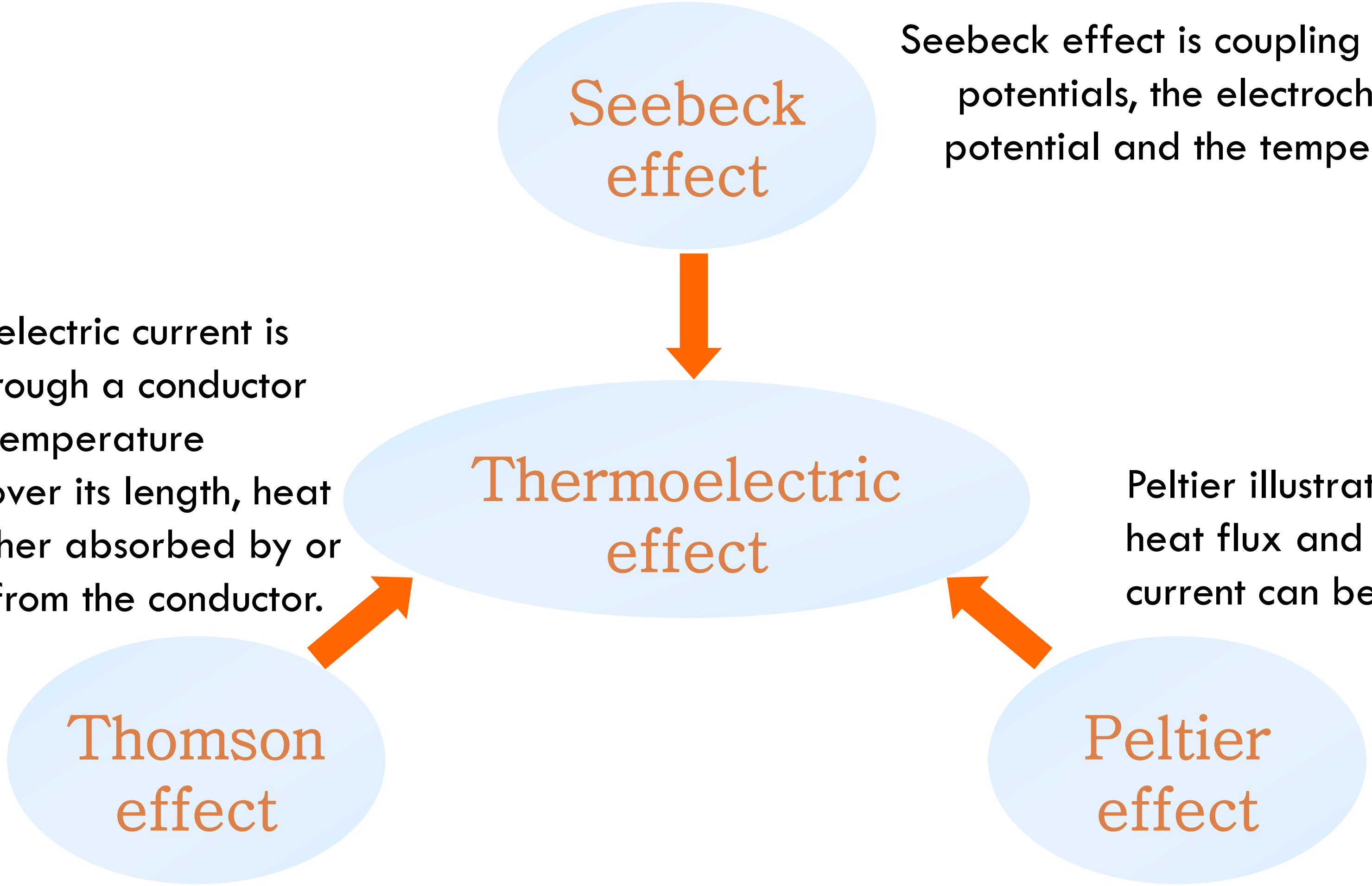
- Where P_n and P_p are absolute thermoelectric powers for electrons and holes and are calculated using:

$$P_n = -\frac{k_B}{Q}\left(\frac{5}{2} + \ln\left(\frac{N_c}{n}\right) + KSN + \zeta_n\right)$$

$$P_p = \frac{k_B}{Q}\left(\frac{5}{2} + \ln\left(\frac{N_v}{p}\right) + KSP + \zeta_p\right)$$

Wachutka, G.K., “Rigorous Thermodynamic Treatment of Heat Generation in Semiconductor Device Modeling”, *IEEE Trans., Computer-Aided Design* Vol. 9, No. 11 (1990): 1141-1149.

Thermo-Electric Effects



Seebeck effect

Thermoelectric effect

Thomson effect

Peltier effect

Seebeck effect is coupling of two potentials, the electrochemical potential and the temperature.

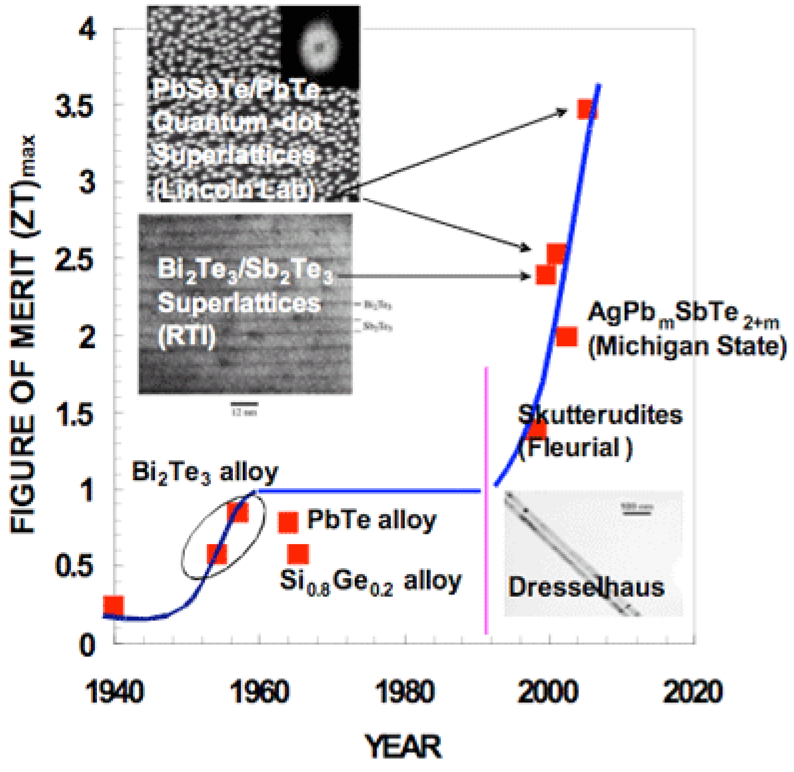
When an electric current is passed through a conductor having a temperature gradient over its length, heat will be either absorbed by or expelled from the conductor.

Peltier illustrated that heat flux and electrical current can be coupled.

Thermo-Electric Effects Explained

- When any two metals are connected together, a voltage is developed which is a function of the temperatures of the junctions and (mainly) the difference in temperatures.
- It was later found that the Seebeck voltage is the sum of two effects: the ***Peltier effect***, and the ***Thompson effect***.
  - The ***Peltier effect*** explains a voltage generated in a junction of two metal wires.
  - The ***Thompson effect*** explains a voltage generated by the temperature gradient in the wires.

Peltier Effect: ZT Factor Over the Years



$$ZT = S^2T\,\sigma/\kappa$$

- ❑ The ZT of a thermoelectric material is a dimensionless unit that is used to compare the efficiencies of various materials.
- ❑ ZT is determined by three physical parameters:
  - the thermopower S (also known as Seebeck factor),
  - the electrical conductivity σ, the thermal conductivity $k = k_e + k_{ph}$, where the k_e and k_{ph} are the thermal conductivities of electrons and phonons, respectively,
  - and the absolute temperature T

Analogy Between Electrical and Thermal Variables

$$J = \sigma E = -\sigma \frac{dV}{dx} \therefore current\ density$$

$$F = -\kappa \frac{dT}{dx} \therefore heat\ flux$$

$$\begin{cases} J \Leftrightarrow F \\ V \Leftrightarrow T \\ \sigma \Leftrightarrow \kappa \end{cases}$$

Skopje, Capitol of Republic of Macedonia

Previous Work Done in Thermal Modeling

Previous Work in Thermal Modeling

- Mostly, the previous work performed and related to thermal modeling can be split into:
  - Solutions of the Phonon Boltzmann Transport Equation
  - Analysis of self-heating effects in devices

Phonon BTE Solvers

- ***Peterson*** performed a Monte Carlo Simulation for phonons in the Debye approximation and using single relaxation time
- ***Mazumder and Majumdar*** followed Peterson approach but included the dispersion relation and the different acoustic polarization branches
  - Limit: The N and the U processes are not treated separately although they do not contribute the same way to the thermal conductivity

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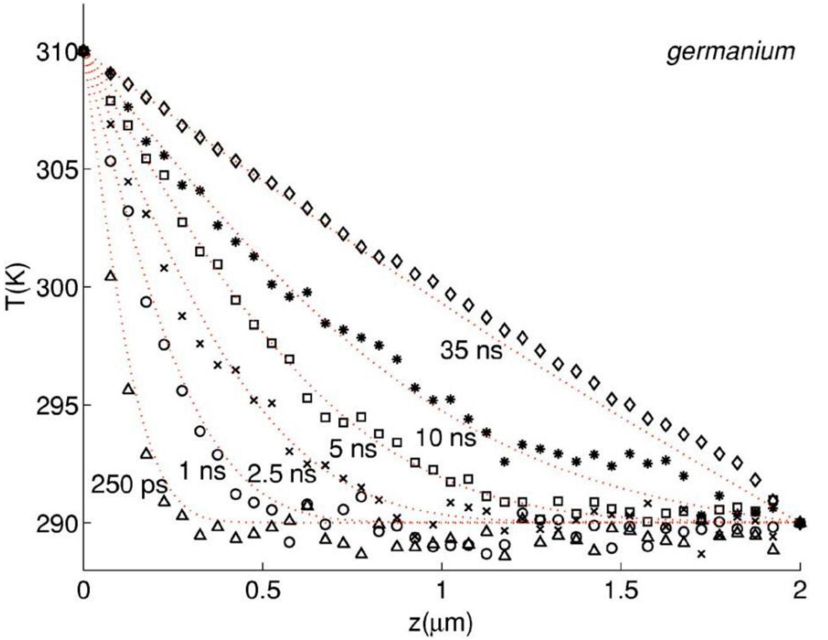
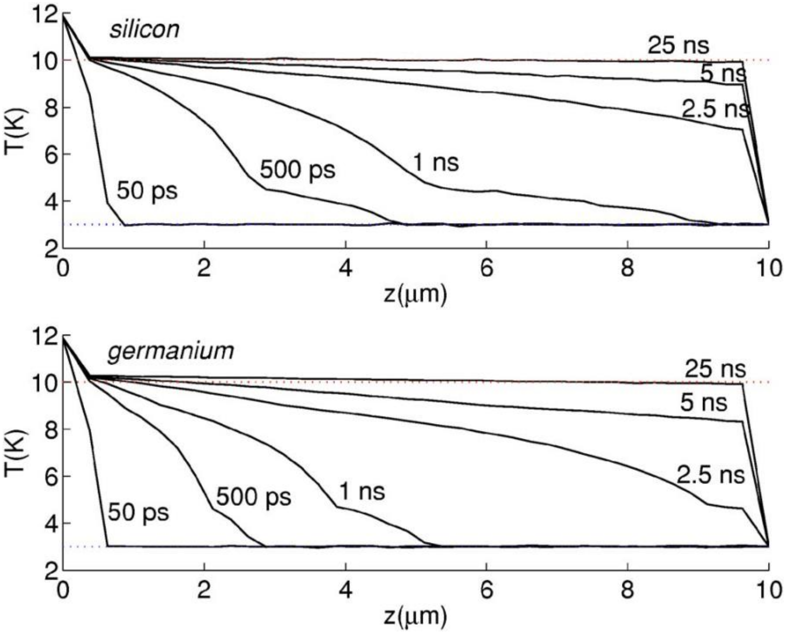
* Peterson, R. B. (1994). "Direct Simulation of Phonon-Mediated Heat Transfer in a Debye Crystal." *Journal of Heat Transfer*, Vol. 116(4), pp. 815-822.

* Mazumder, S. and Majumdar, A. (2001). "Monte Carlo Study of Phonon Transport in Solid Thin Films Including Dispersion and Polarization." *Journal of Heat Transfer*, Vol.123(4), pp. 749-759.

Phonon BTE Solvers, Cont'd

- ***Lacroix*** further generalized the model:
  - By incorporation of N and U processes
  - Transient conditions are also being considered





Lacroix, D., Joulain, K. and Lemonnier, D. (2005). "Monte Carlo Transient Phonon Transport in Silicon and Germanium at Nanoscales." *Physical Review B*, Vol. 72(6), pp. 064305/1-11.

Modeling Self-Heating in Devices

- Work of ***Eric Pop, Goodson, Robert Dutton***
  - Non-parabolic model with analytical phonon dispersion
  - study heat transfer and energy conversion processes at nanoscales. Applications include semiconductor devices and packaging, thermoelectric and photonic energy conversion, and microfluidic heat exchangers.
- Work of ***Kelsall and Sadi***
  - Nanoscale transistors, GaN HEMTs

E. Pop, R.W Dutton, K.E. Goodson, "Analytic Band Monte Carlo Model for Electron Transport in Si Including Acoustic and Optical Phonon Dispersion," *J. Appl. Phys.* **96**, 4998 (2004)


Popova Sapka Ski Resort, Tetovo, Republic of Macedonia

The ASU Model to Addressing Self-Heating

Theoretical Model

Application of the Model to Modeling of:

- FD SOI Devices, Dual Gate Structures, SOD and SOAIN Devices
- Nanowire Transistors
- GaN HEMTs

Theoretical Model

$$\left(\frac{\partial}{\partial t}+v_e(\mathrm{k})\cdot\nabla_r+\frac{e}{\hbar}E(\mathrm{r})\cdot\nabla_k\right)f=\sum_{\mathrm{q}}\left\{W_{e,\mathrm{q}}^{\mathrm{k+q}\to\mathrm{k}}+W_{a,-\mathrm{q}}^{\mathrm{k+q}\to\mathrm{k}}-W_{e,-\mathrm{q}}^{\mathrm{k}\to\mathrm{k+q}}-W_{a,\mathrm{q}}^{\mathrm{k}\to\mathrm{k+q}}\right\}$$

$$\left(\frac{\partial}{\partial t}+v_p(\mathrm{q})\cdot\nabla_r\right)g=\sum_{\mathrm{k}}\left\{W_{e,\mathrm{q}}^{\mathrm{k+q}\to\mathrm{k}}-W_{a,\mathrm{q}}^{\mathrm{k}\to\mathrm{k+q}}\right\}+\left(\frac{\partial g}{\partial t}\right)_{p-p}$$

J. Lai and A. Majumdar, “Concurent thermal and electrical modeling of submicrometer silicon devices”, J. Appl. Phys. , Vol. 79, 7353 (1996).

$$C_{LO}\frac{\partial T_{LO}}{\partial t}=\frac{3nk_B}{2}\left(\frac{T_e-T_L}{\tau_{e-LO}}\right)+\frac{nm^*v_d^2}{2\tau_{e-LO}}-C_{LO}\left(\frac{T_{LO}-T_A}{\tau_{LO-A}}\right),$$

$$C_A\frac{\partial T_A}{\partial t}=\nabla\cdot\left(k_A\nabla T_A\right)+C_{LO}\left(\frac{T_{LO}-T_A}{\tau_{LO-A}}\right)+\frac{3nk_B}{2}\left(\frac{T_e-T_L}{\tau_{e-L}}\right).$$

K. Raleva, D. Vasileska, S. M. Goodnick and M. Nedjalkov, Modeling Thermal Effects in Nanodevices, IEEE Transactions on Electron Devices, vol. 55, issue 6, pp. 1306-1316, June 2008.

Theoretical Model …

Energy gain from the electrons

Energy loss to acoustic phonons

$$C_{LO}\frac{\partial T_{LO}}{\partial t}=\frac{3nk_B}{2}\left(\frac{T_e-T_L}{\tau_{e-LO}}\right)+\frac{nm^*v_d^2}{2\tau_{e-LO}}-C_{LO}\left(\frac{T_{LO}-T_A}{\tau_{LO-A}}\right),$$

$$C_A\frac{\partial T_A}{\partial t}=\nabla\cdot\left(k_A\nabla T_A\right)+C_{LO}\left(\frac{T_{LO}-T_A}{\tau_{LO-A}}\right)+\frac{3nk_B}{2}\left(\frac{T_e-T_L}{\tau_{e-L}}\right).$$

Heat Diffusion

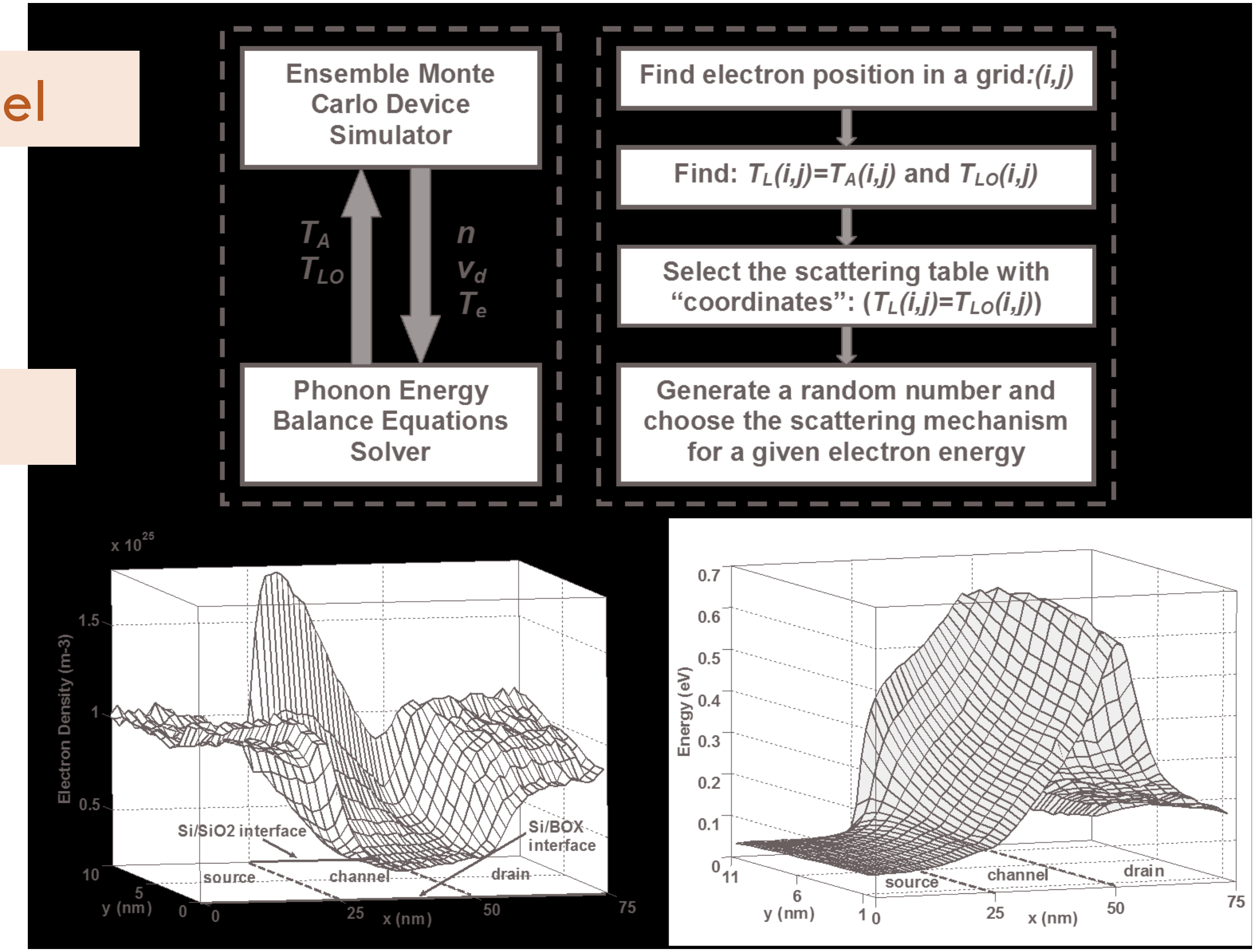
Gain term due to optical phonons

Gain term due to electrons (omitted if acoustic phonon scattering is treated as elastic scattering process)

Theoretical Model …

Particle Model

Fluid Model



Ensemble Monte Carlo Device Simulator

Phonon Energy Balance Equations Solver

Find electron position in a grid:(i,j)

Find: $T_L(i,j)=T_A(i,j)$ and $T_{LO}(i,j)$

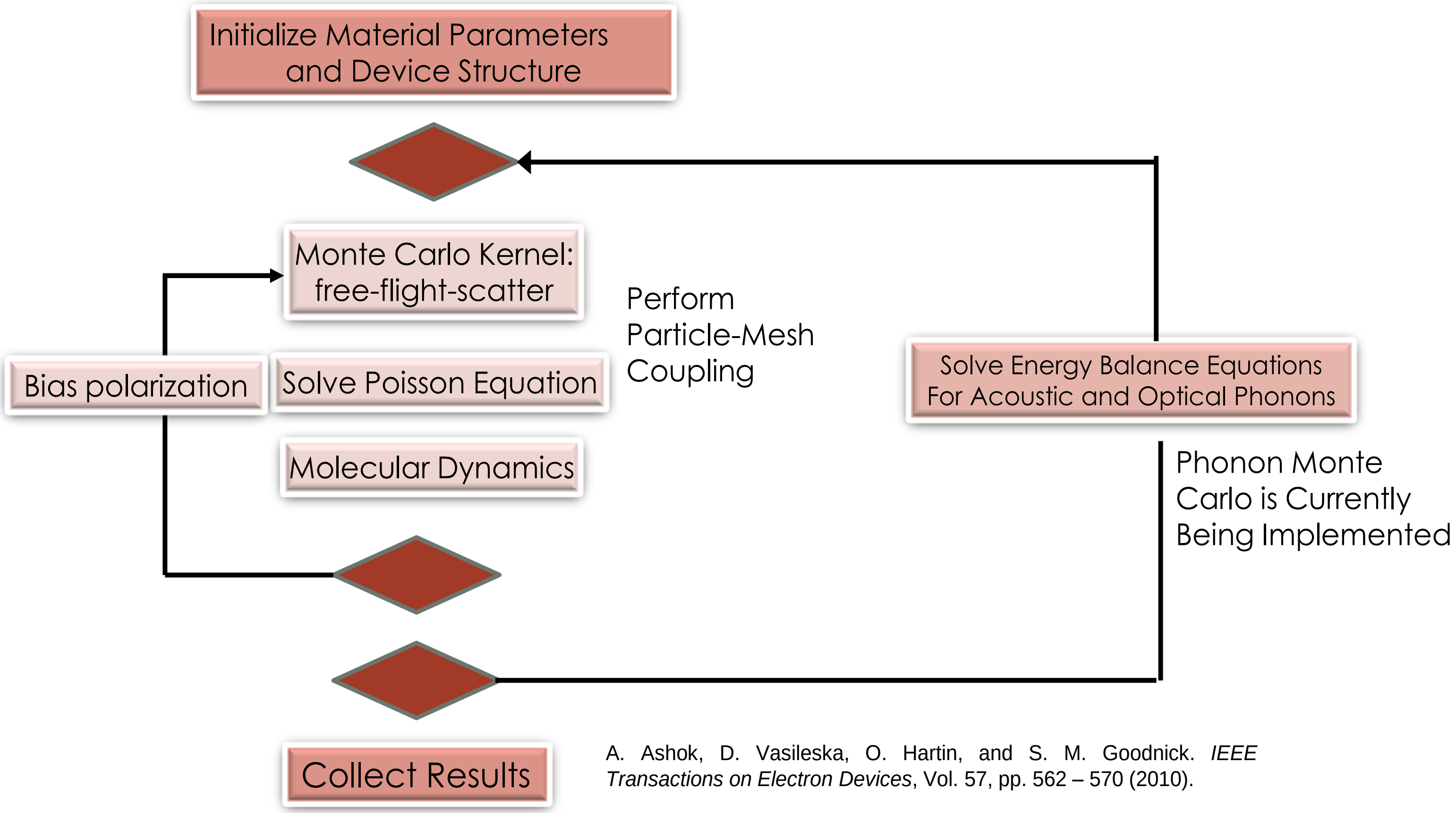
Select the scattering table with “coordinates”: $(T_L(i,j)=T_{LO}(i,j))$

Generate a random number and choose the scattering mechanism for a given electron energy

K. Raleva, D. Vasileska, S. M. Goodnick and M. Nedjalkov, Modeling Thermal Effects in Nanodevices, IEEE Transactions on Electron Devices, vol. 55, issue 6, pp. 1306-1316, June 2008.

Theoretical Model …

- Gummel cycles



Initialize Material Parameters and Device Structure

Monte Carlo Kernel: free-flight-scatter

Bias polarization

Solve Poisson Equation

Molecular Dynamics

Perform Particle-Mesh Coupling

Solve Energy Balance Equations For Acoustic and Optical Phonons

Phonon Monte Carlo is Currently Being Implemented

Collect Results

A. Ashok, D. Vasileska, O. Hartin, and S. M. Goodnick. *IEEE Transactions on Electron Devices*, Vol. 57, pp. 562 – 570 (2010).

K. Raleva, D. Vasileska, S. M. Goodnick and M. Nedjalkov, Modeling Thermal Effects in Nanodevices, IEEE Transactions on Electron Devices, vol. 55, issue 6, pp. 1306-1316, June 2008.

Theoretical Model: Thermal Conductivity

- Solid transmit thermal energy by two modes , either one of which, or both, may operate.

  1. In all solids , energy may be transferred by means of elastic vibrations of the lattice moving through the crystal in the form of waves .
  2. In some solids , notably metals , free electrons moving through the lattice also carry energy in a manner similar to thermal conduction by a True gas phase .

Thermal Conductivity: $k = k_e + k_p$

Thermal Conductivity

$$k_p = \frac{1}{3} C \; v \; l$$

Phonon *mfp*

Specific heat

Sound velocity

Specific heat :

If $T > \Theta$, $C \sim \textit{constant}$

If $T << \Theta$, $C \sim T^{d}$ (d: dimension)

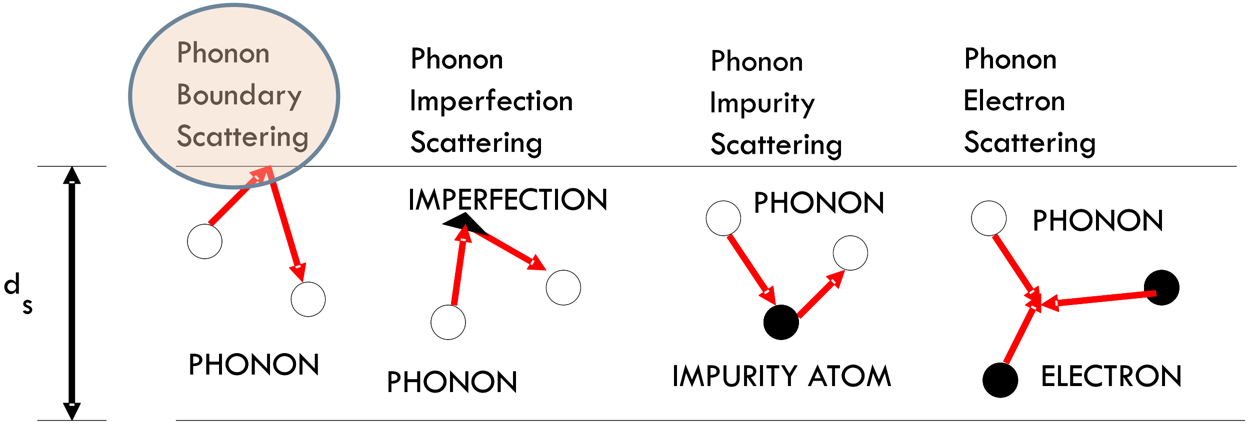
Mean free path:

$$\frac{1}{l} = \frac{1}{l_{st}} + \frac{1}{l_{um}}$$

Static scattering (phonon -- defect, boundary): $l_{st} \sim \textit{constant}$

Umklapp phonon scattering: $l_{um} \sim e^{\Theta / T}$

Thermal Conductivity of Thin Films

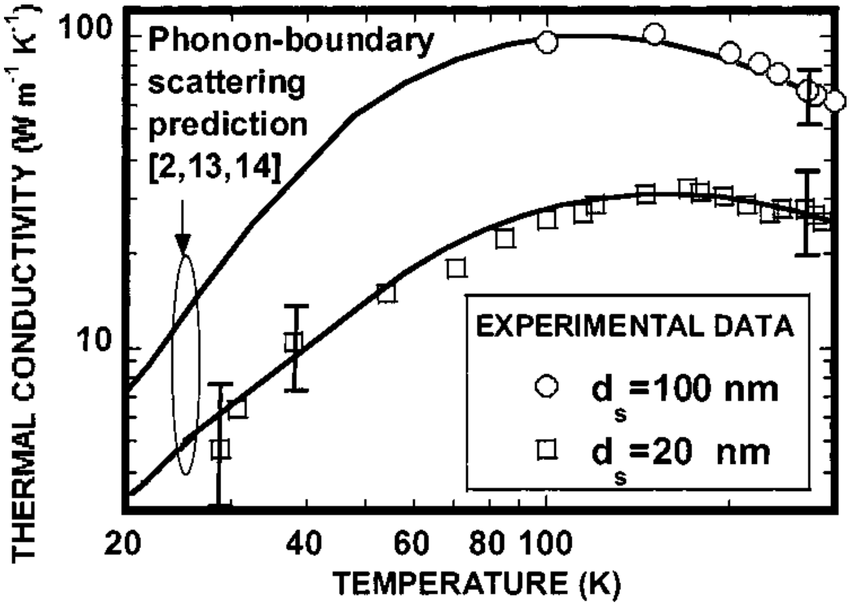


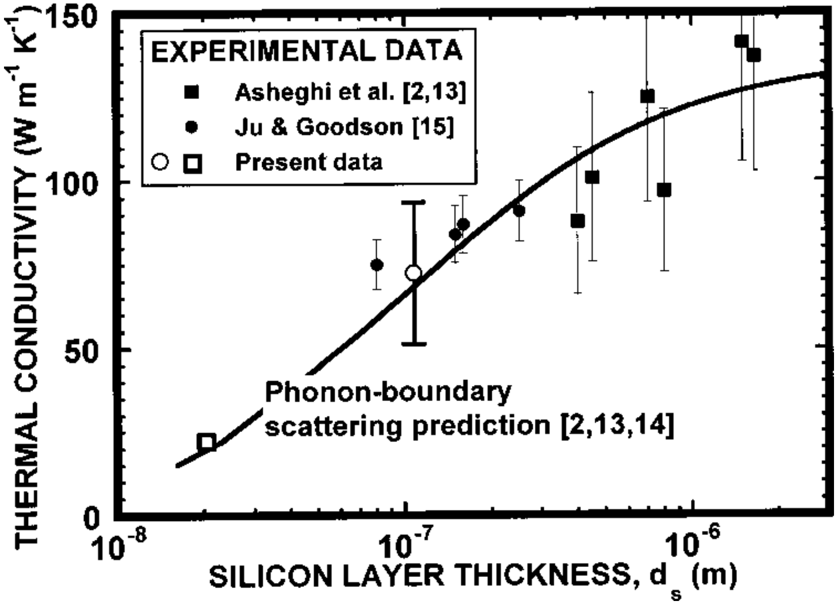
Phonon Boundary Scattering

Phonon Imperfection Scattering

Phonon Impurity Scattering

Phonon Electron Scattering





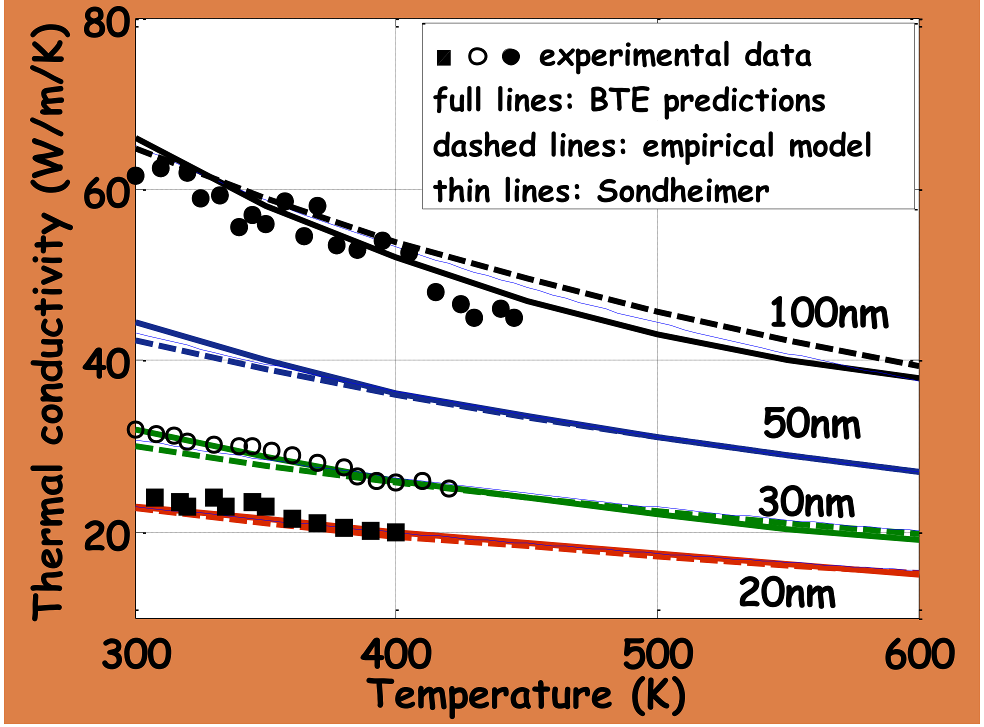
Analytical Model for Thin Films

$$\kappa(z)=\kappa_0(T)\int_0^{\pi/2}\sin^3\theta\left\{1-\exp\left(-\frac{a}{2\lambda(T)\cos\theta}\right)\cosh\left(\frac{a-2z}{2\lambda(T)\cos\theta}\right)\right\}d\theta$$

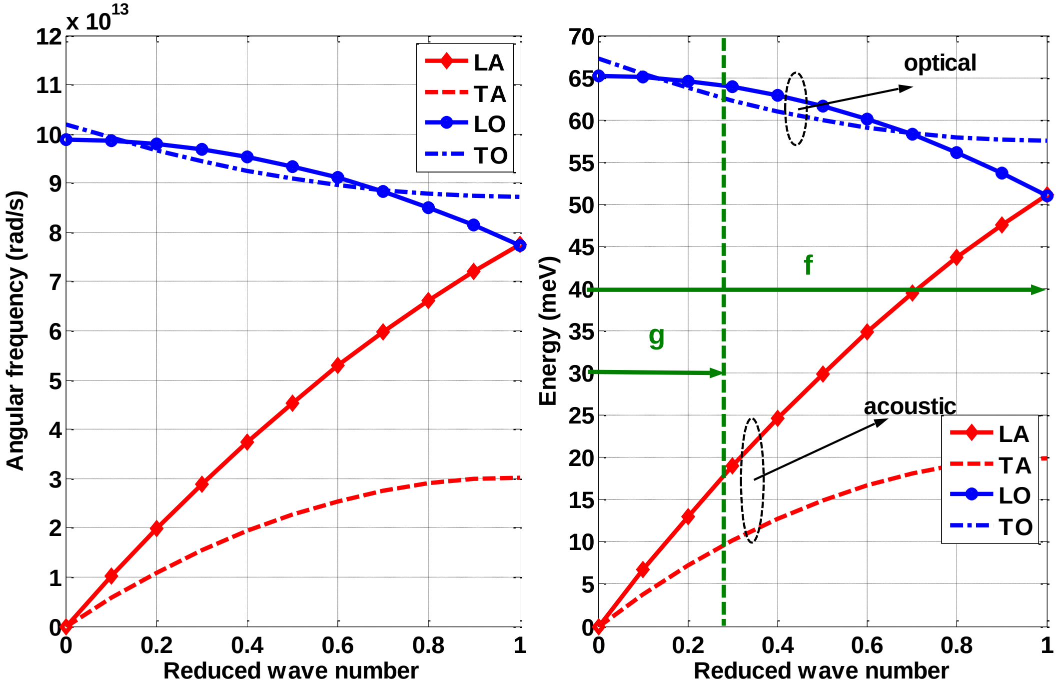
$$\lambda(T)=\lambda_0(300/T)$$

$$\kappa_0(T)=\frac{135}{a+bT+cT^2}\quad \text{W/m/K}$$

- E. H. Sondheimer, “The Mean Free Path of Electrons in Metals”, Advances in Physics, Vol. 1, no. 1, Jan. 1952, reprinted in Advances in Physics, Vol. 50, pp. 499-537, 2001.
- M. Asheghi,., M. N. Touzelbaev., K. E. Goodson, Y. K. Leung, and S. S. Wong., “Temperature Dependent Thermal Conductivity of Single-Crystal Silicon Layers in SOI Substrates,” ASME Journal of Heat Transfer, Vol.120, pp. 30-33, 1998.



Theoretical Model – Phonon Dispersions



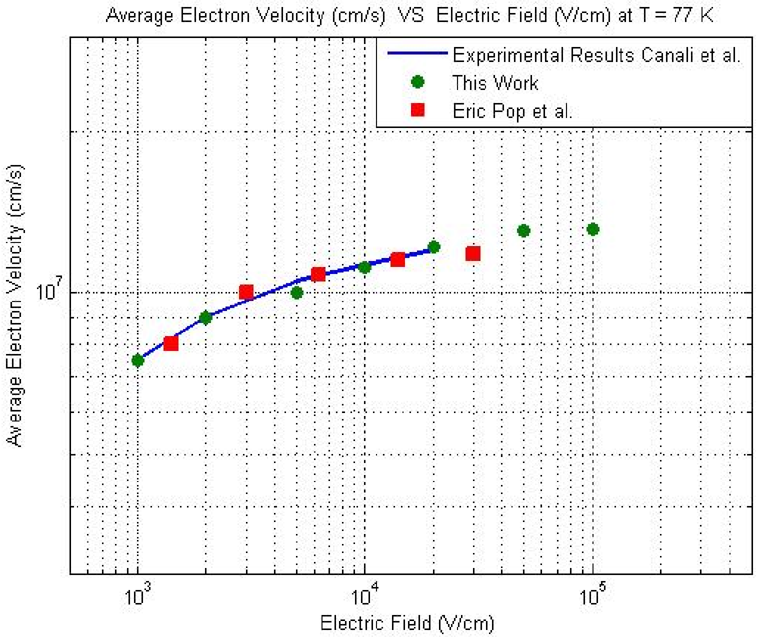
QUADRATIC FIT TO PHONON DISPERSIONS

	ω_o (10^{13} rad/s)	υ_s (10^5 cm/s)	c 10^{-3} cm^2/s
LA	0.00	9.01	-2.00
TA	0.00	5.23	-2.26
LO	9.88	0.00	-1.60
TO	10.20	-2.57	1.11

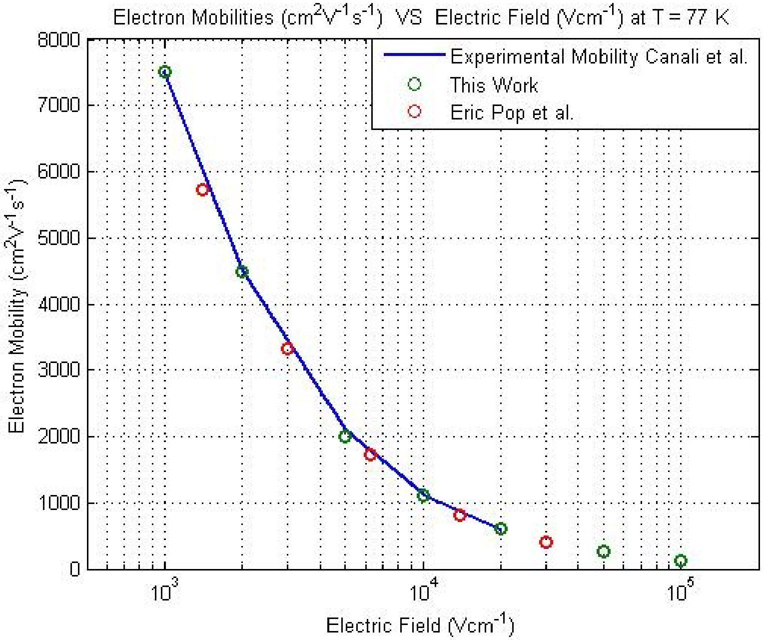
E. Pop, R.W Dutton, K.E. Goodson, "Analytic Band Monte Carlo Model for Electron Transport in Si Including Acoustic and Optical Phonon Dispersion," *J. Appl. Phys.* **96**, 4998 (2004)

Phonon Dispersions: Proof of Concept

Drift Velocity in Silicon at T=77K

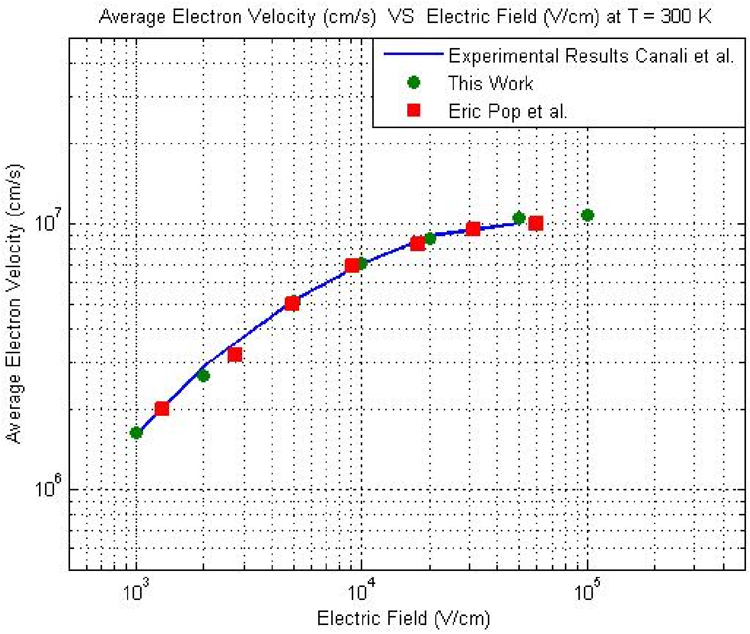


Mobility at T=77K

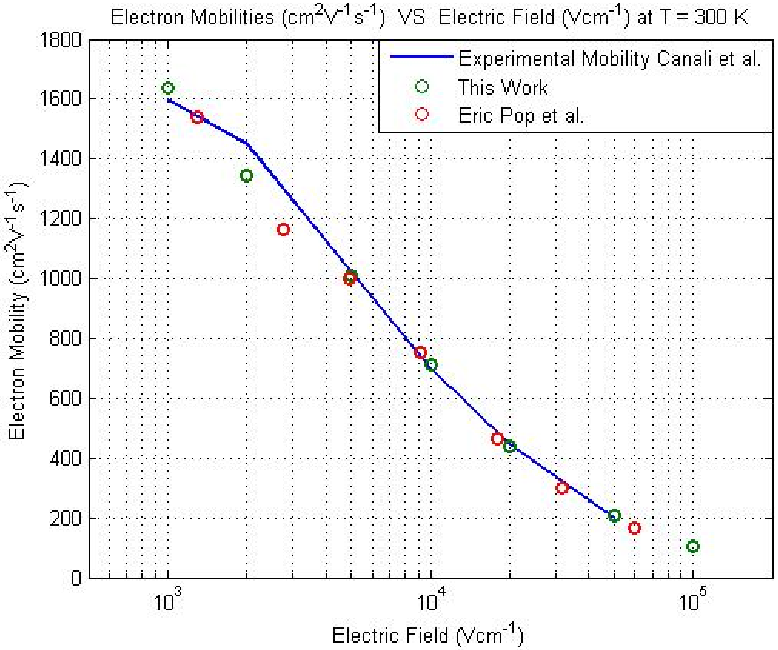


Phonon Dispersions: Proof of Concept

Drift Velocity in Silicon at T=300K



Mobility at T=300K

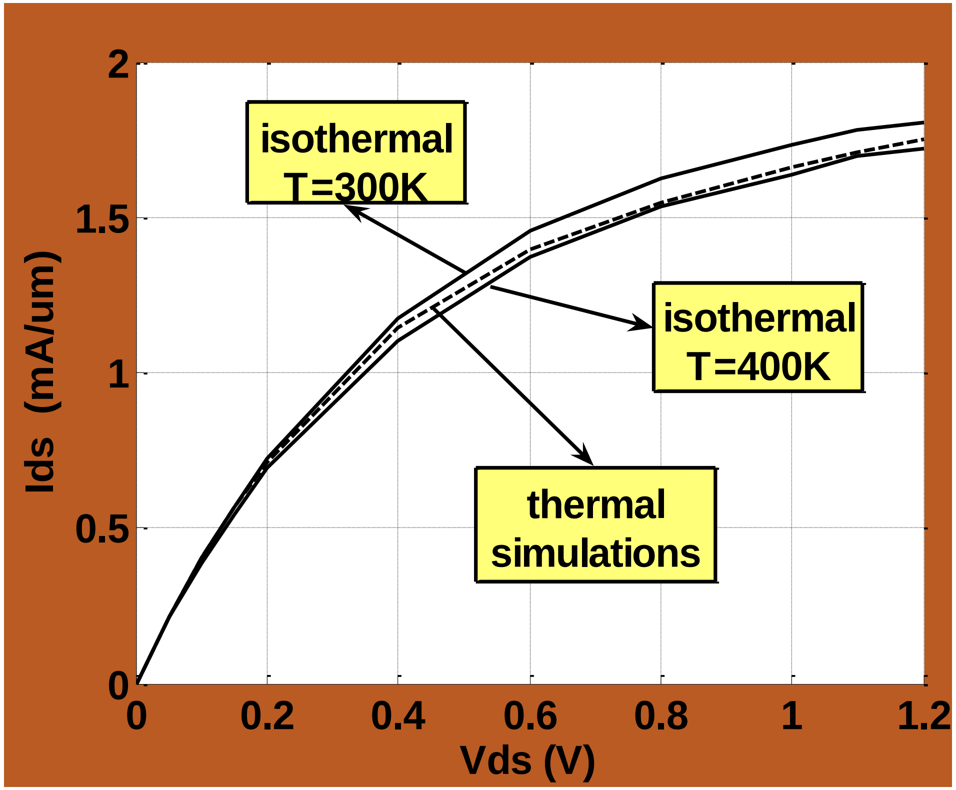


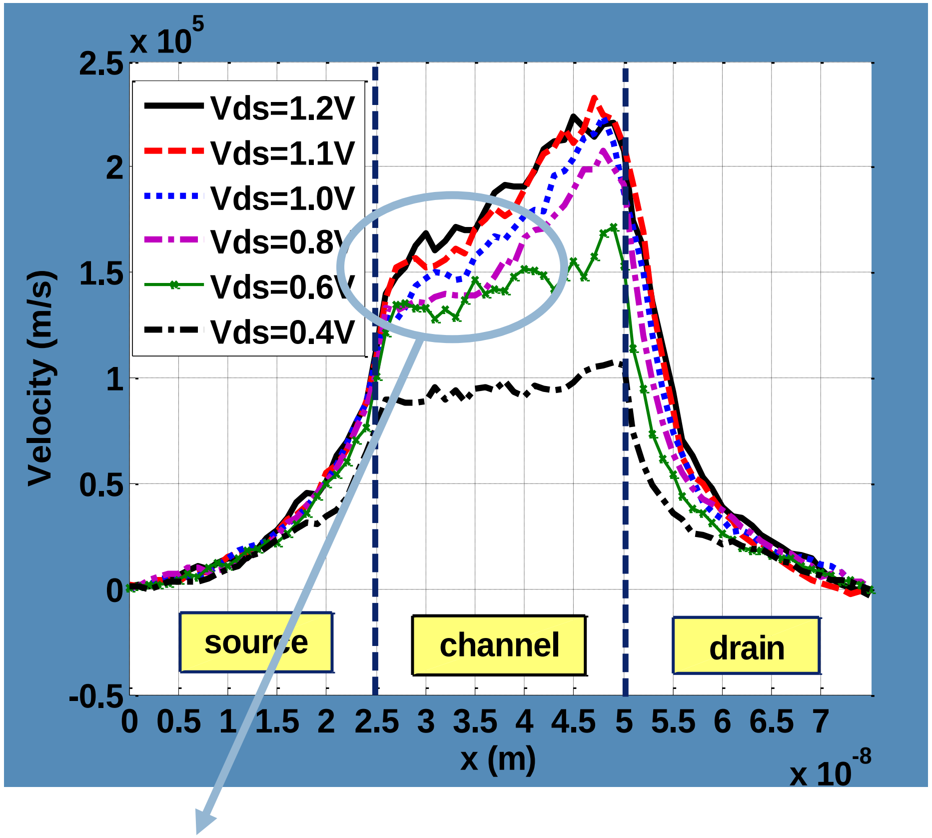
FULLY DEPLETED SOI DEVICES

Lake Powell, Arizona

Simulation Results: FD SOI Devices

- 25 nm Channel Length Device

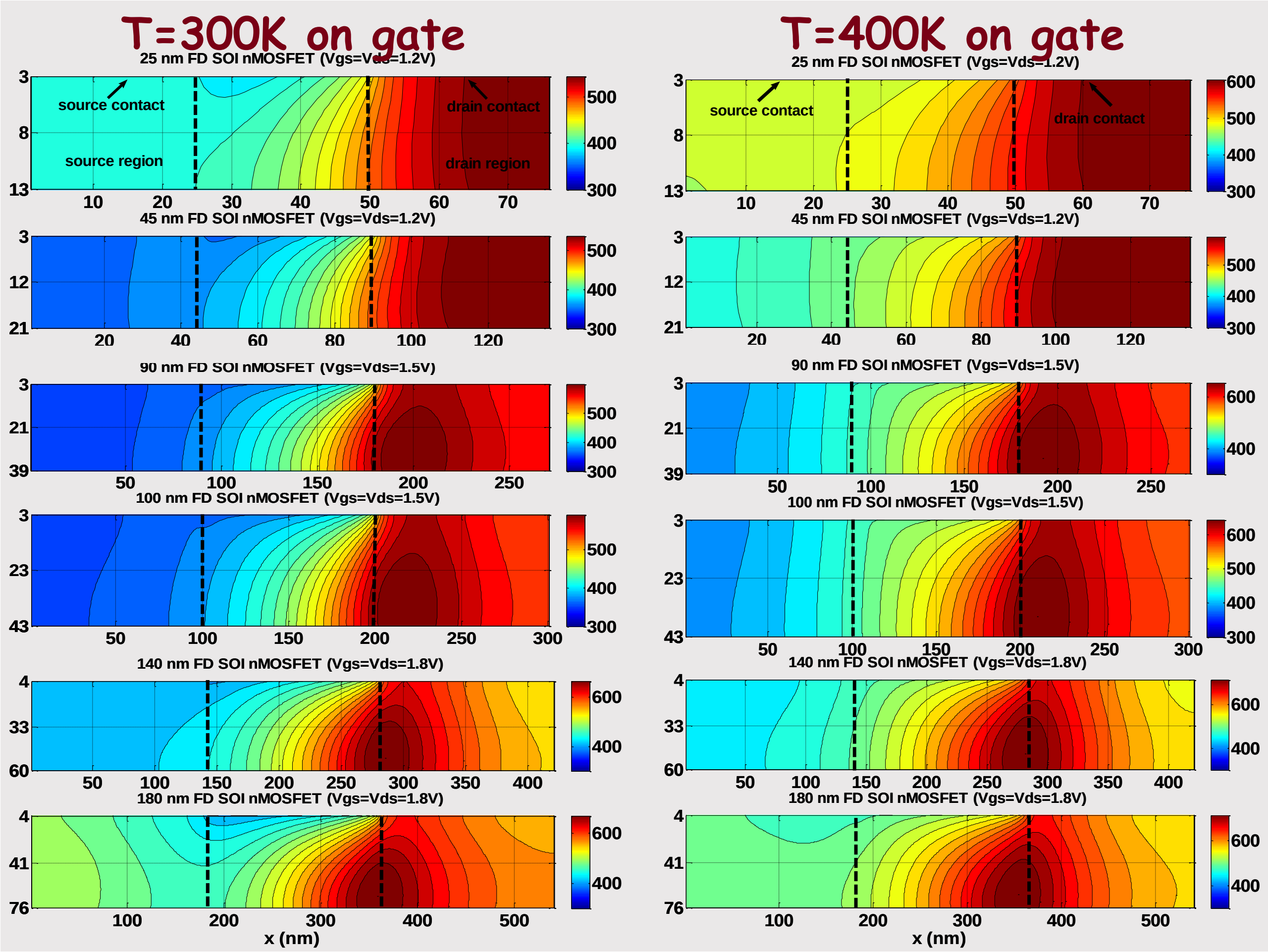




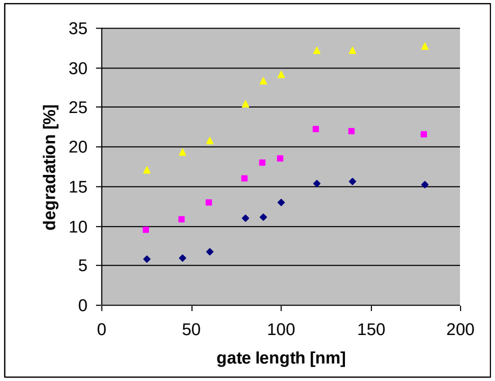
K. Raleva, D. Vasileska, S. M. Goodnick and T. Dzekov, "Modeling thermal effects in nano-devices", *Journal of Computational Electronics, DOI 10.1007/s10825-008-0189-3 © Springer Science+Business Media LLC 2008, J. Computational Electronics*, Vol. 7, pp. 226-230 (2008).

Carriers are in the velocity overshoot

Heat Dissipation Across Technology Nodes



Parameter is the temperature on the Gate Electrode.

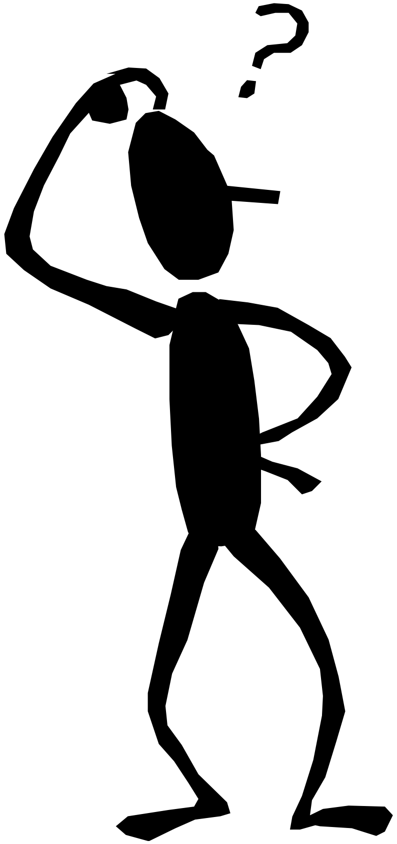


Neumann Boundary Conditions are imposed at the Artificial Boundaries and the Source and Drain contacts

K. Raleva, D. Vasileska, S. M. Goodnick and M. Nedjalkov, IEEE Transactions on Electron Devices, vol. 55, issue 6, pp. 1306-1316, June 2008.

Can We Lower Self-Heating Effects?

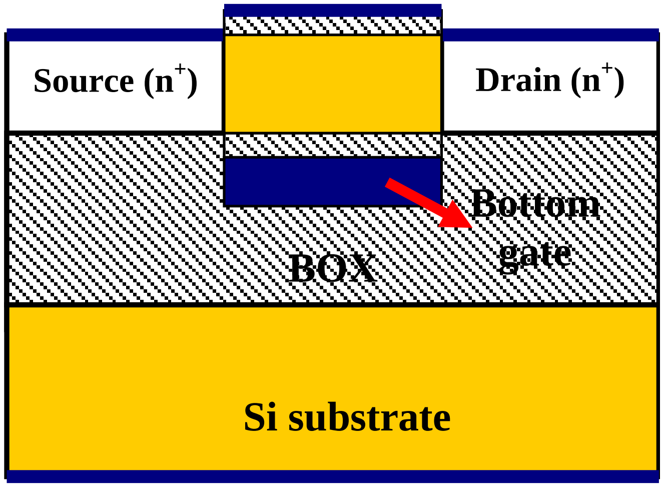
- Dual-Gate Devices
- SOI vs. SOD vs. SOAIN

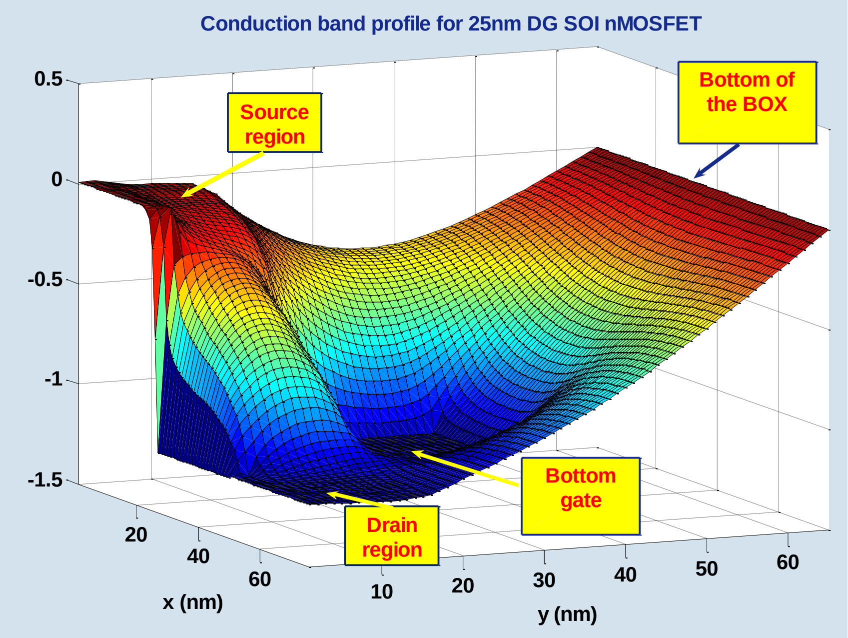


S.M. Goodnick, D. Vasileska, K. Raleva, “Is Dual Gate Device Better From a Thermal Perspective?”, *Proceedings of 2008 SISPAD Conference*, pp. 125 - 128.

K. Raleva, D. Vasileska, S. M. Goodnick, Is SOD Technology the Solution to Heating Problems in SOI Devices?, Electron Device Letters, IEEE, Volume 29, Issue 6, June 2008 Page(s):621 - 624.

Dual-Gate SOI Devices

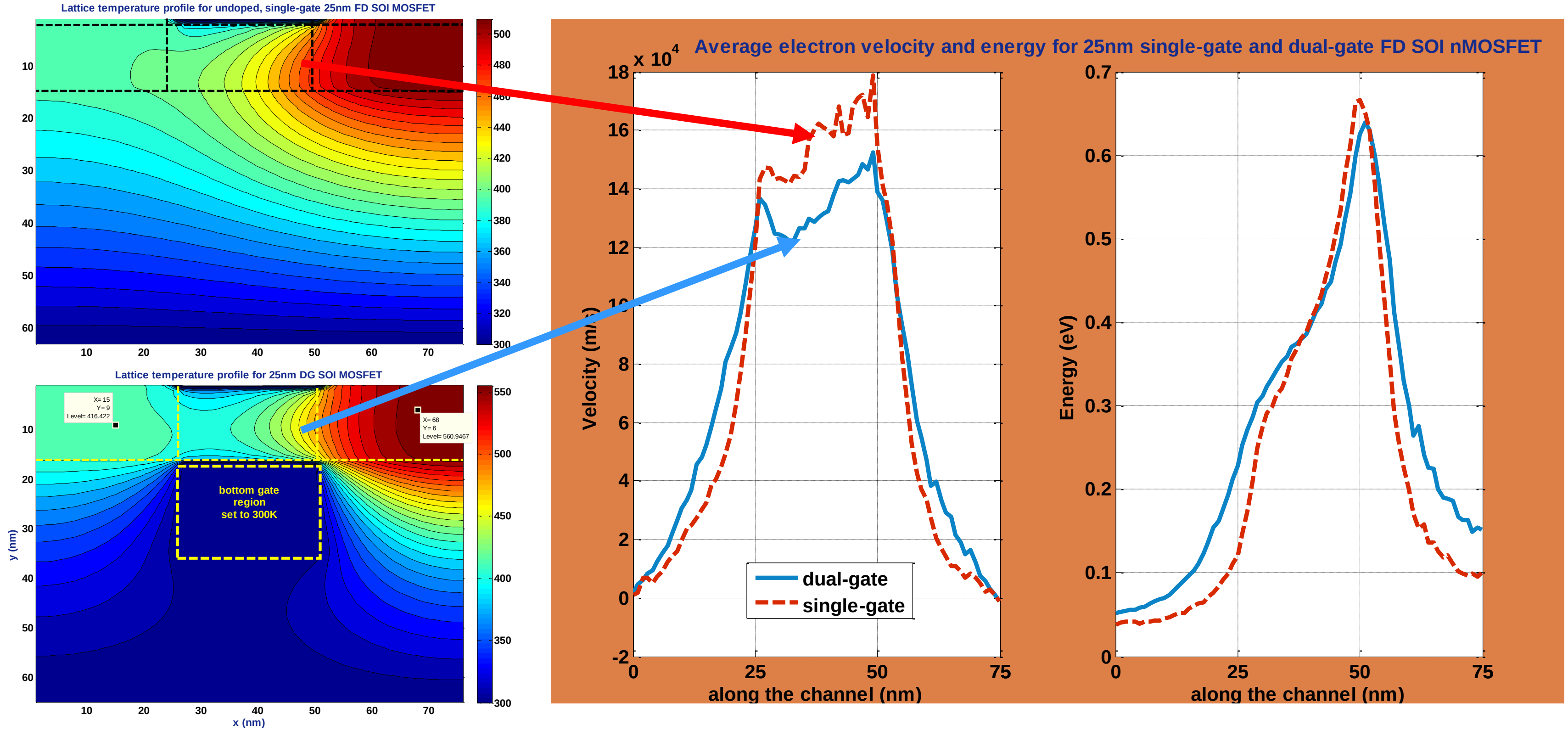




S.M. Goodnick, D. Vasileska, K. Raleva, "Is Dual Gate Device Better From a Thermal Perspective?", *Proceedings of the 2008 SISPAD Conference*, pp. 125 - 128.

A Closer Look …

Single gate lattice temperature profile



Dual gate lattice temperature profile

Where Does the Benefit of the DG Structure Come From?

For almost the same Current degradation DG devices offer **1.5-1.7** times more current

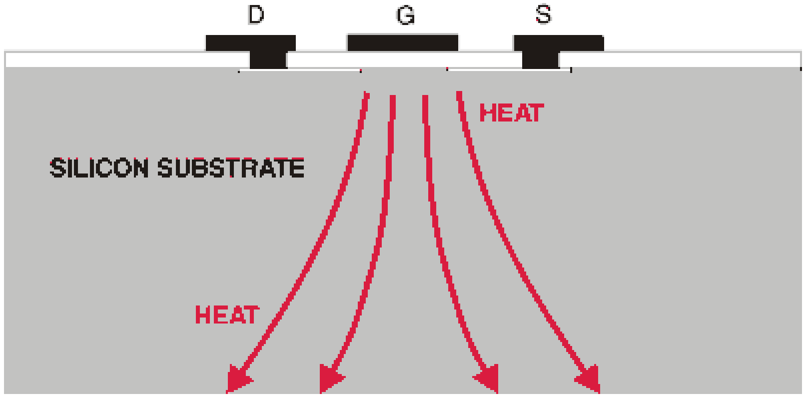
25nm FD SOI nMOSFET

Type of simulation	*Gate temperature*	*Bottom of the BOX temperature*	*Current (mA/um)*	**Current decrease (%)**
isothermal	300K	300K	1.9428	\
thermal	300K	300K	1.7644	**9.18**
thermal	400K	300K	1.6641	**14.35**
thermal	600K	300K	1.4995	**22.82**

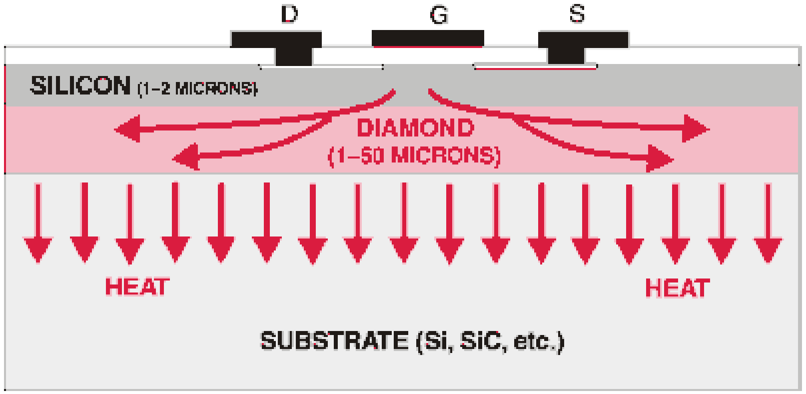
25nm DG SOI nMOSFET

<table>
<tr><th colspan="6"><i>25nm DG SOI nMOSFET
(Vgate-top=Vgate-bottom=1.2V; Vdrain=1.2V; Vsource=0V; Vsubstrate=0V)</i></th></tr>
<tr><th>Type of simulation</th><th>Top gate temperature</th><th>Bottom gate temperature</th><th>Bottom of the BOX temperature</th><th>Current (mA/um)</th><th>Current decrease (%)</th></tr>
<tr><td>isothermal</td><td>300K</td><td>300K</td><td>300K</td><td>3.0682</td><td>\</td></tr>
<tr><td>thermal</td><td>300K</td><td>300K</td><td>300K</td><td>2.7882</td><td>9.13</td></tr>
<tr><td>thermal</td><td>400K</td><td>400K</td><td>300K</td><td>2.6274</td><td>14.37</td></tr>
<tr><td>thermal</td><td>600K</td><td>600K</td><td>300K</td><td>2.3153</td><td>24.54</td></tr>
</table>

SOI vs. SOD vs. SOAlN



Standard Si technology

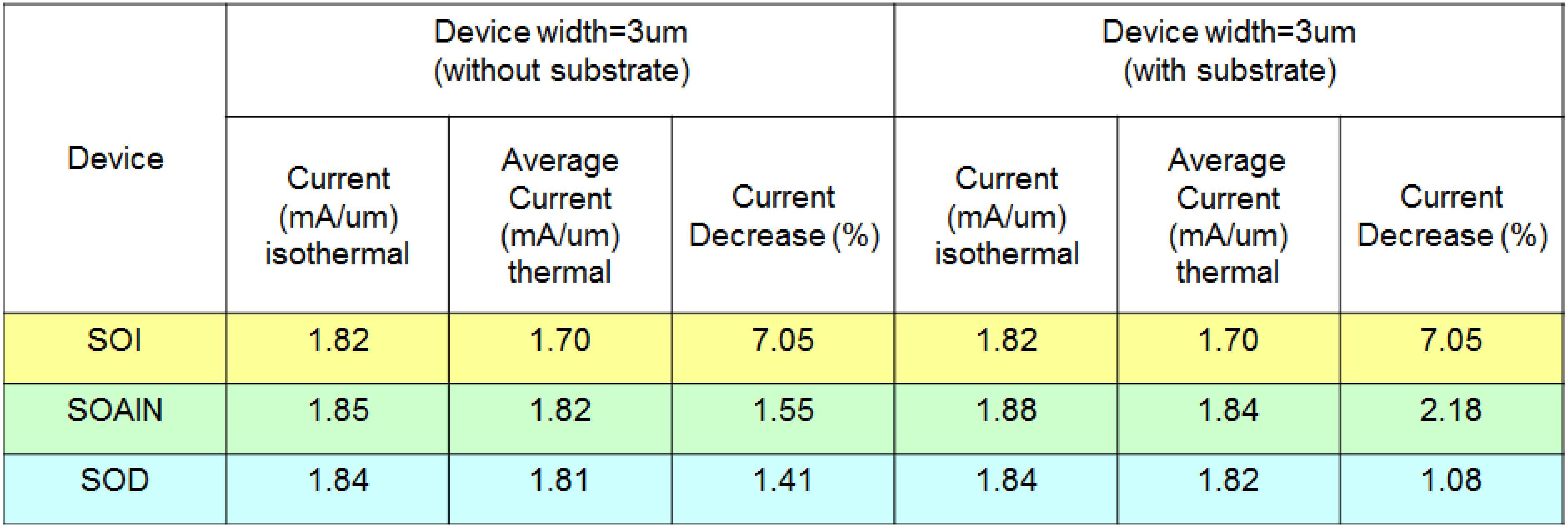


SOD technology

Silicon-On-Diamond and Silicon-On-Aluminum Nitride (SOAlN) Technologies as viable alternatives to Silicon-On-Insulator Devices

BOX Material	Dielectric constant	K_{th} (W/mK)
SiO_2	3.9	1.38
Diamond	5.68	2000
AlN	9.14	272

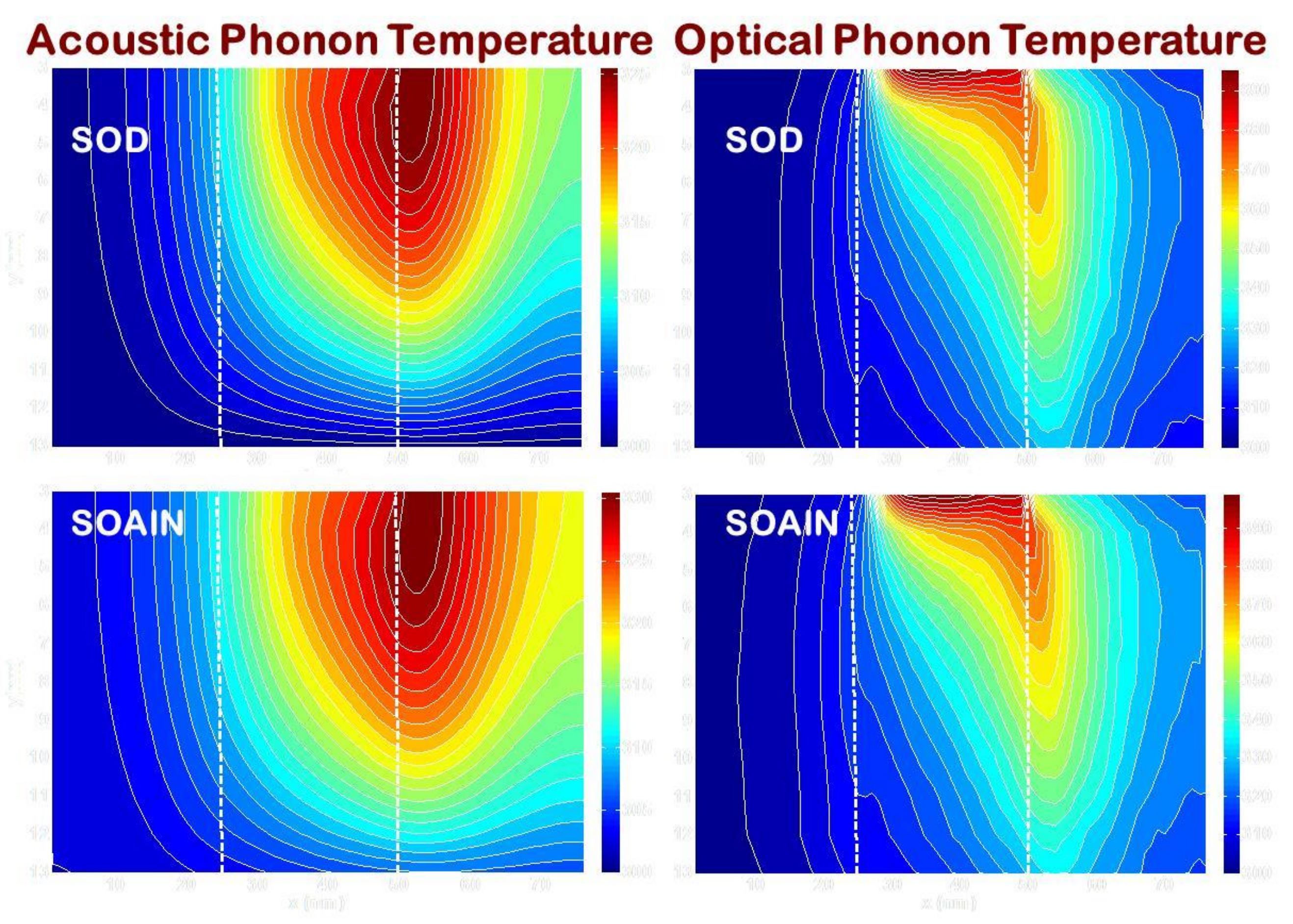
Current Degradation



Device	Device width=3um (without substrate)			Device width=3um (with substrate)		
	Current (mA/um) isothermal	Average Current (mA/um) thermal	Current Decrease (%)	Current (mA/um) isothermal	Average Current (mA/um) thermal	Current Decrease (%)
SOI	1.82	1.70	7.05	1.82	1.70	7.05
SOAlN	1.85	1.82	1.55	1.88	1.84	2.18
SOD	1.84	1.81	1.41	1.84	1.82	1.08

K. Raleva, D. Vasileska, S. M. Goodnick, Is SOD Technology the Solution to Heating Problems in SOI Devices?, Electron Device Letters, IEEE, Volume 29, Issue 6, June 2008 Page(s):621 - 624.

Heat Spreading

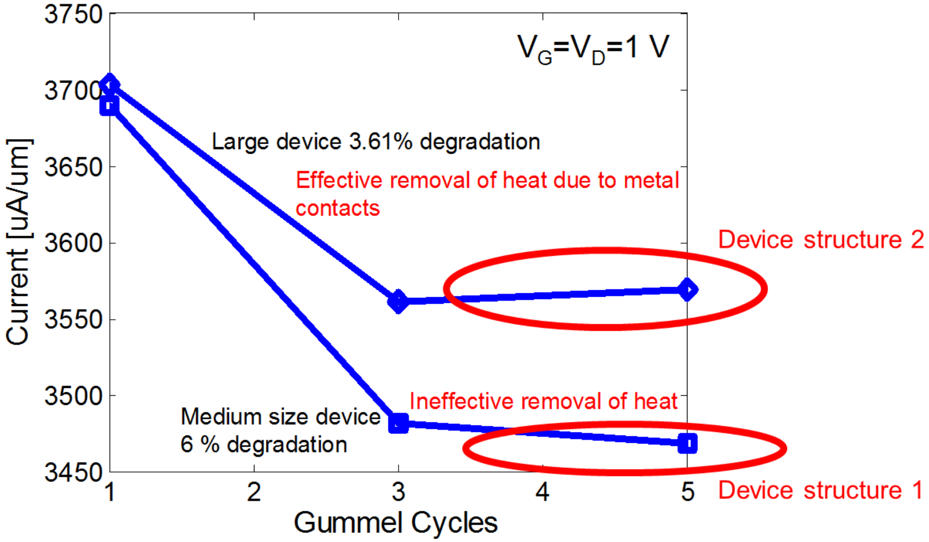


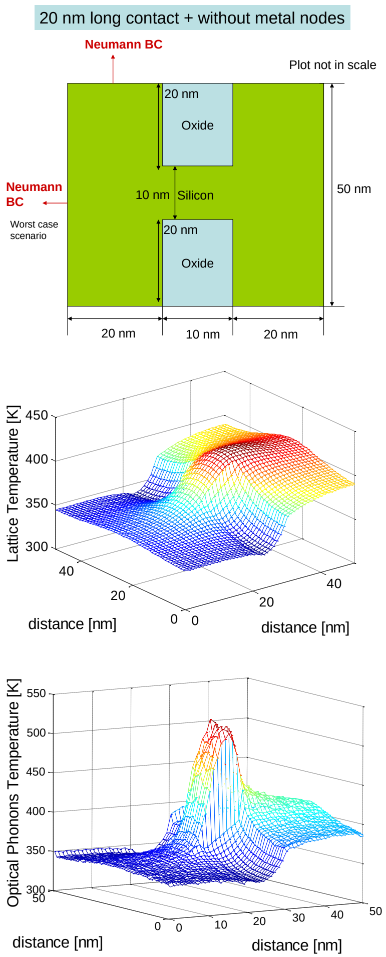
NANOWIRE TRANSISTORS

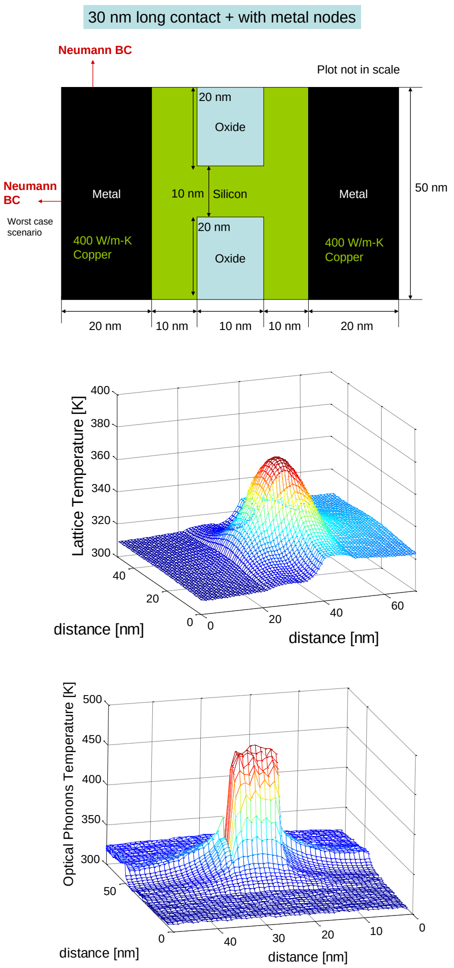
Lake Powell, Arizona

Nanowires – The Role of the Contacts

Convergence plot

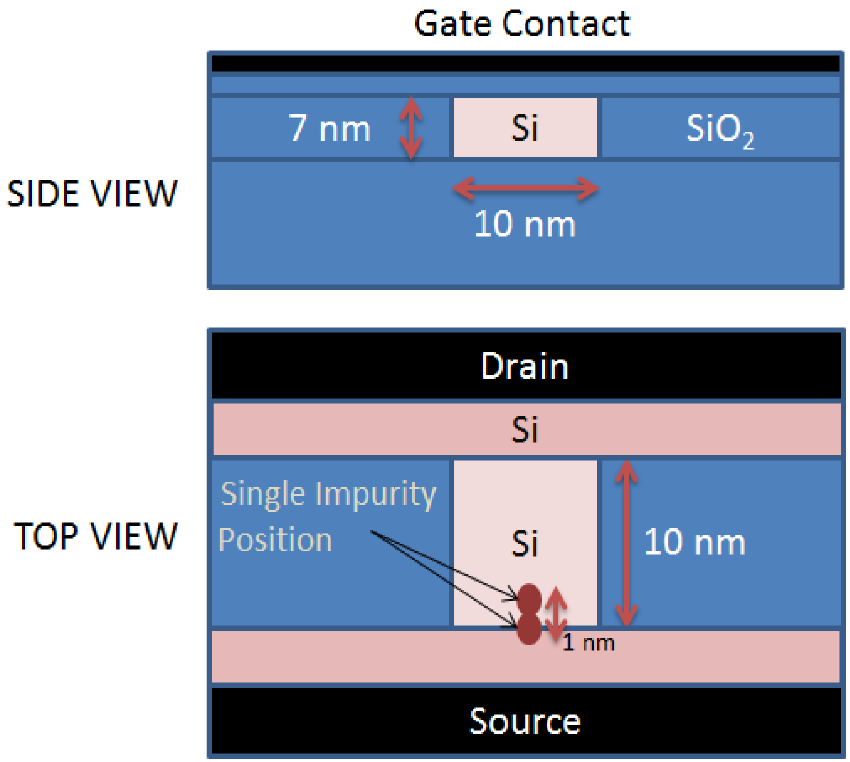






D. Vasileska, A. Hossain and S. M. Goodnick, *ECS Transactions*, Volume 31, No. 1, pp. 83-91 (September 2010).

Nanowires – Unintentional Dopant



SINGLE IMPURITY IMPACT

GUMMEL CYCLE	No impurity case [µA/µA]	Source Edge [µA/µA]	1 nm Towards Drain [µA/µA]
1	4154	4122	4075
3	4068	4030	3974
5	4052	4035	3968
Degradation	N/A	0.47%	2.12%

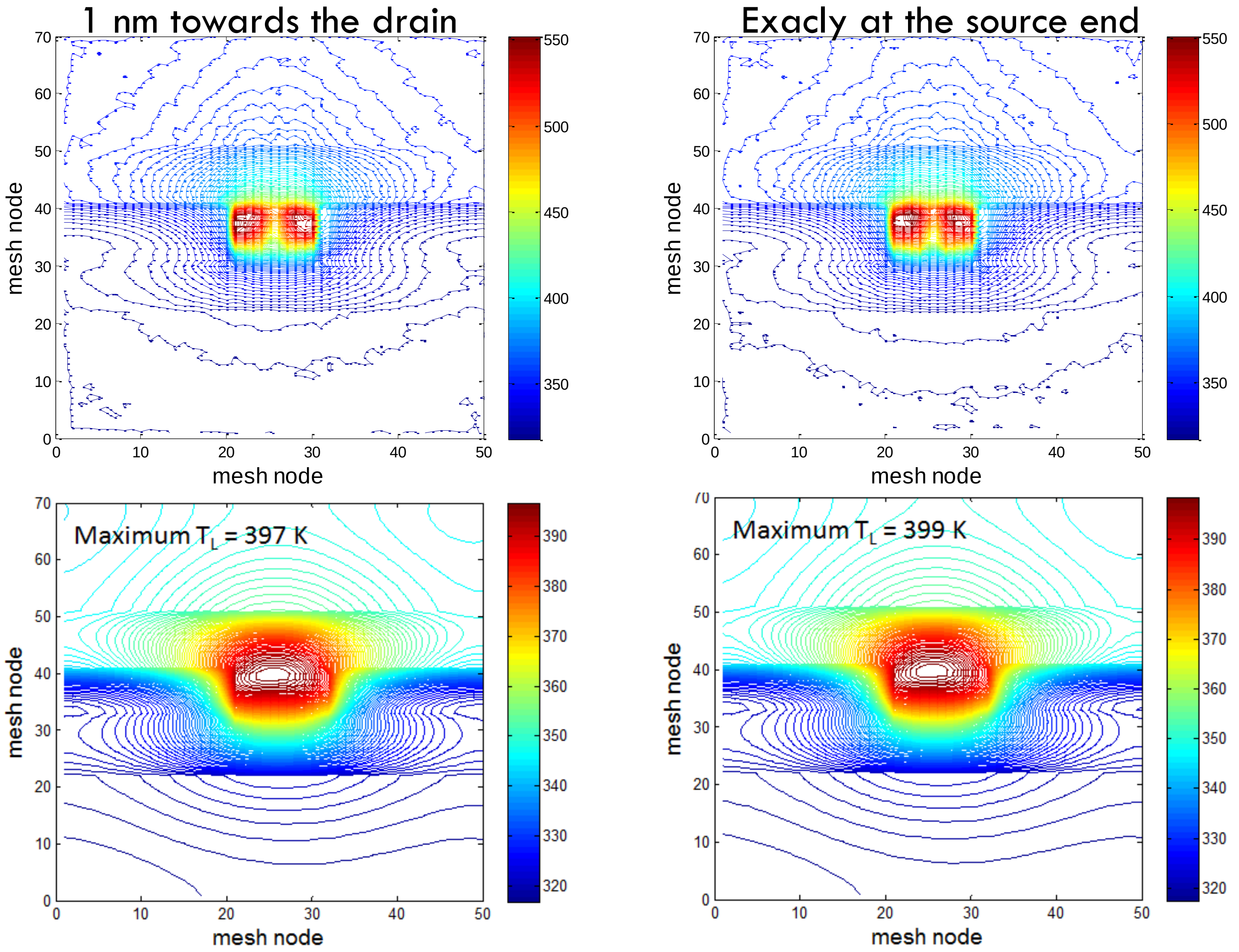
Screening of the source charges
Reduces the impact of the negative trap.

Maximal impact

Unintentional Dopant

optical

acoustic



1 nm towards the drain

Exacly at the source end

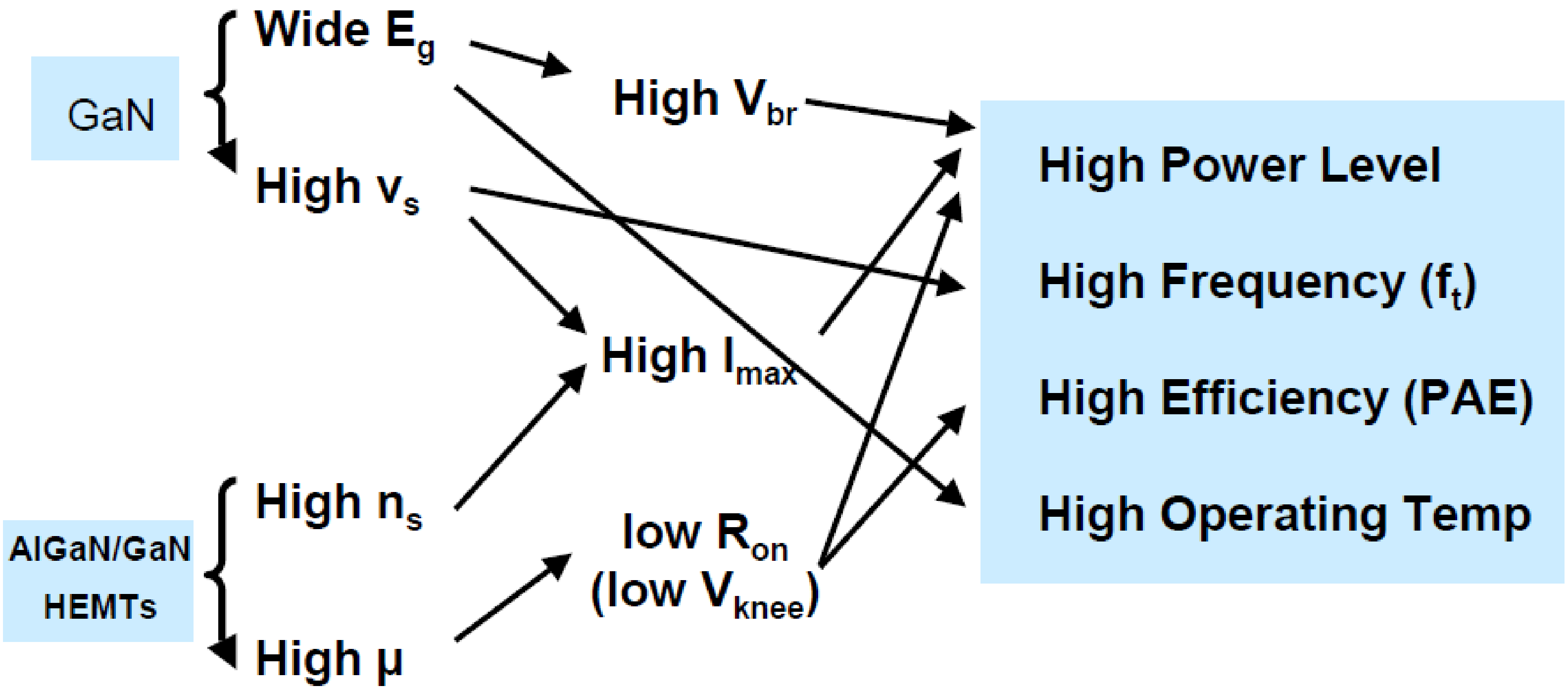
Maximum T_L = 397 K

Maximum T_L = 399 K

GaN HEMTS

Rainbow Bridge, Arizona

Why GaN HEMTs?



GaN

Wide E_g

High v_s

AlGaN/GaN HEMTs

High n_s

High μ

High V_{br}

High I_{max}

low R_{on} (low V_{knee})

High Power Level

High Frequency (f_t)

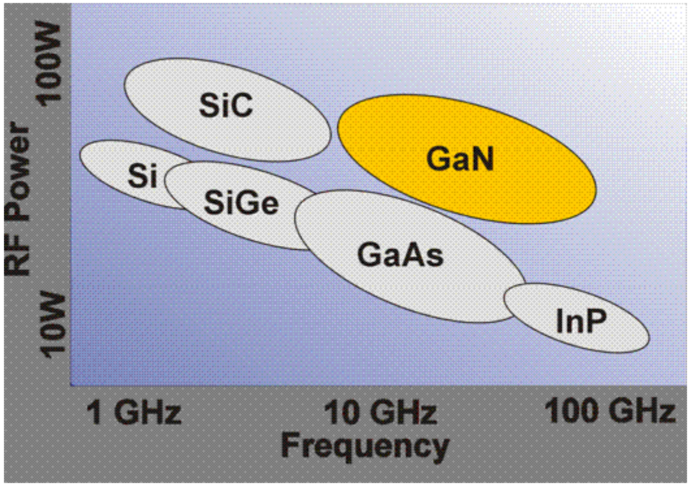
High Efficiency (PAE)

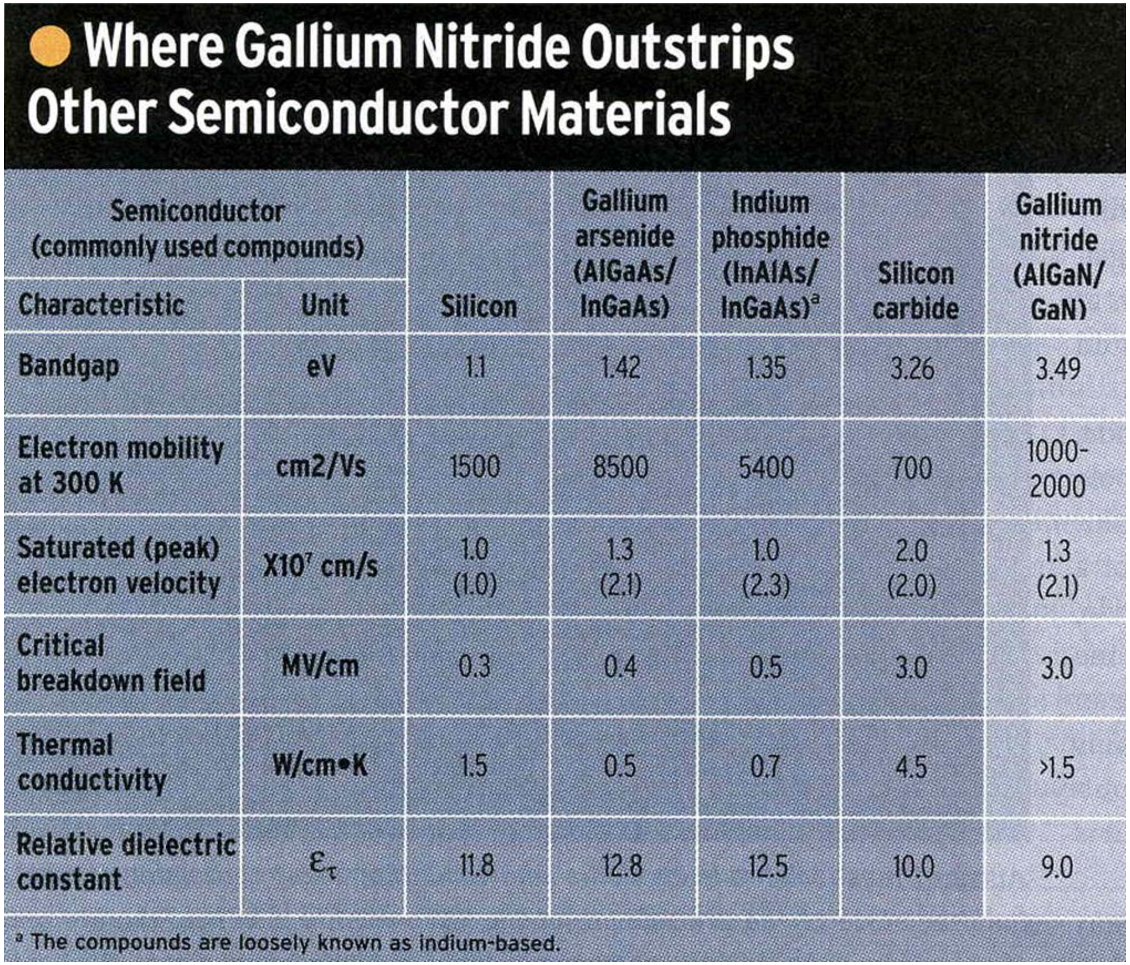
High Operating Temp

Promising Microwave Power Device

Simulation Results: GaN HEMTs

- Why GaN HEMTs?



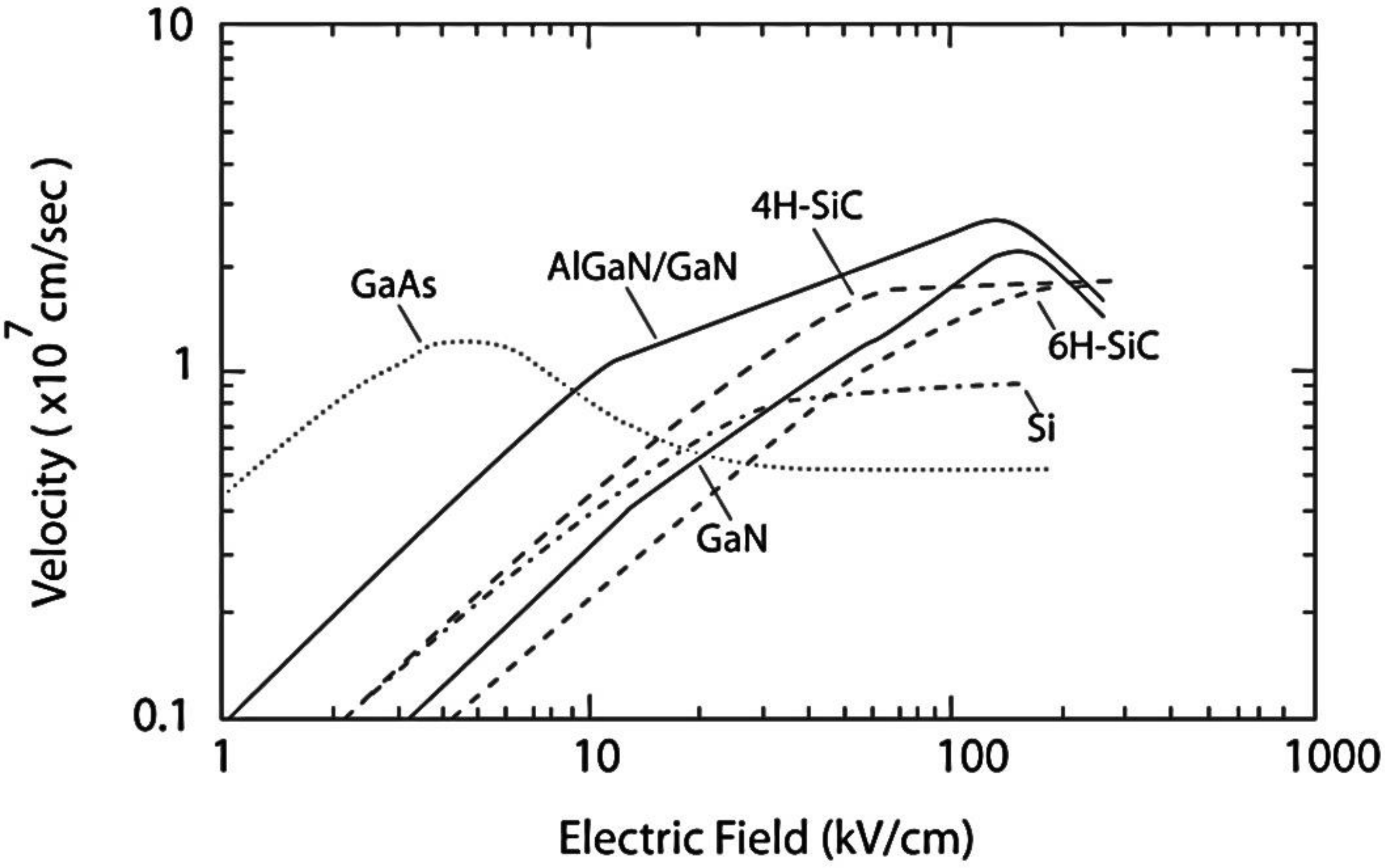


Where Gallium Nitride Outstrips Other Semiconductor Materials

Semiconductor (commonly used compounds)						
Characteristic	Unit	Silicon	Gallium arsenide (AlGaAs/ InGaAs)	Indium phosphide (InAlAs/ InGaAs)[a]	Silicon carbide	Gallium nitride (AlGaN/ GaN)
Bandgap	eV	1.1	1.42	1.35	3.26	3.49
Electron mobility at 300 K	cm2/Vs	1500	8500	5400	700	1000-2000
Saturated (peak) electron velocity	$X10^7$ cm/s	1.0 (1.0)	1.3 (2.1)	1.0 (2.3)	2.0 (2.0)	1.3 (2.1)
Critical breakdown field	MV/cm	0.3	0.4	0.5	3.0	3.0
Thermal conductivity	W/cm•K	1.5	0.5	0.7	4.5	>1.5
Relative dielectric constant	ε_r	11.8	12.8	12.5	10.0	9.0

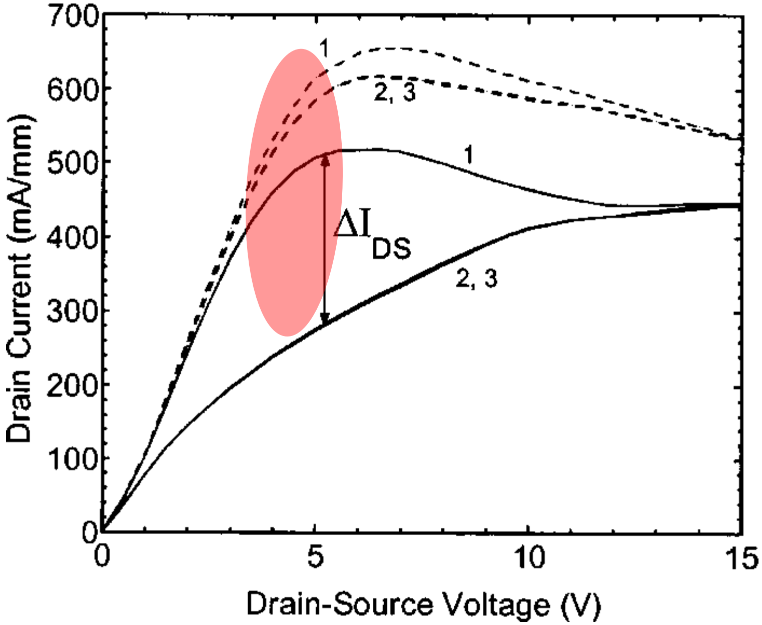
[a] The compounds are loosely known as indium-based.

GaN HEMTs …



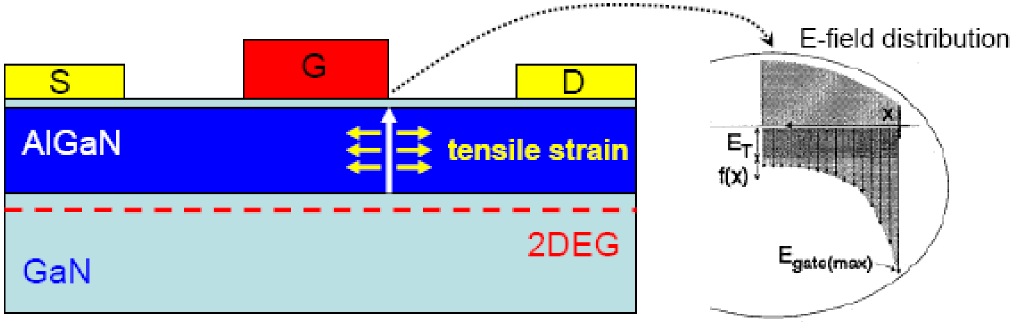
10
1
0.1
Velocity (x10^7 cm/sec)
1
10
100
1000
Electric Field (kV/cm)
GaAs
AlGaN/GaN
4H-SiC
6H-SiC
Si
GaN

Problems With GaN HEMTs



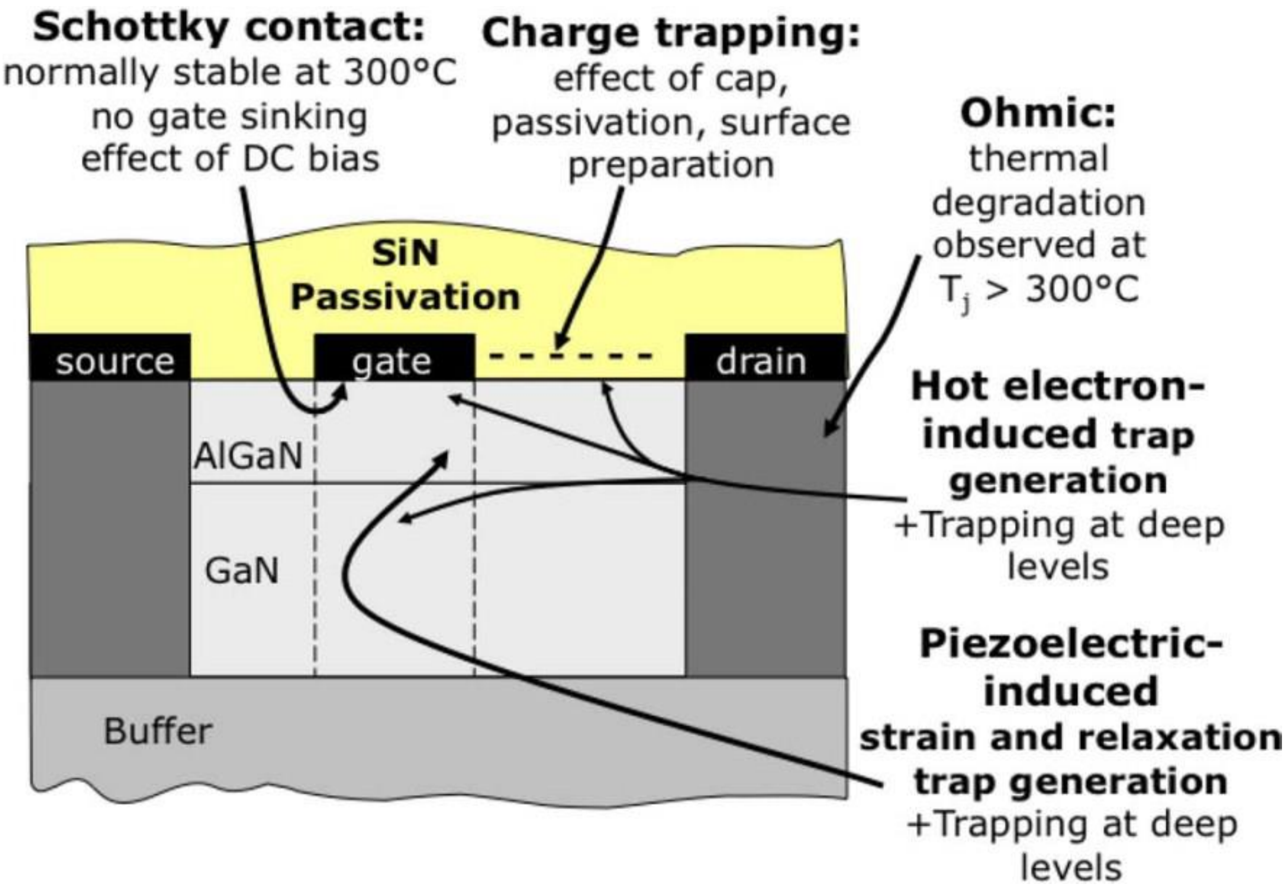
Current Collapse induced in GaN HEMT device characteristics as a result of short-term (~*10 hours*) DC bias stress.

Trapping of hot electrons by trap/defect sites in the AlGaN buffer layer as well as GaN substrate reduces the net polarization charge.



J. A. del Alamo and J. Joh, GaN HEMT reliability, Microelectronics Reliability, Volume 49, Issues 9-11, September-November 2009, Pages 1200-1206.

Problems With GaN HEMTs …



Schottky contact:
normally stable at 300°C
no gate sinking
effect of DC bias

Charge trapping:
effect of cap,
passivation, surface
preparation

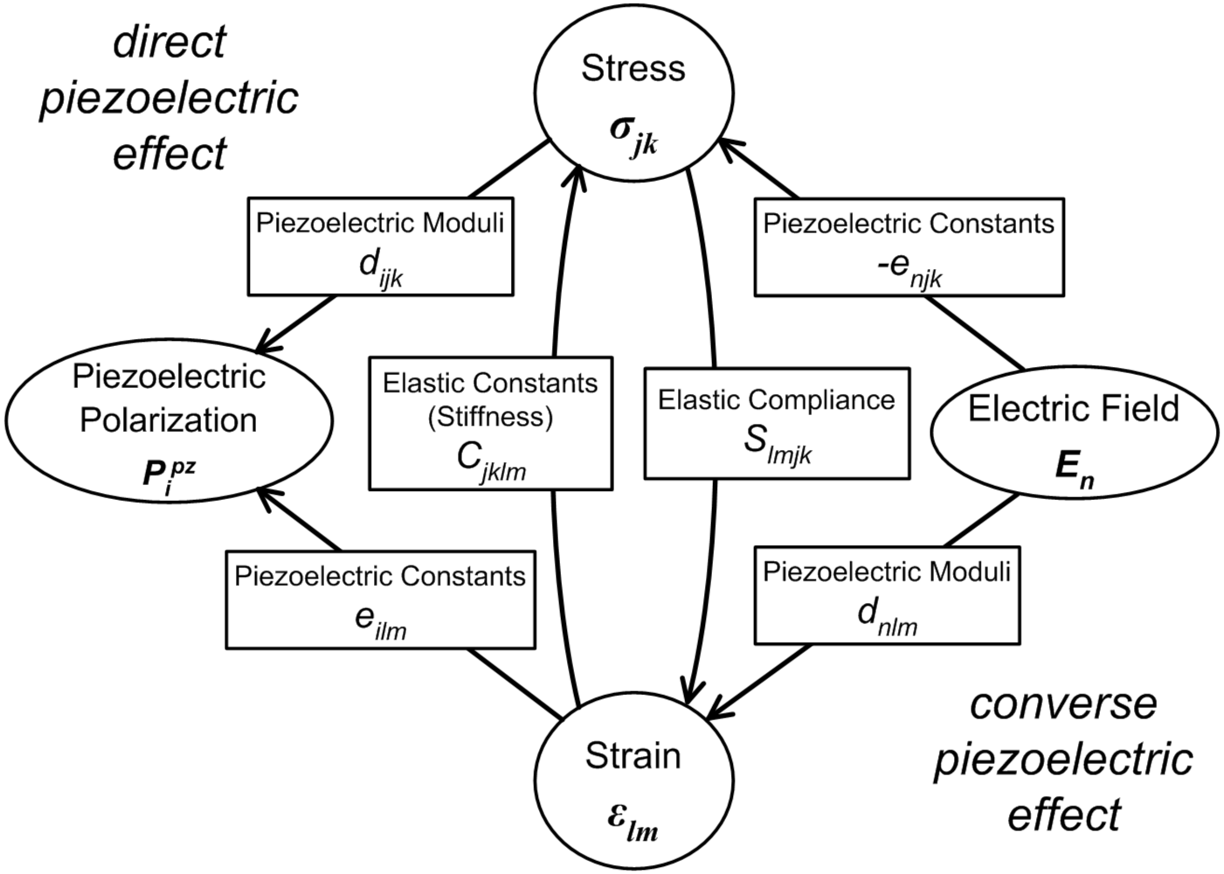
Ohmic:
thermal
degradation
observed at
$T_j > 300°C$

Hot electron-induced trap generation
+Trapping at deep
levels

Piezoelectric-induced strain and relaxation trap generation
+Trapping at deep
levels

MODELING REQUIREMENTS

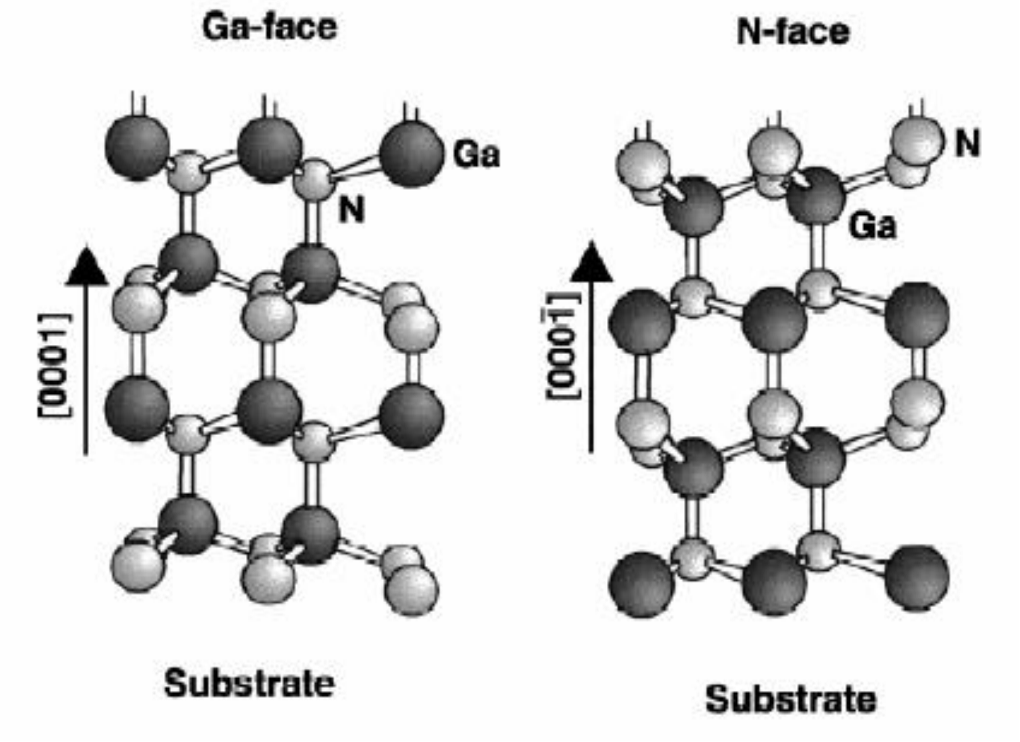
INCORPORATION OF ELECTROMECHANICAL COUPLING



SELF-HEATING EFFECT

GaN HEMTs Basics

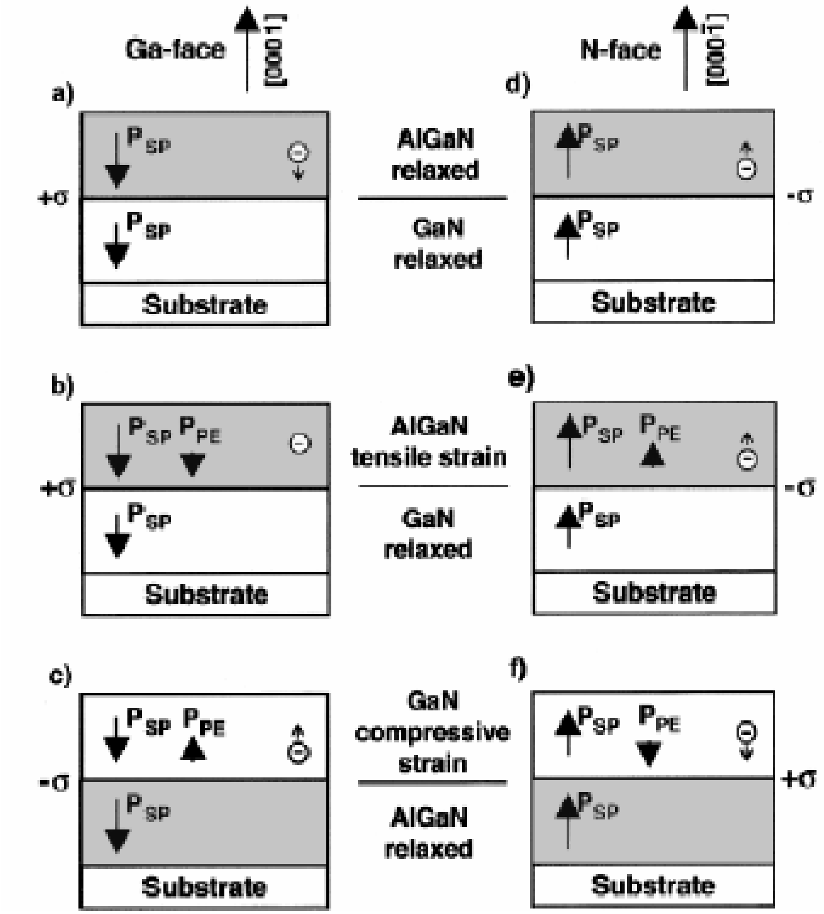
- Wurtzite AlGaN/GaN

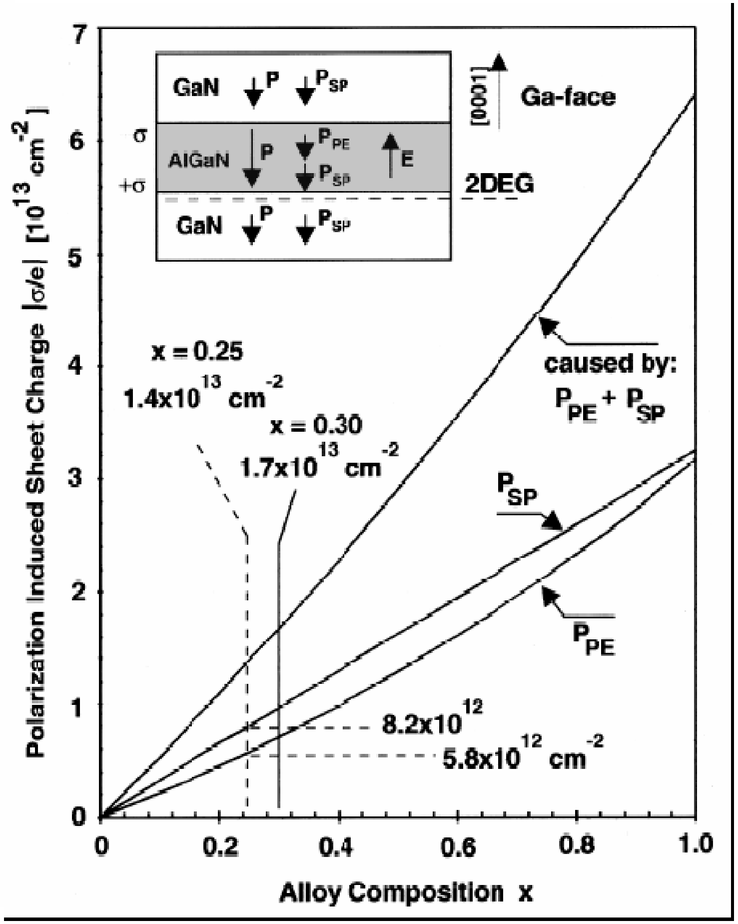


AlGaN/GaN grown on sapphire by MOCVD is always Ga-faced, but material grown by MBE can have either Ga- or N-faced surface depending on the existence of AlN nucleation layer.

GaN HEMTs Basics …

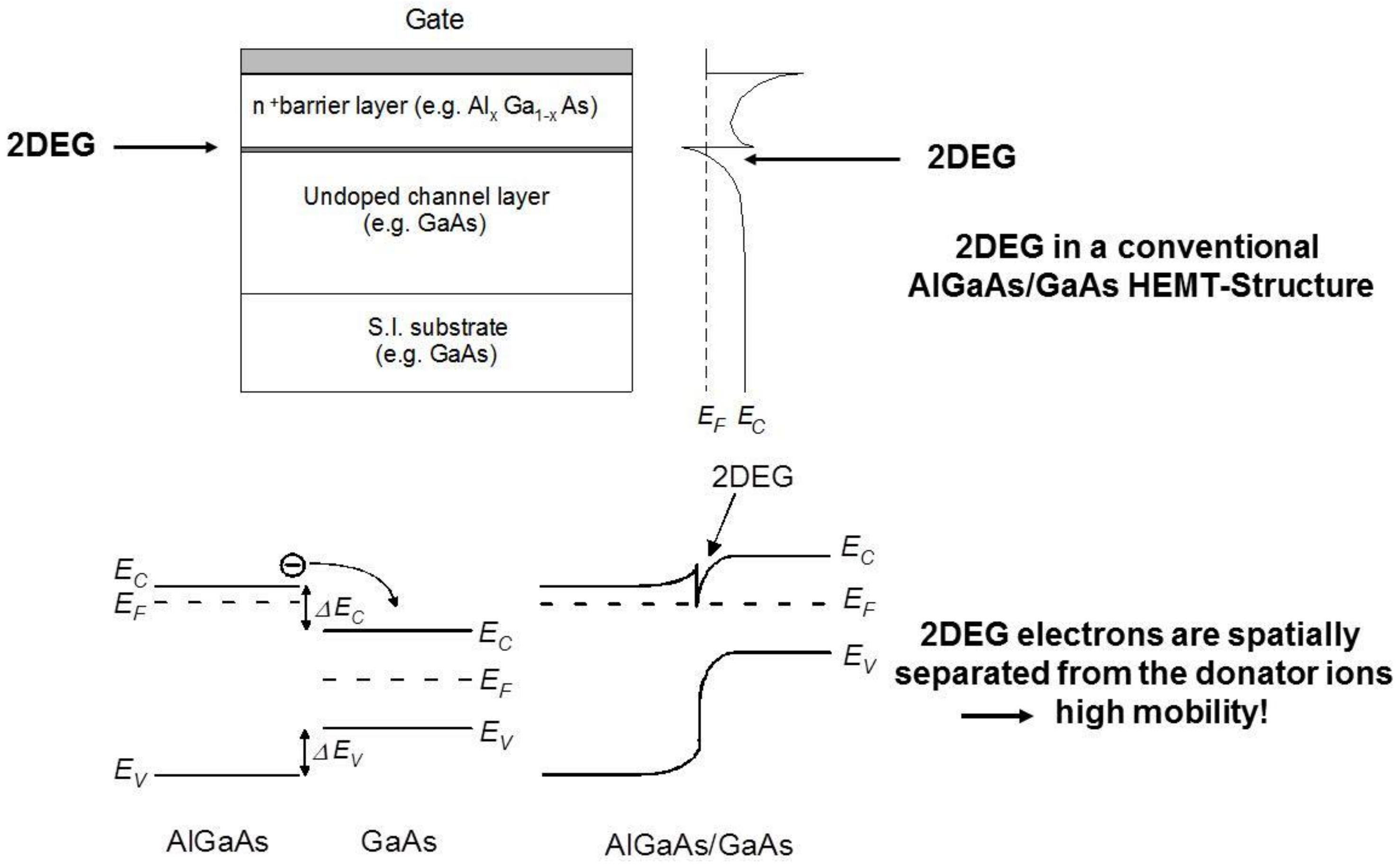
- ☐ Spontaneous and Piezoelectric Polarization Charge





GaN HEMTs …

- Comparison to GaAs devices



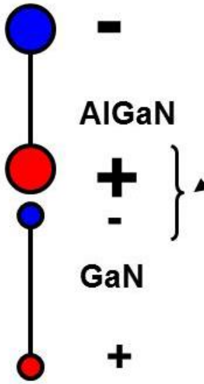
Two-Dimensional Electron Gas - 2DEG

2DEG in a conventional AlGaAs/GaAs HEMT-Structure

2DEG electrons are spatially separated from the donator ions → high mobility!

GaN HEMTs …

- What is different in GaN HEMTs …

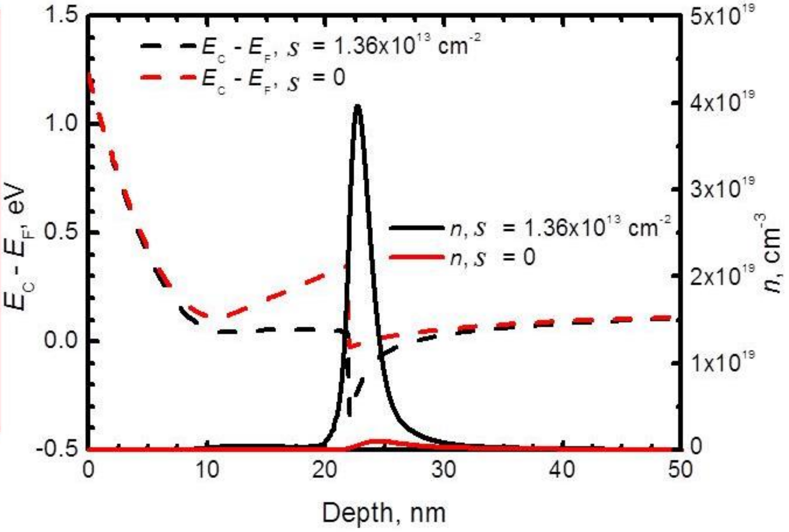


At the AlGaN/GaNinterface occurs a positive net charge

+ σ leading to the formation of a 2DEG in the GaN.

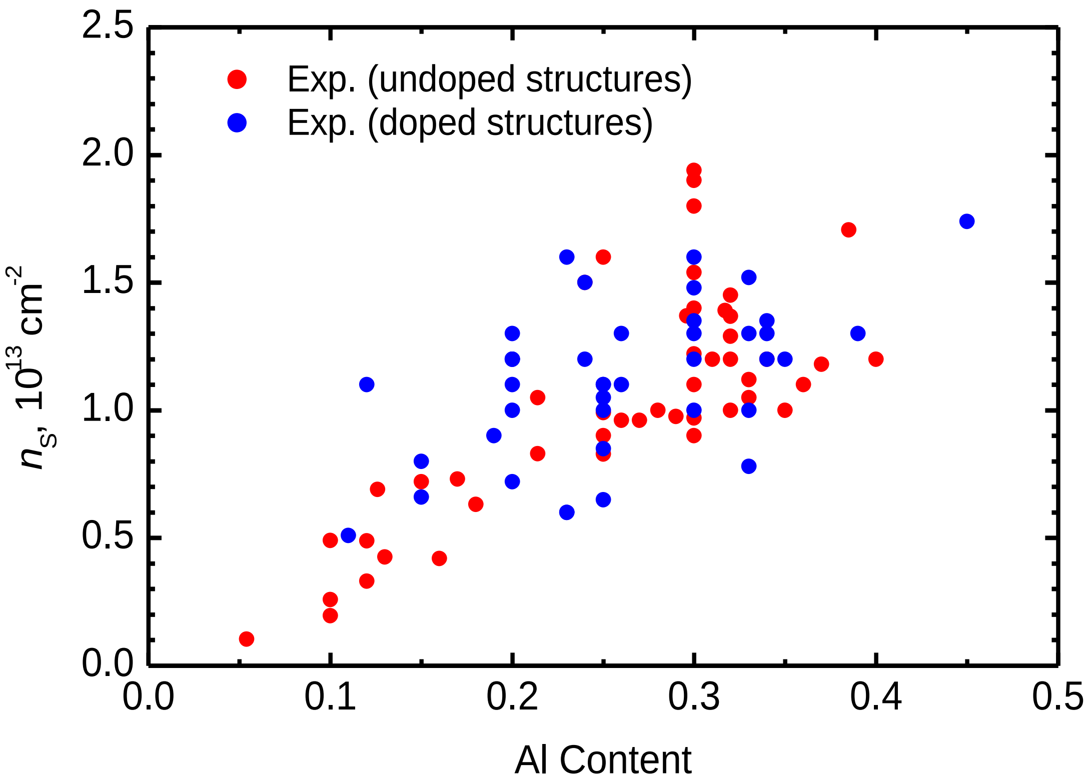
Two important messages:

- Only a small portion of the 2DEG elecrons is caused by the barrier doping !
- Even without any doping very high 2DEG sheet concentrations are possible!



GaN HEMTs …

- Large sheet electron densities



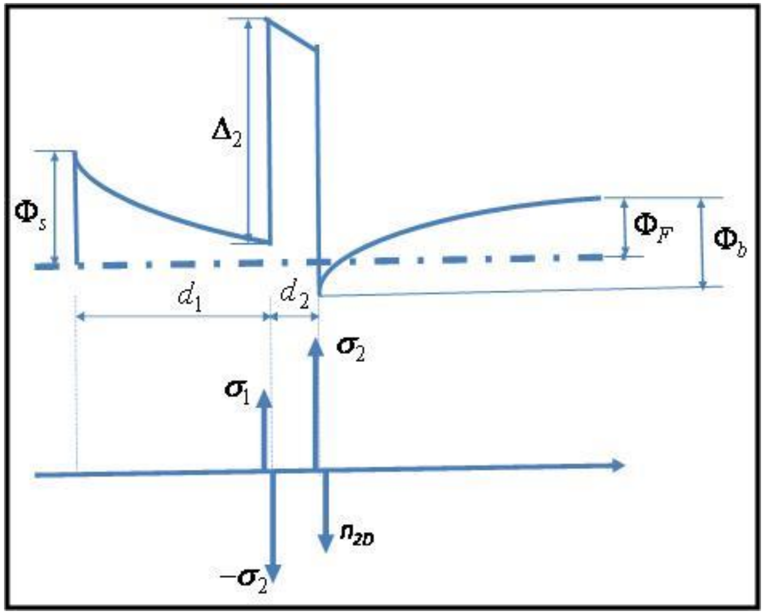
Measured 2DEG sheet concentration n_S in $Al_xGa_{1-x}N$/GaN heterostructures vs. Al content x

Electro-mechanical coupling model developed at ASU

Model implemented in Synopsys Sentaurus simulation software.

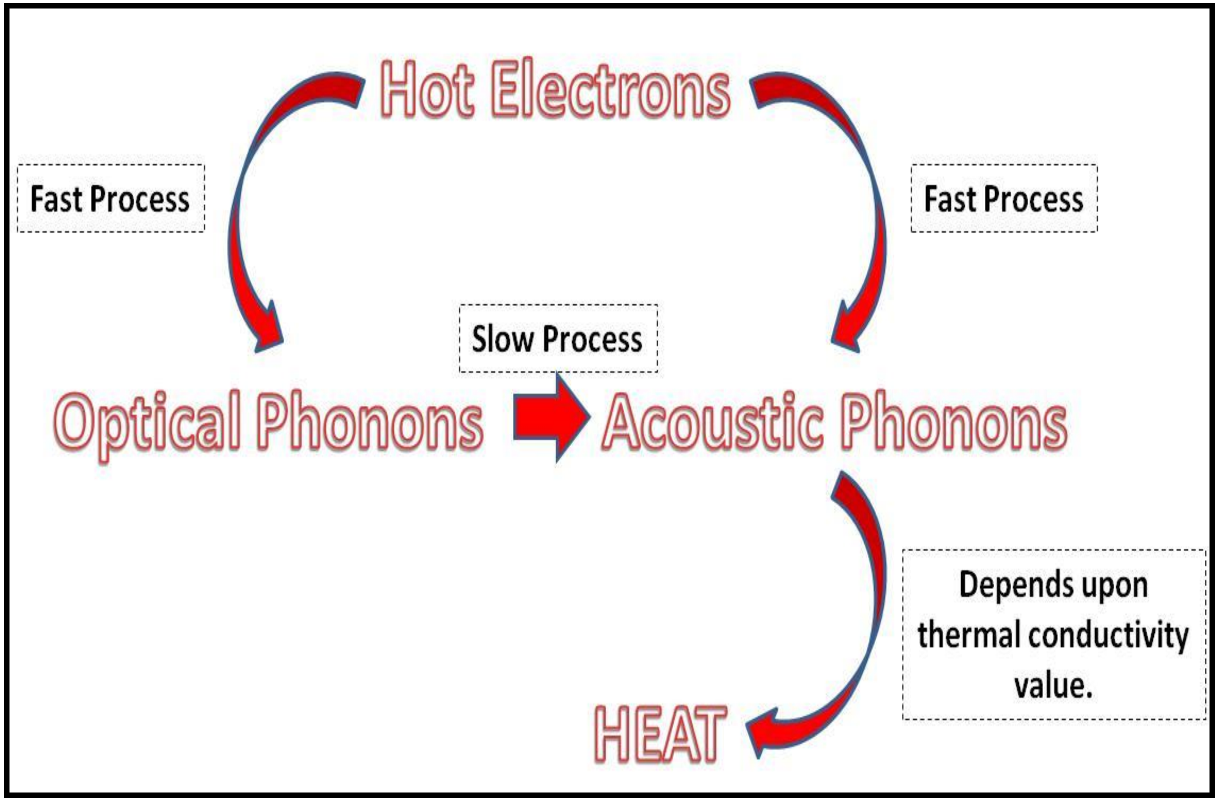
Basic idea of the method:

$$P_{PE}^{\alpha} = 2\Xi_x^{\alpha}\left(e_{31}^{\alpha} - \frac{c_{13}^{\alpha}}{c_{33}^{\alpha}} e_{33}^{\alpha}\right) + E_z^{\alpha}\frac{{e_{33}^{\alpha}}^{2}}{c_{33}^{\alpha}}$$



Energy relaxation processes

Acoustic and optical phonon bath

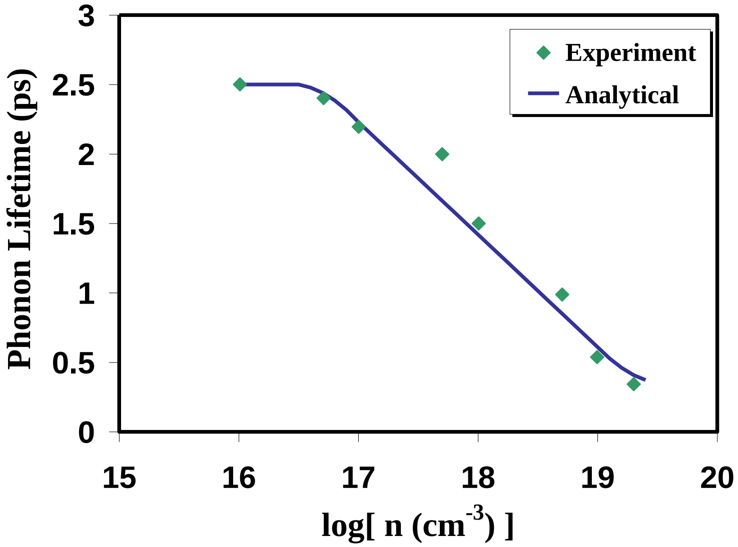


Energy balance Equation Solver for Phonons

Depends on n(i,j)

$$C_{LO}\frac{\partial T_{LO}}{\partial t} = \frac{3nk_B}{2}\left(\frac{T_e - T_L}{\tau_{e-LO}}\right) + \frac{nm^* v_d^2}{2\tau_{e-LO}} - C_{LO}\left(\frac{T_{LO}-T_A}{\tau_{LO-A}}\right),$$

$$C_A\frac{\partial T_A}{\partial t} = \nabla\cdot\left(k_A\nabla T_A\right) + C_{LO}\left(\frac{T_{LO}-T_A}{\tau_{LO-A}}\right) + \frac{3nk_B}{2}\left(\frac{T_e-T_L}{\tau_{e-L}}\right).$$

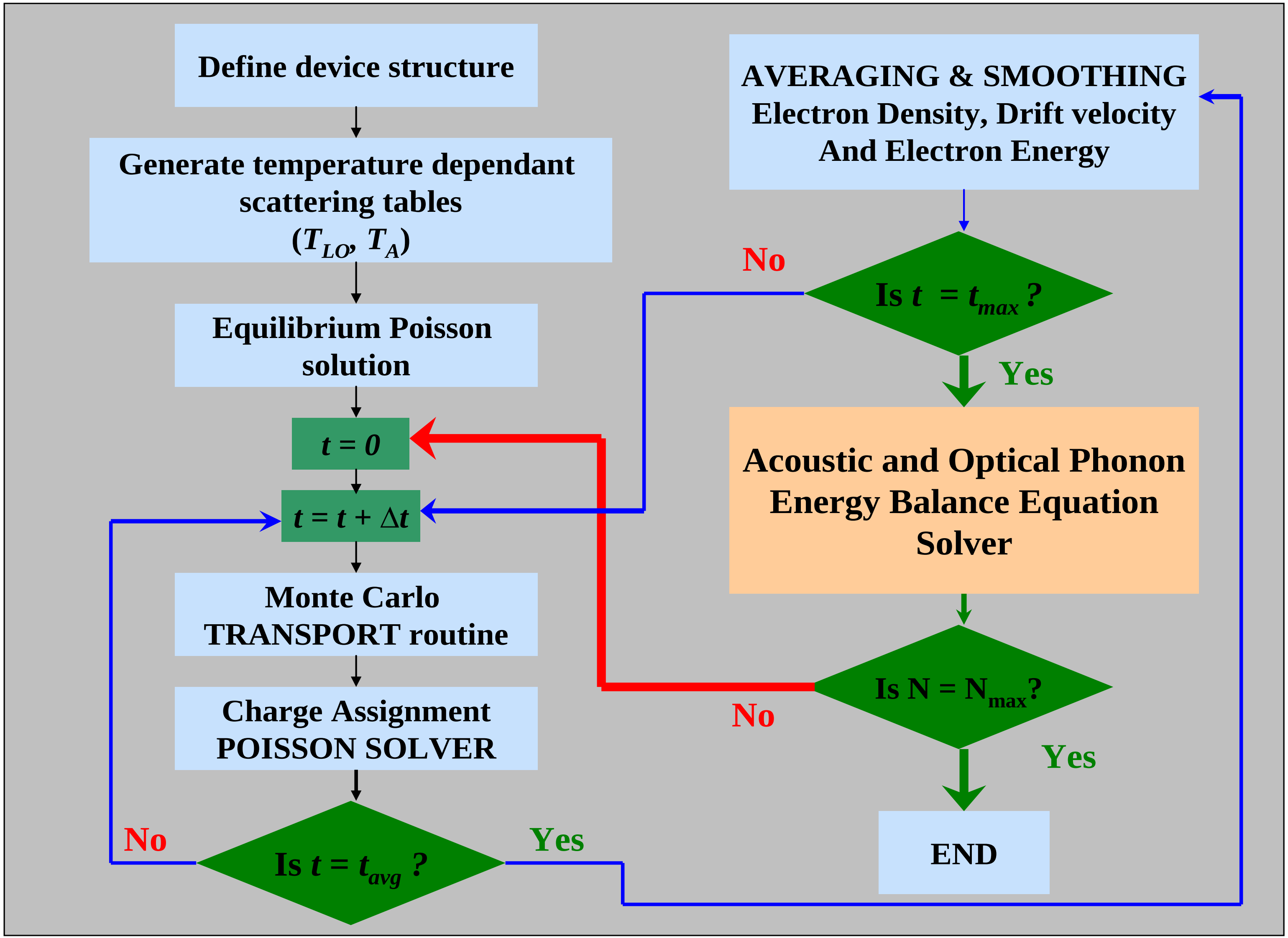


Carrier density dependent phonon lifetime, τ_{LO}

Optical Phonon Lifetime → function of carrier density n(i,j)

Carrier density dependant phonon lifetimes results in an indirect dependence of the choice of SCATTERING MECHANISM on the CARRIER DENSITIES

Flow-chart of Electro-thermal simulator



Define device structure

Generate temperature dependant scattering tables (T_{LO}, T_A)

Equilibrium Poisson solution

$t = 0$

$t = t + \Delta t$

Monte Carlo TRANSPORT routine

Charge Assignment POISSON SOLVER

Is $t = t_{avg}$?

No

Yes

AVERAGING & SMOOTHING Electron Density, Drift velocity And Electron Energy

Is $t = t_{max}$?

No

Yes

Acoustic and Optical Phonon Energy Balance Equation Solver

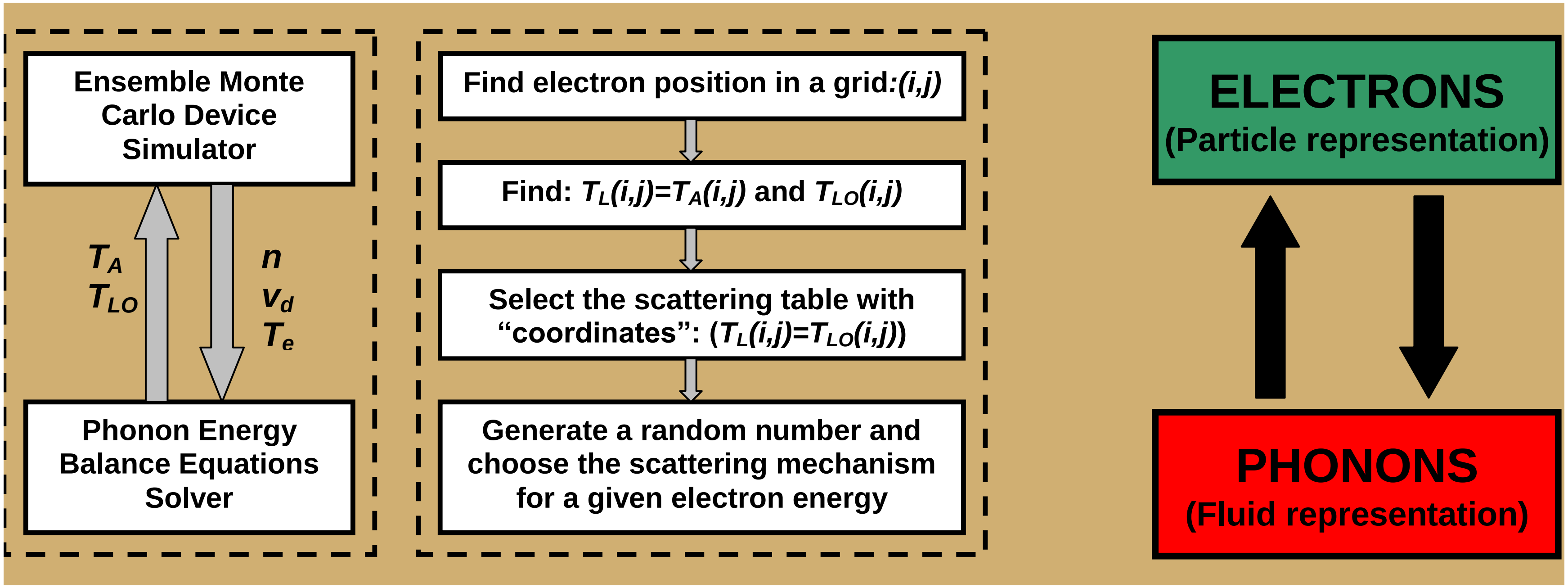
Is $N = N_{max}$?

No

Yes

END

Exchange of variables between solvers



Ensemble Monte Carlo Device Simulator

T_A T_{LO}

n v_d T_e

Phonon Energy Balance Equations Solver

Find electron position in a grid: ***(i,j)***

Find: $T_L(i,j)=T_A(i,j)$ **and** $T_{LO}(i,j)$

Select the scattering table with "coordinates": $(T_L(i,j)=T_{LO}(i,j))$

Generate a random number and choose the scattering mechanism for a given electron energy

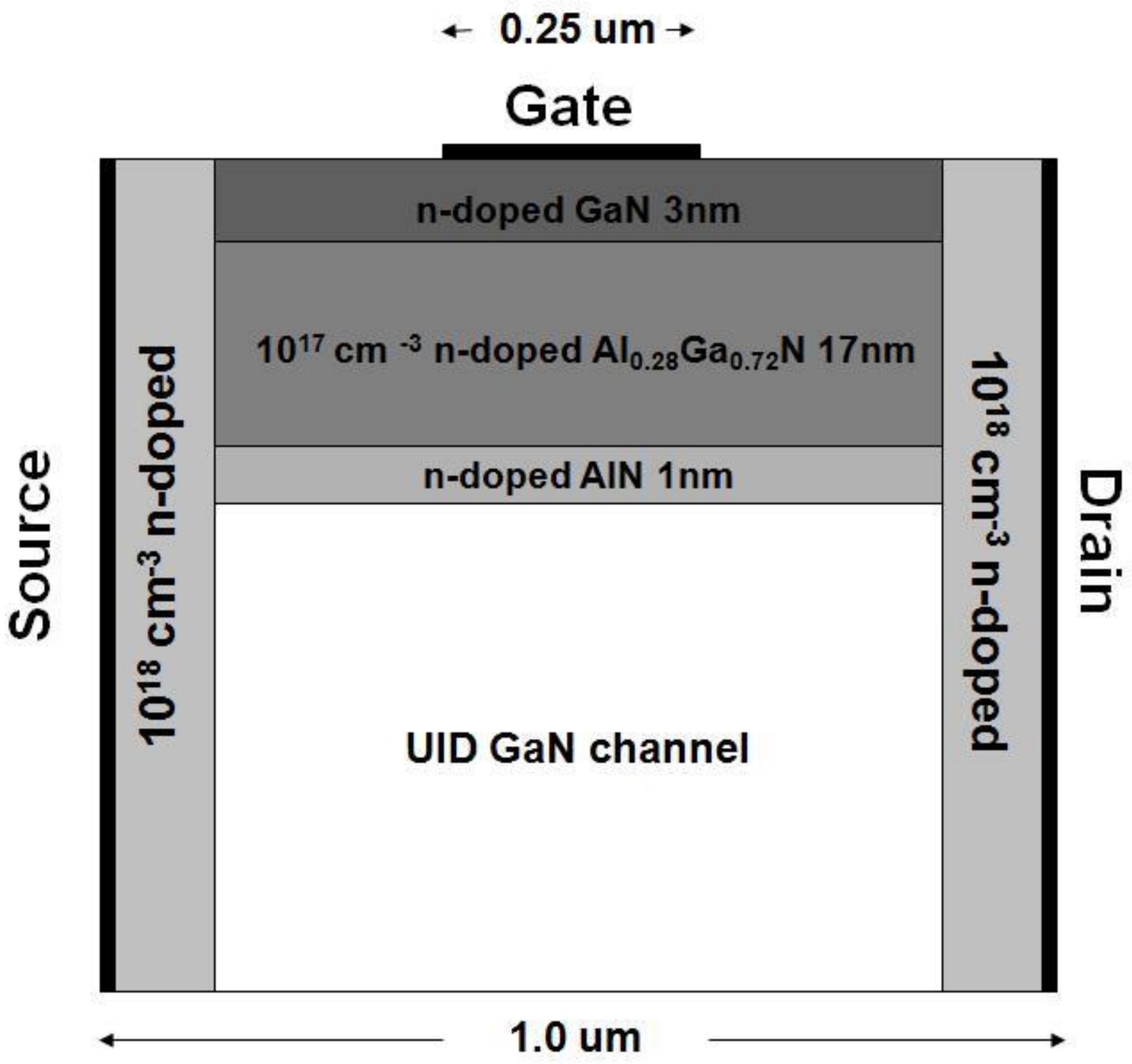
ELECTRONS
(Particle representation)

PHONONS
(Fluid representation)

Modifications to our existing Monte Carlo Simulator

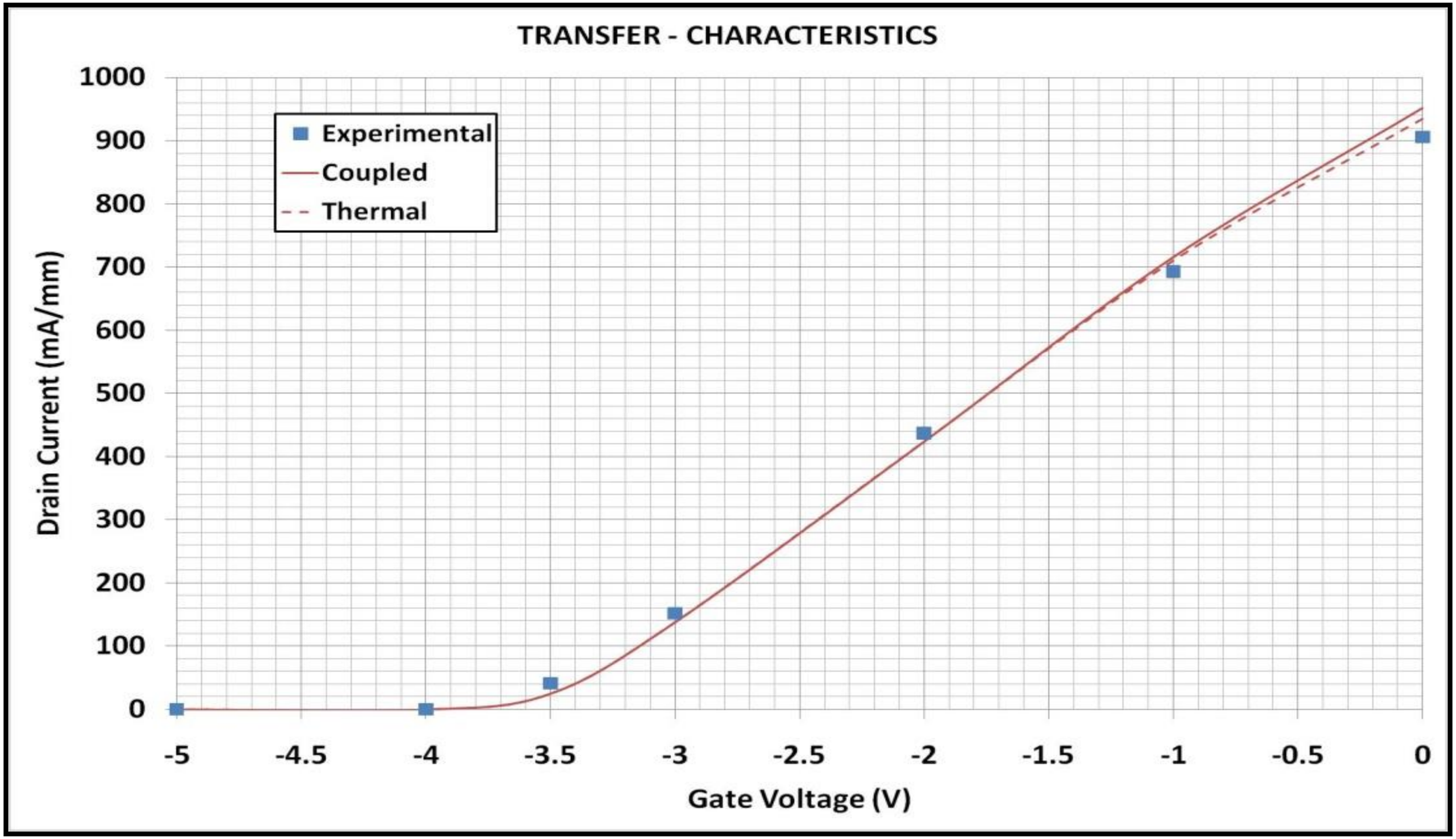
- **Temperature dependent Scattering Tables.**
- **Averaging and smoothing of electron density, drift velocity and electron energy for solving phonon balance equations.**
- **Density dependent phonon lifetimes – analytical model fitted to experimental values.**

Simulated structure

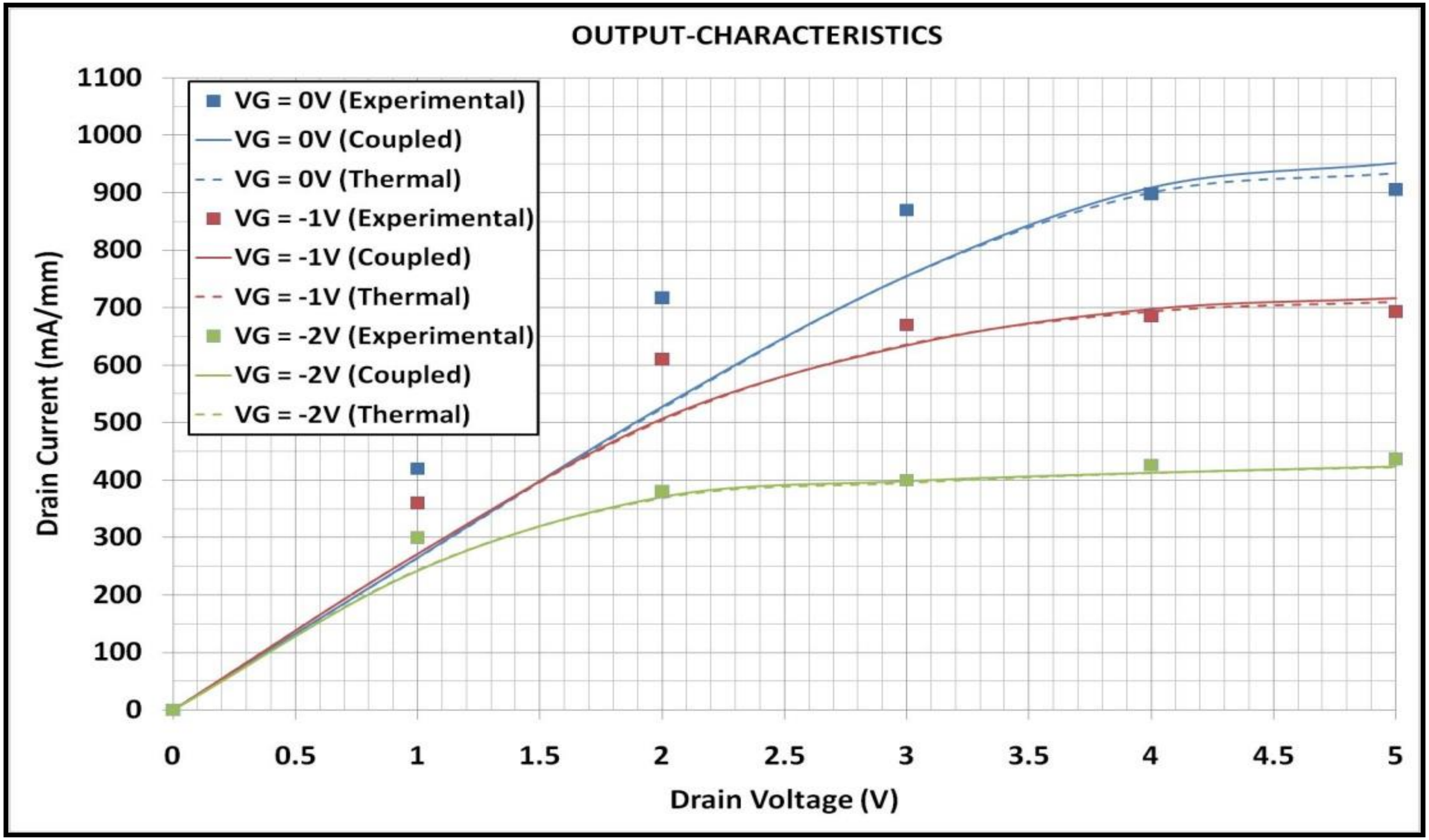


J. A. del Alamo structure

I_d-V_G Characteristic

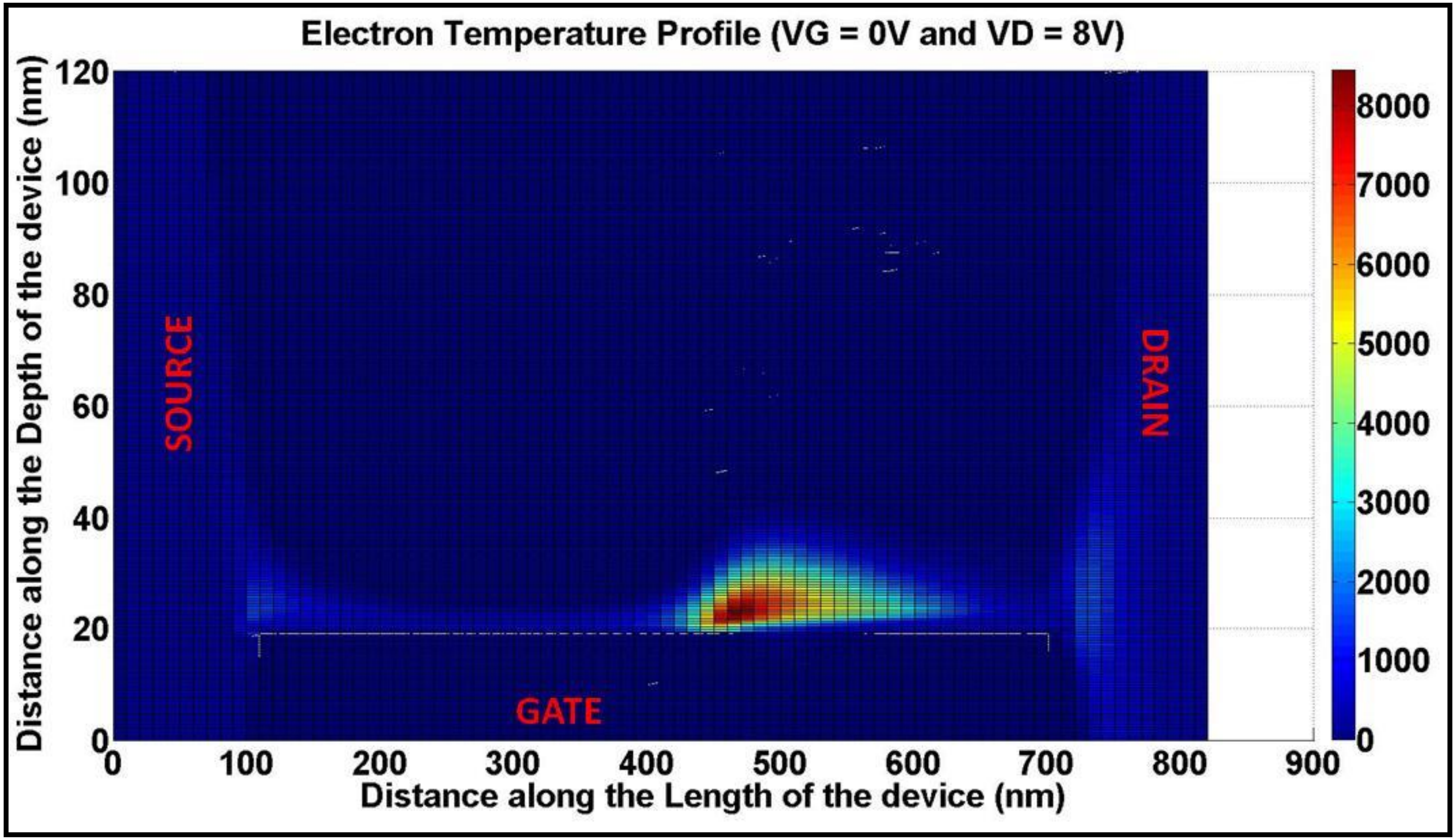


I_d-V_d characteristic

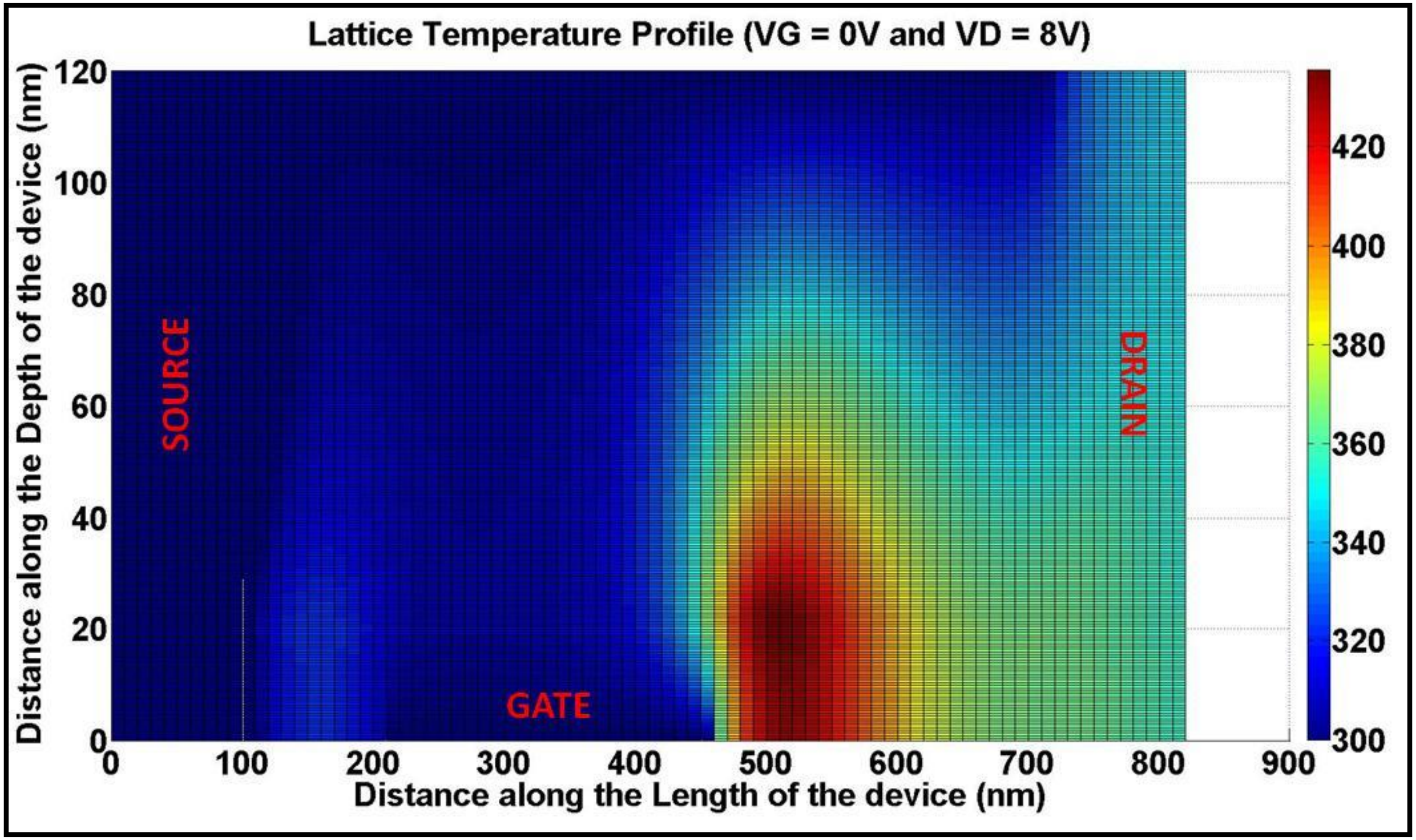


K. T. Tsen, et al., *Appl. Physc. Lett.* vol. 89, 112111, 2006.

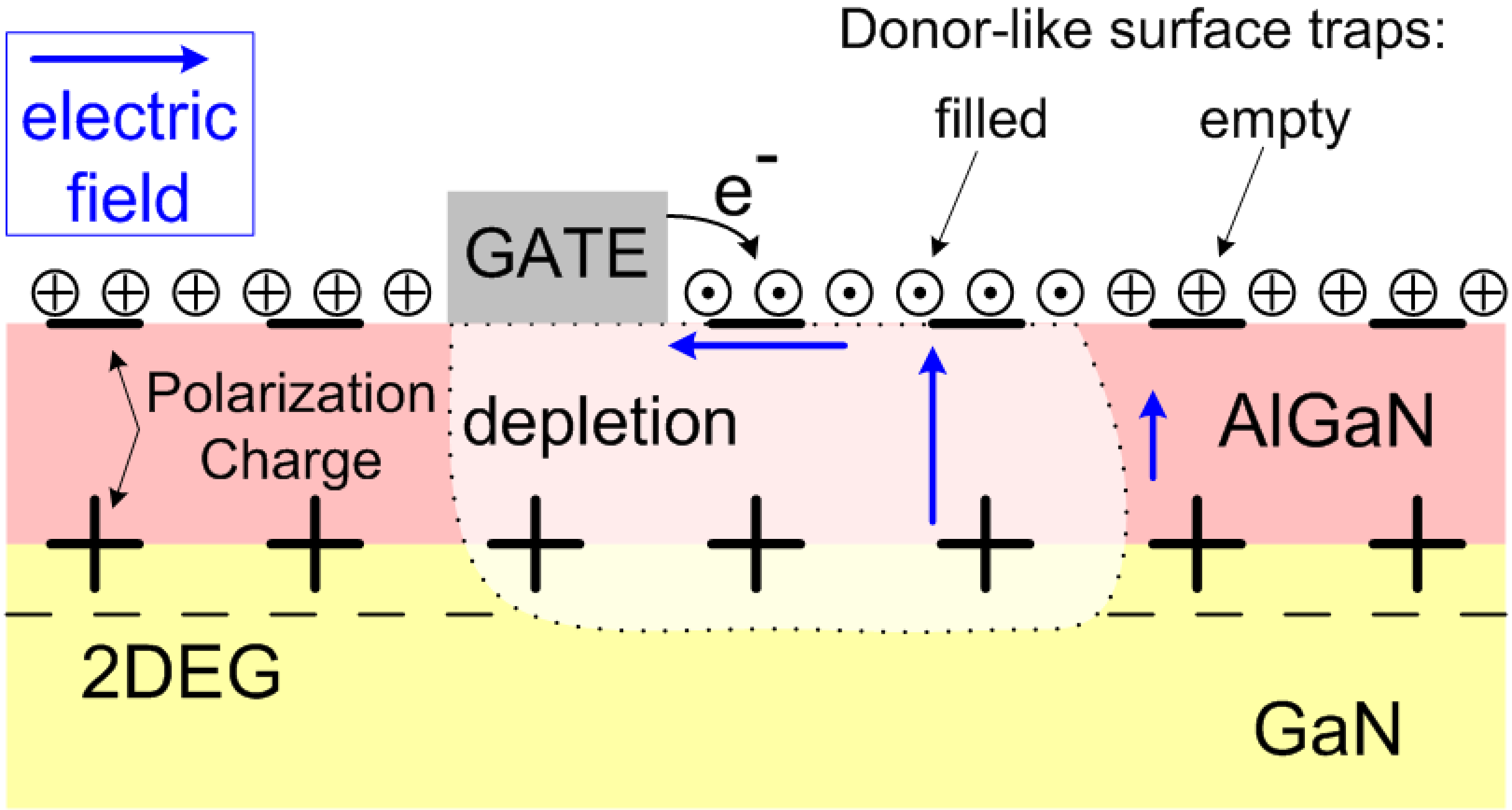
Electron temperature map



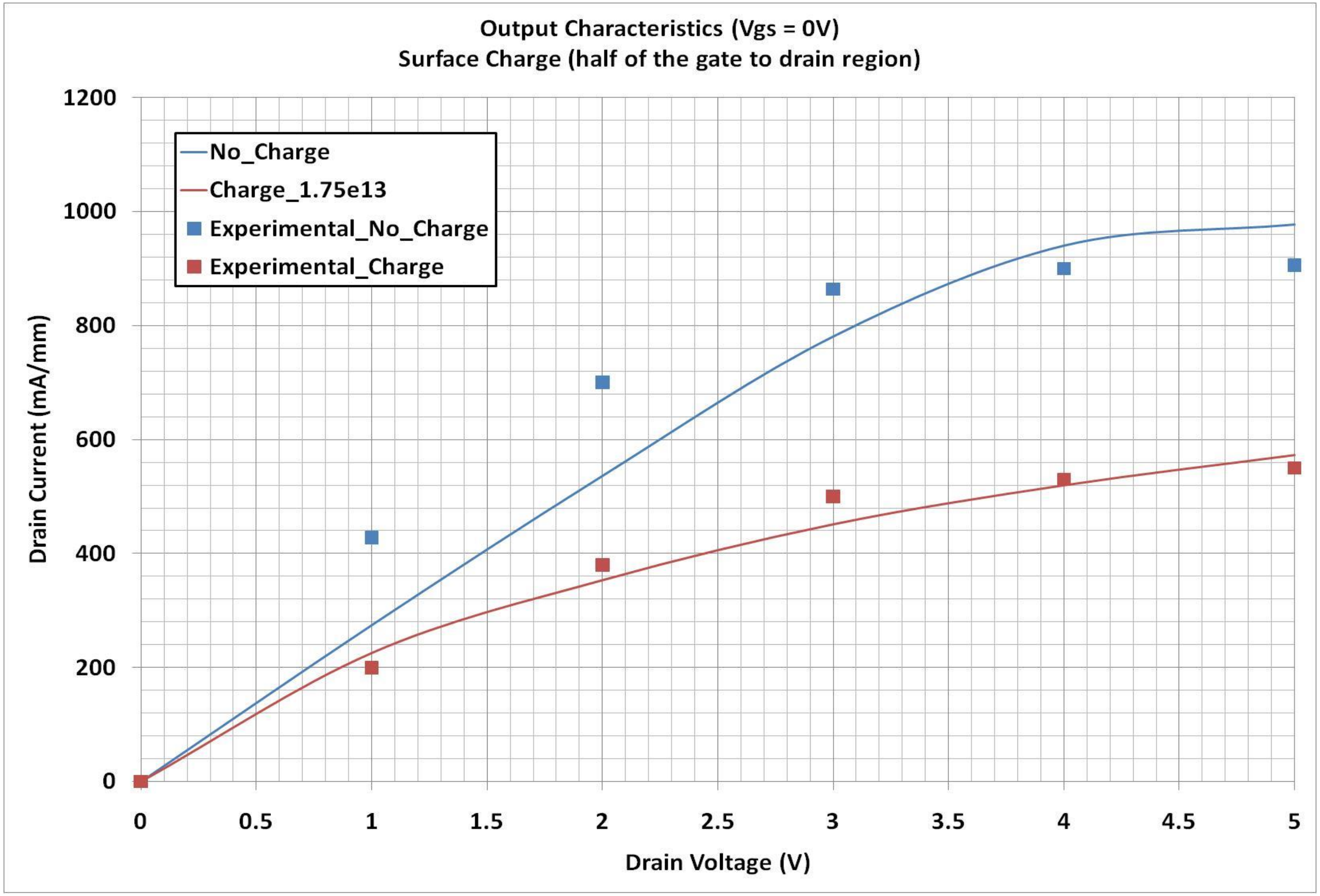
Acoustic phonon temperature map



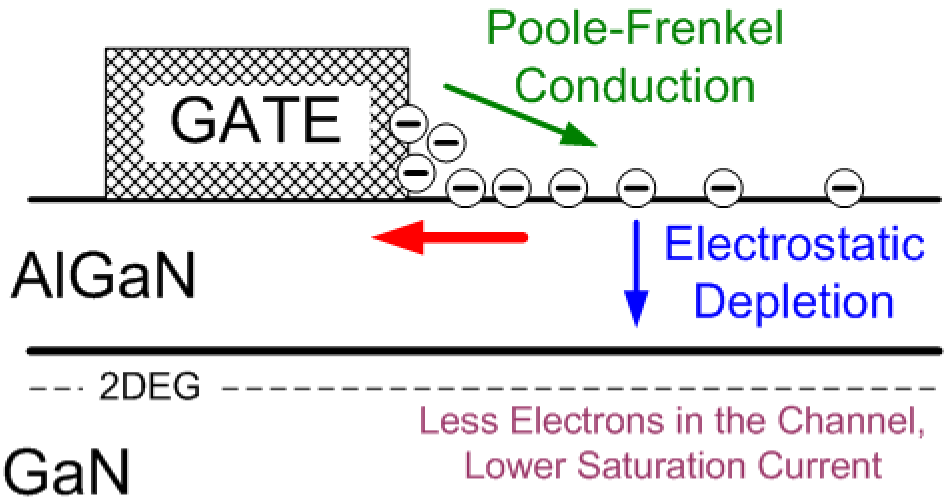
Current collapse



Supporting Evidence: I_d-V_d curve



Mechanism responsible for current collapse



Poole-Frenkel Conduction

GATE

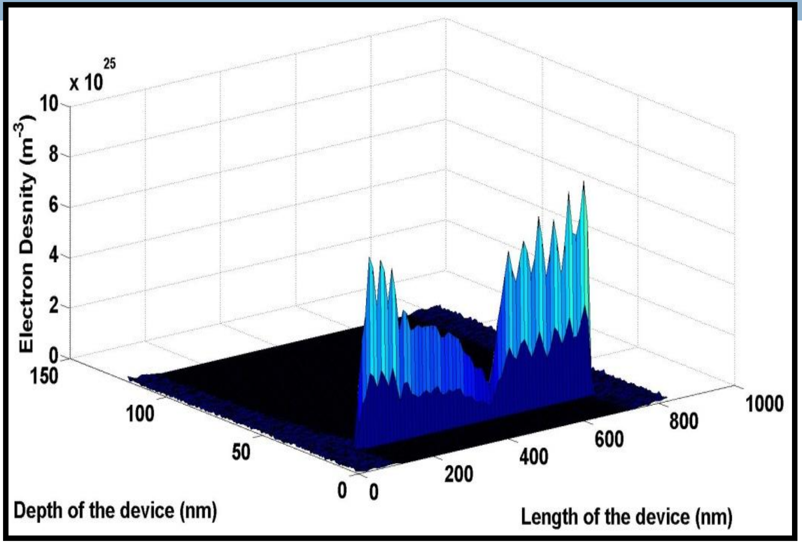
AlGaN

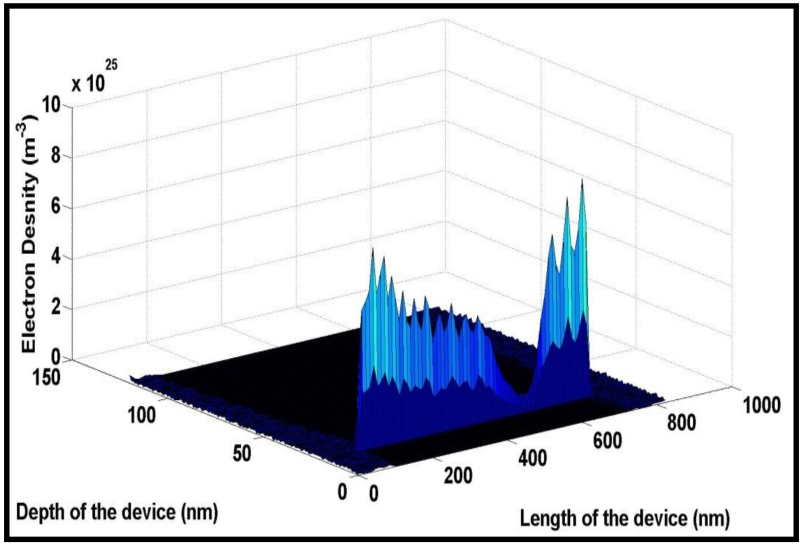
Electrostatic Depletion

2DEG

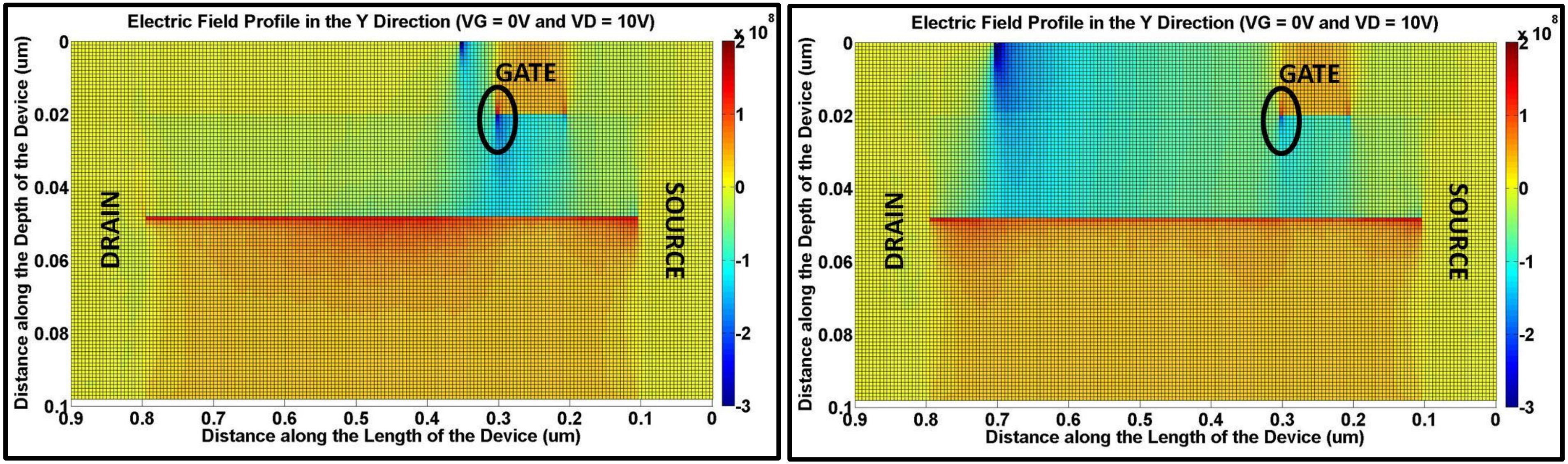
GaN

Less Electrons in the Channel, Lower Saturation Current

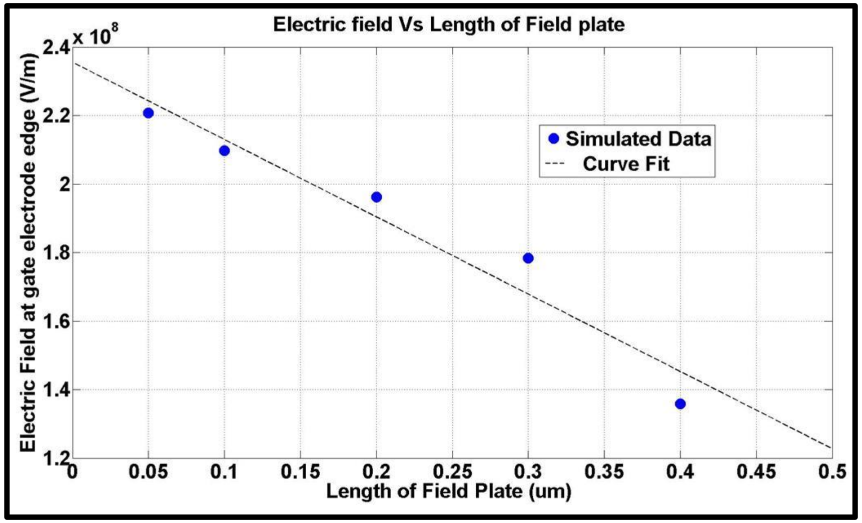




Simulation Results

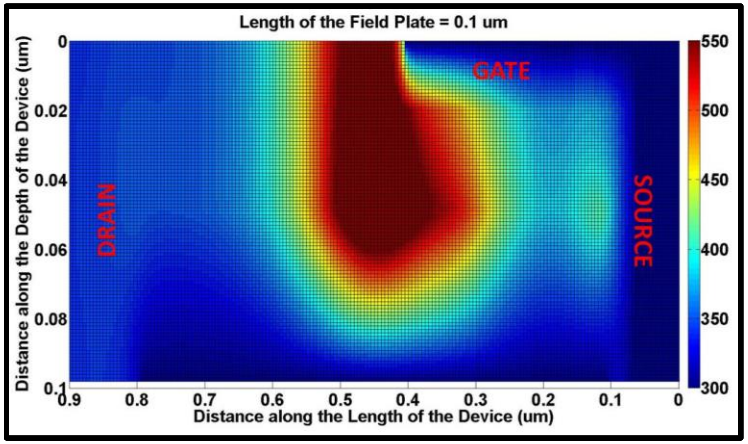


Electric Field Profile in the device with (a) 0.05 µm and (b) 0.4 µm shield lengths respectively

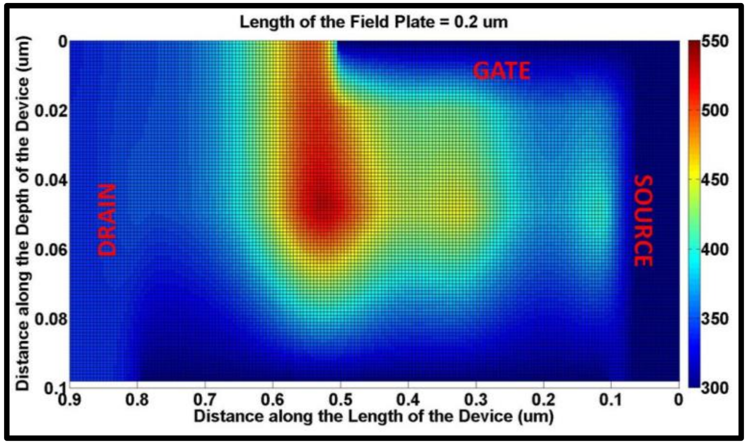


Vertical component of the Electric field at the gate drain edge Vs. field plate length

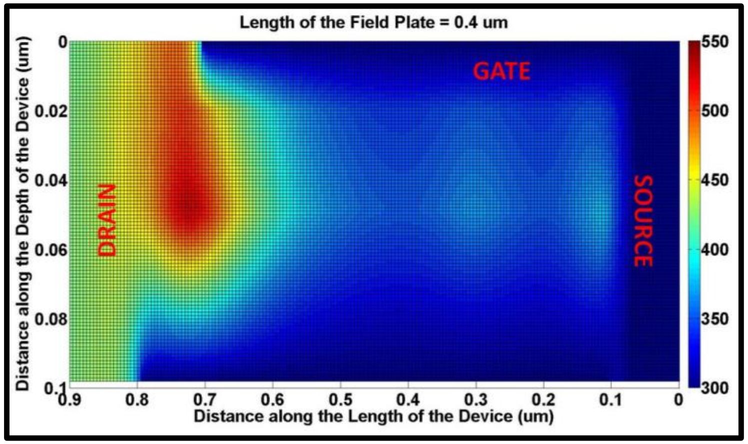
Simulation Results



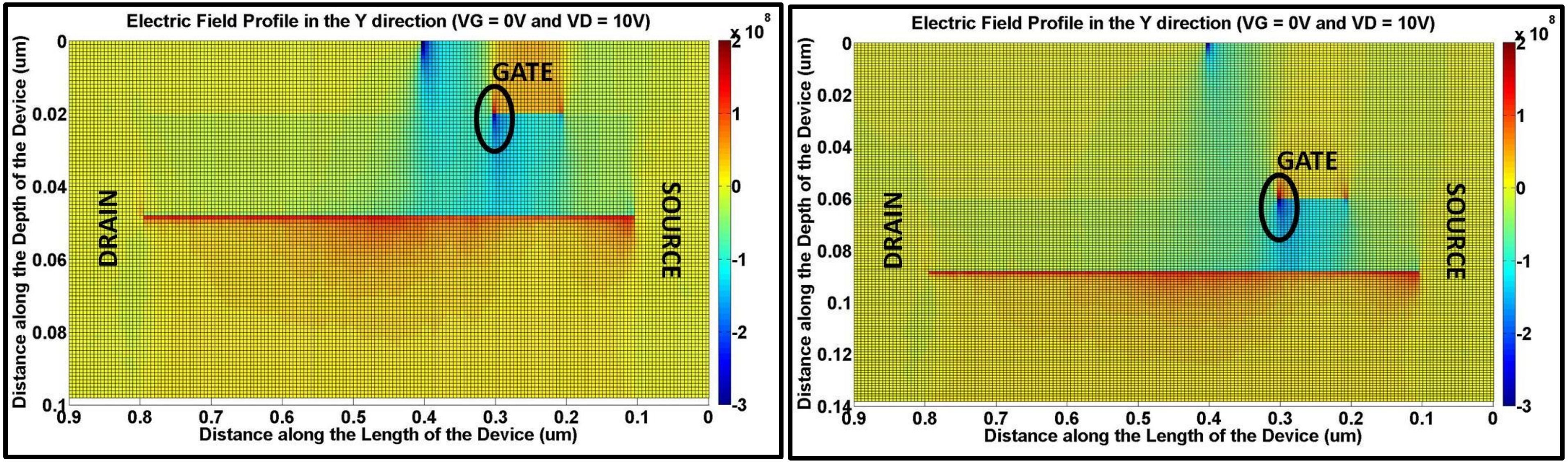
Lattice Temperature Profiles in the AlGaN/GaN HEMT for varying shield lengths (a) 0.1 µm (b) 0.2 µm and (c) 0.4 µm



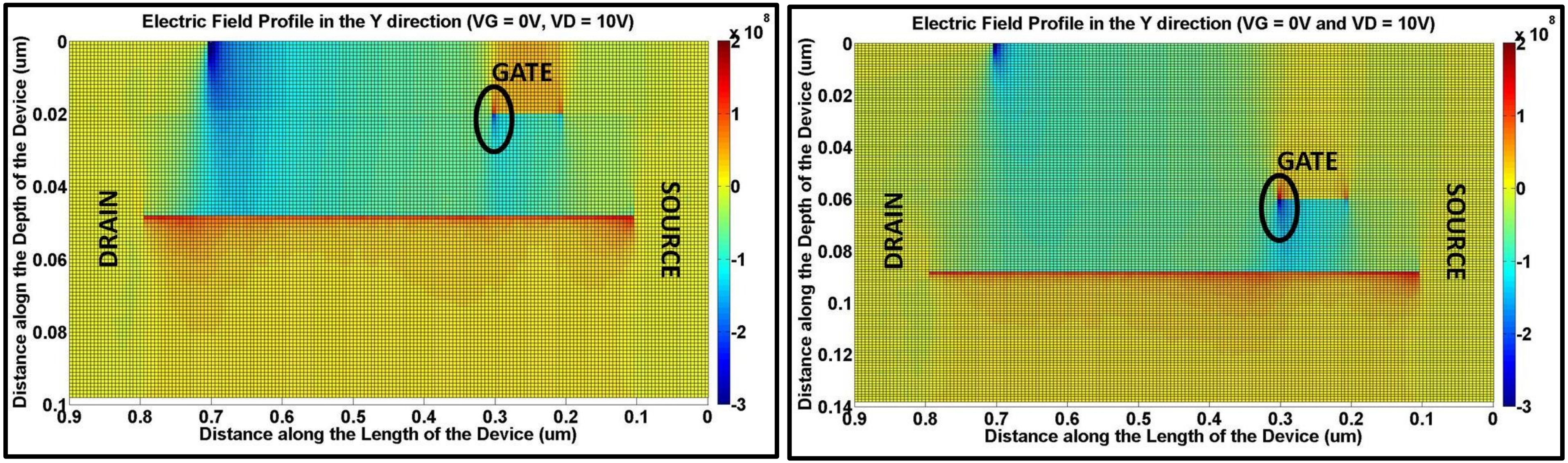
As the peak electric field moves far away from the gate-drain edge, the peak electron velocity also moves with it. The peak lattice temperature follows the peak electron velocity, as the energy of the electrons is highest in this region.



Simulation Results

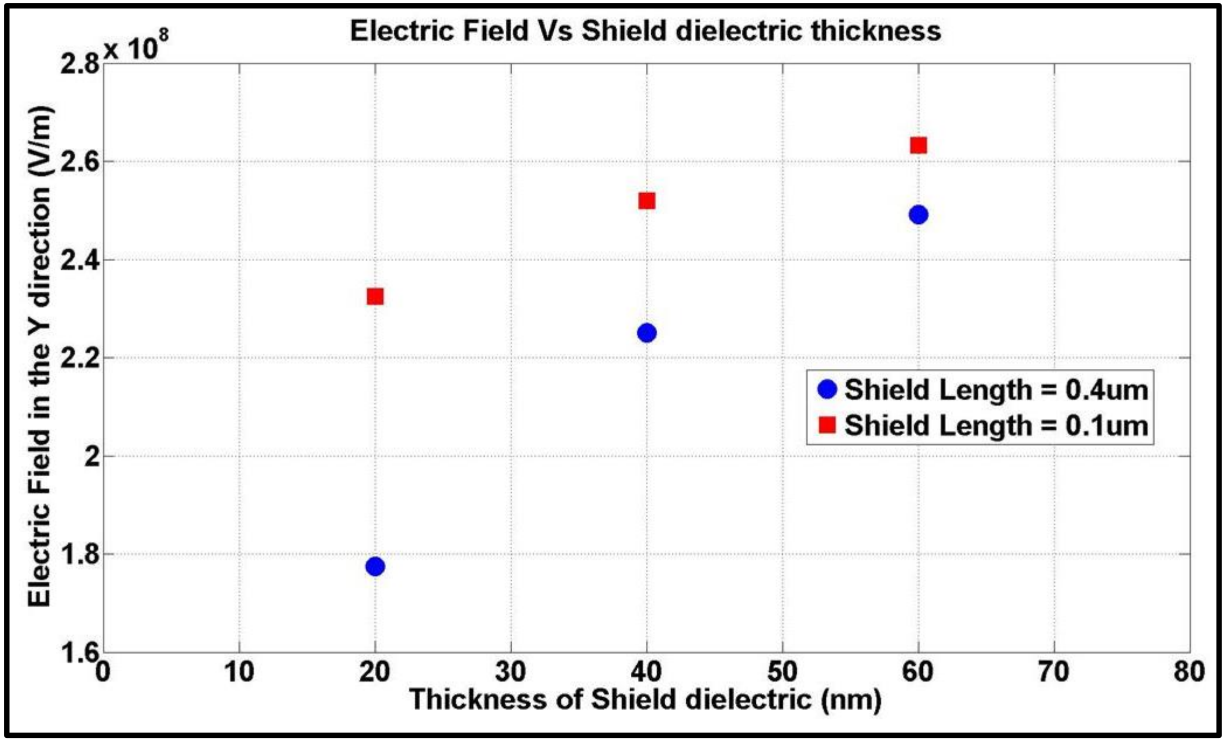


Electric Field Profile in the device for a shield length of 0.1 µm (a) 20 nm and (b) 60 nm shield dielectric lengths respectively



Electric Field Profile in the device for a shield length of 0.4 µm (a) 20 nm and (b) 60 nm shield dielectric lengths respectively

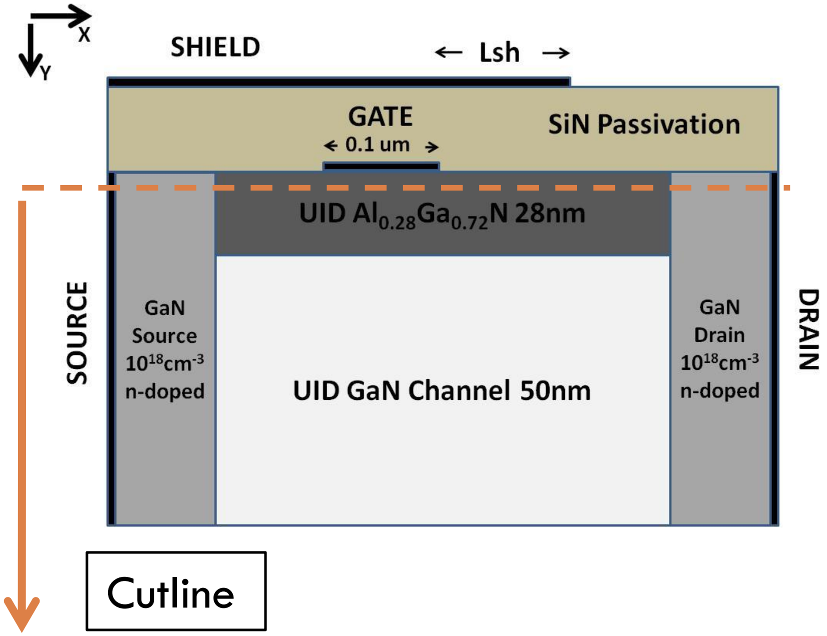
Simulation Results

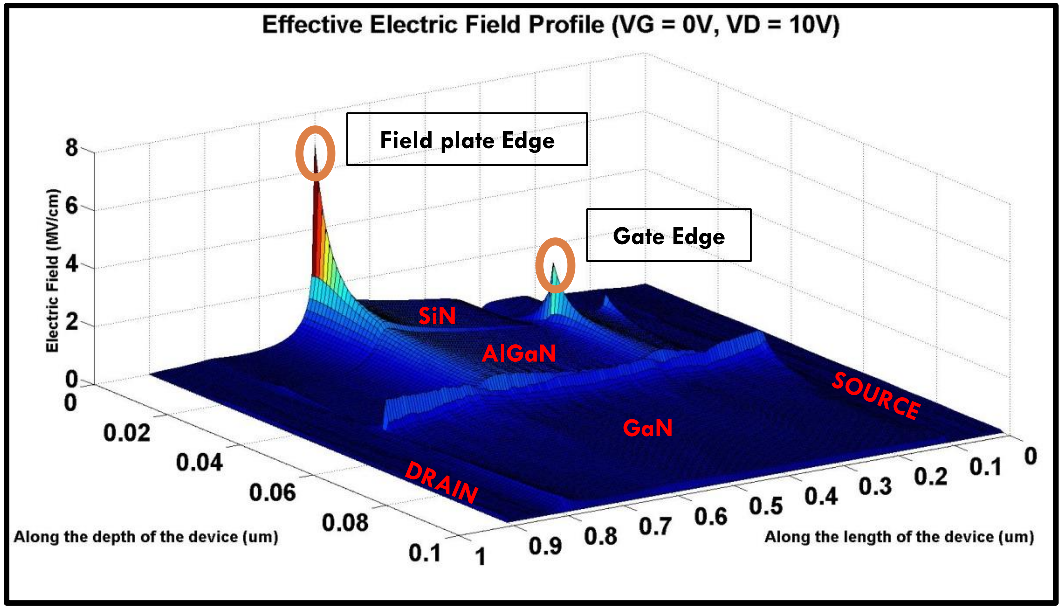


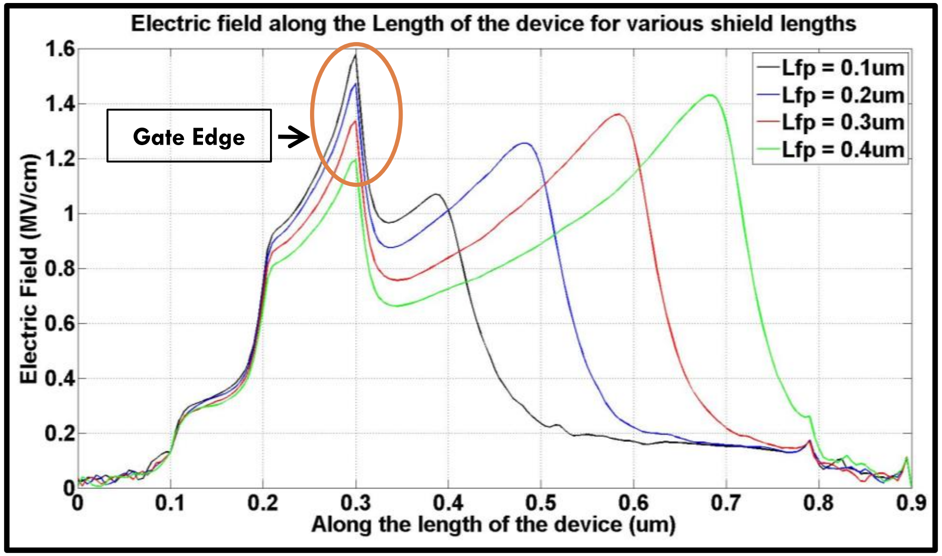
Vertical component of the Electric field at the gate drain edge
Vs. shield dielectric thickness for varying field plate length

- As the shield length increases, the electric field near the critical gate-drain edge reduces. This is because, as the shield electrode length increases, it spreads the electric field over a wider region.
- As the shield dielectric thickness increases, its ability to capacitively couple the electric field with the structure reduces. This results in increase in the electric field near the gate drain edge for a given shield plate length.
- As the field near the gate-drain edge reduces, the potential for electron trapping in the defect sites also reduces and improves the reliability performance of the device structure.

Simulation Results





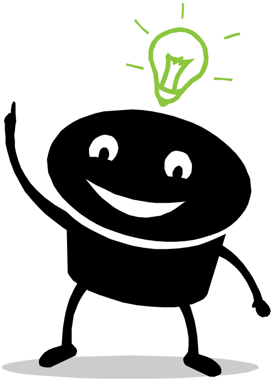


Effective Electric field in the AlGaN Layer for various field plate lengths

- We clearly observe from the electric cutline that as the field plate length is increased the electric field at the gate edge is reduced.

- We also observe that the electric field at the shield edge keeps increasing as its length increases. This is due to the fact that the edge of the shield plate is getting closer to the drain electrode.

PROPOSED RESEARCH AT ASU

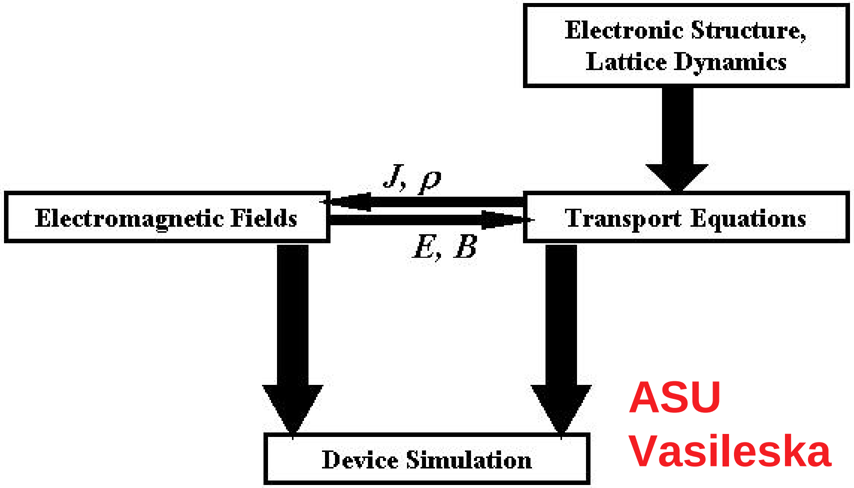


Proposed Tasks

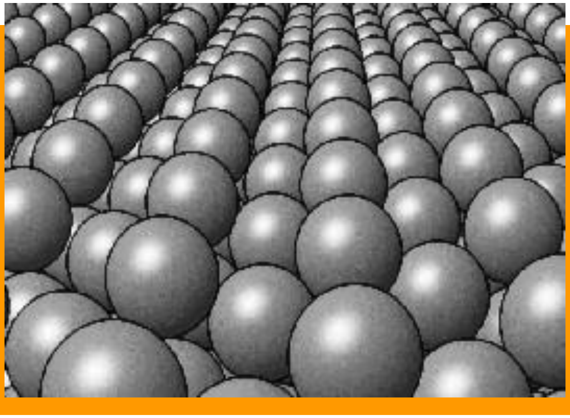
- Creation of regional scattering tables near the PITS and CRACKS
- Formulation of DEFORMATION POTENTIAL THEORY from results obtained with first principle calculations

Proposed Research …

- **Develop theoretical understanding for the formation of cracks in GaN HEMTs**
- **Approach:**
  - **Semiconductor device simulation** to get the electric field profiles in the critical device region
  - Use these external fields into the **molecular dynamics calculations** to see if they are sufficient to nucleate a crack or a permanent defect



ASU Vasileska



Purdue Klimeck

Thanks to **Tsvetanka Zheleva** and the Financial Support From **ARL.**

Conclusions

- Self-heating effects are important factor that must be accounted for as they limit device lifetime
- In ultra-nanoscale devices, due to the ballistic transport of the carriers, the heat dissipation occurs at the contacts **(thermal Landauer picture)**
- In GaN HEMTs heat plays considerable role with respect of the observation of the current collapse phenomena by modifying the vertical electric fields

Lake Ohrid, Republic of Macedonia

Thanks to …

Army Research Laboratory

National Science Foundation