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TCAD assessment of gate-underlapped, Si and 4H-SiC, normally-on, vertical DG JFETs

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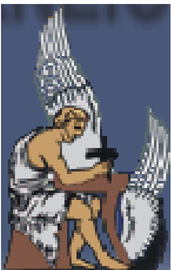


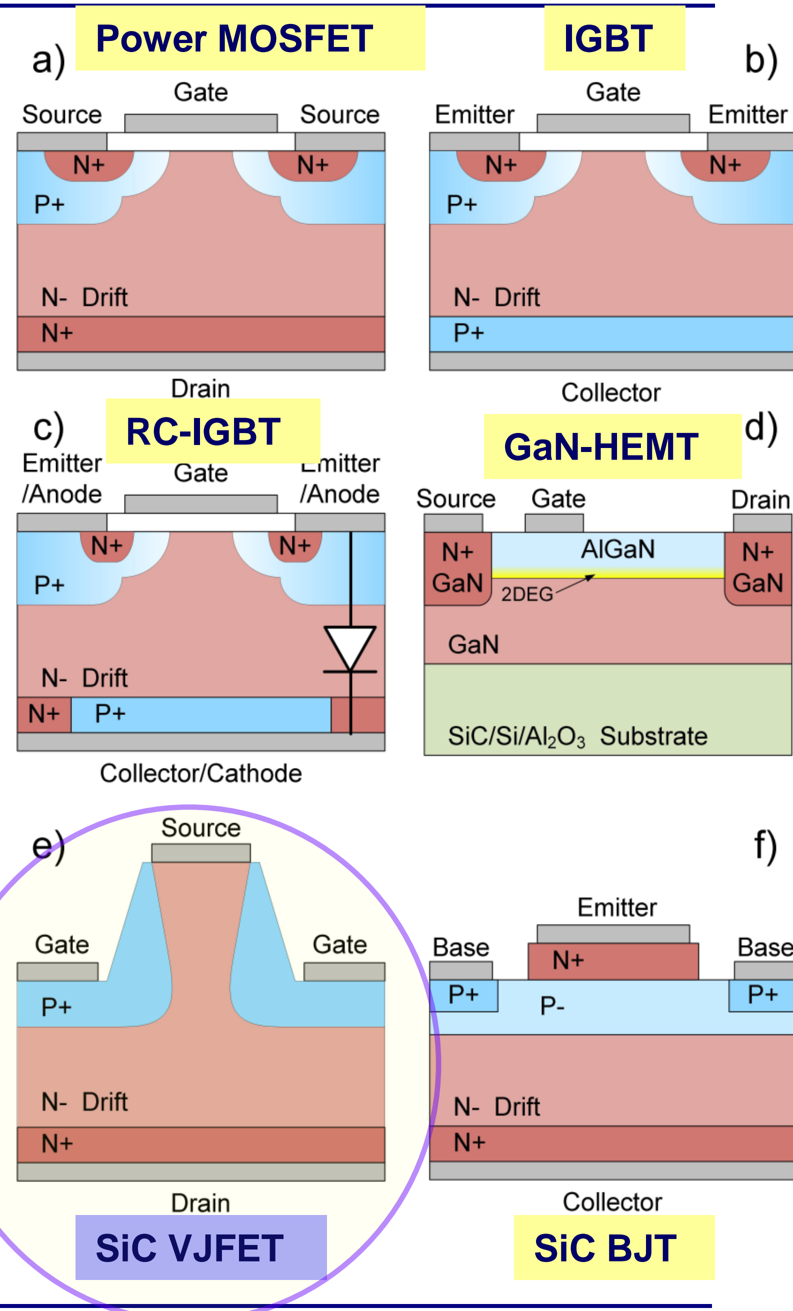
Outline

- SiC based Power Devices
- Comparison of Silicon and Silicon Carbide Materials
- Physical structure of 4H-SiC VJFETs
- Optimization of the Structure
- Thermal Analysis
- Conclusions

SiC based power devices

- SiC Power MOSFETs
- IGBTs
- GaN HEMTs
- SiC VJFETs
- SiC BJTs

- Goal of the project
  - ✓ Inverter for photovoltaic applications, using 4H-SiC JFETs
  - ✓ Development of compact model



Silicon and 4H-Silicon Carbide

- **4H-SiC**
  - ✓ SiC bandgap is three times that of Si
    - Breakdown field (10 times greater than Si)
    - Thinner highly doped voltage-blocking layers
    - High-temperature applications possible >> 300°C
  - ✓ 4H-SiC: mobility much higher than for 6H- or 3C-SiC
  - ✓ Saturated electron velocity of 4H-SiC is twice that of Si
- **Si**
  - Higher mobility than 4H-SiC
  - Higher switching speed
  - Low cost, ease of fabrication

Comparison of SiC with other Semiconductor Materials

Property	6H SiC	4H SiC	3C SiC	GaAs	Si
Wide Energy Bandgap (eV)	2.9	3.26	2.2	1.43	1.12
Electric Field Breakdown ($\times 10^6$ V/cm @ 1000V operation)	2.5	2.2	2.0	0.30	0.25
Thermal Conductivity (W/cm ·€ @ Room T)	4.9	4.8	4.9	0.5	1.5
Saturated Electron Drift ($\times 10^7$ cm/s @ E >2×10^5 V/cm)	2.0	2.0	2.5	1.0	1.0

TCAD simulation – mobility parameters

- **Caughey-Thomas mobility model**

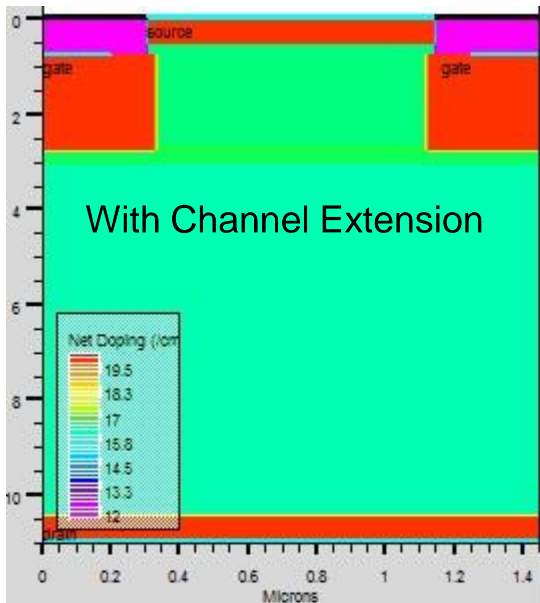
$$\mu_{n0} = \text{MU1N.CAUG} \cdot \left(\frac{T_L}{300K}\right)^{\text{ALPHAN.CAUG}}$$

$$+ \frac{\text{MU2N.CAUG} \cdot \left(\frac{T_L}{300K}\right)^{\text{BETAN.CAUG}} - \text{MU1N.CAUG} \cdot \left(\frac{T_L}{300K}\right)^{\text{ALPHAN.CAUG}}}{1 + \left(\frac{T_L}{300K}\right)^{\text{GAMMAN.CAUG}} \cdot \left(\frac{N}{\text{NCRITN.CAUG}}\right)^{\text{DELTAN.CAUG}}}$$

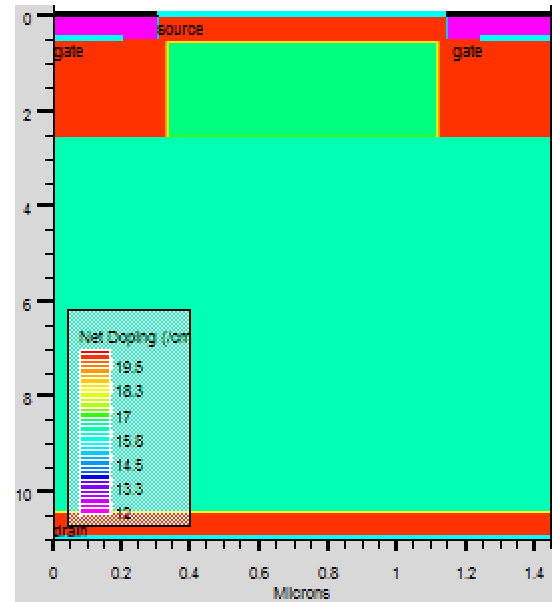
Parameter	Unit	Si	*4H-SiC
MU1N	cm^2/Vs	55.2	40
MU2N	cm^2/Vs	1429	950
NCRITN	cm^{-3}	9.68×10^{16}	2×10^{17}
ALPHAN	-	0	-0.5
BETAN	-	-2.3	-2.4
GAMMAN	-	-3.8	0.0
DELTAN	-	0.73	0.76

* Roschke, Schwierz, IEEE TED 48(7), 2001

VJFETs with and without channel extension



- Normally-on VJFET **with** channel extension
  - ✓ V_T depends on doping of channel & dimensions
  - ✓ V_T less sensitive to drift region doping
  - ✓ Better performance (Ron vs. Breakdown voltage)

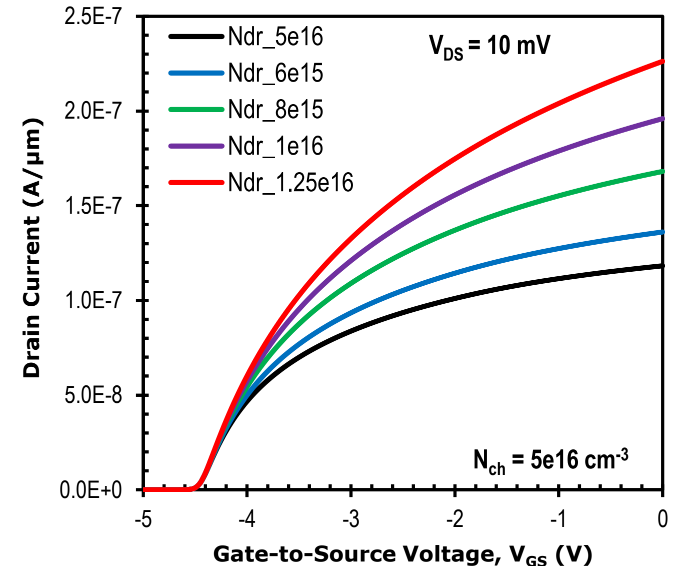


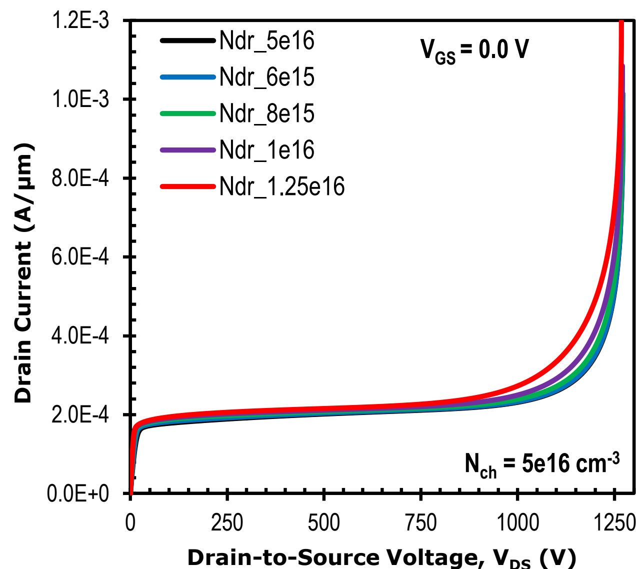
- Normally-on VJFET **without** channel extension
  - ✓ V_T depends on doping of channel, drift region & dimensions
  - ✓ Highly sensitive to drift region doping

- Channel extension VJFET is desirable

Optimization of channel extension vertical DG JFET structure

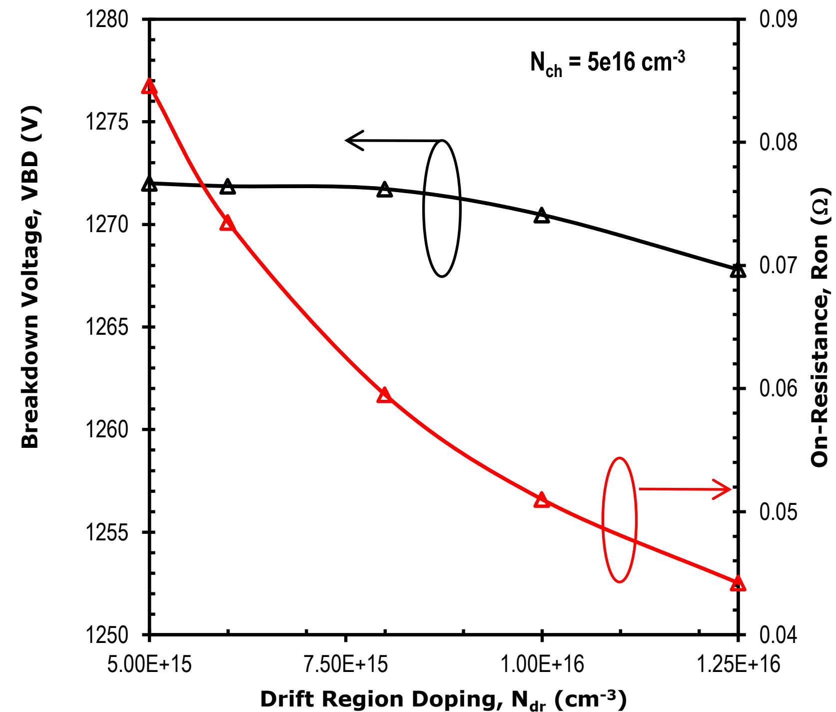
- Normally-on VJFET with channel extension
  - ✓ V_T not sensitive to drift region doping (Ndr)
  - ✓ Increase in drain current with increase of drift region doping





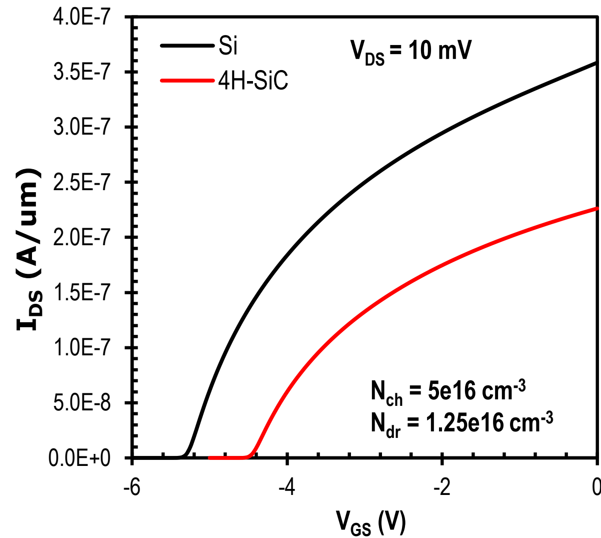
- ✓ Blocking voltage: slightly changes with Ndr

Optimization (breakdown vs. on-resistance)

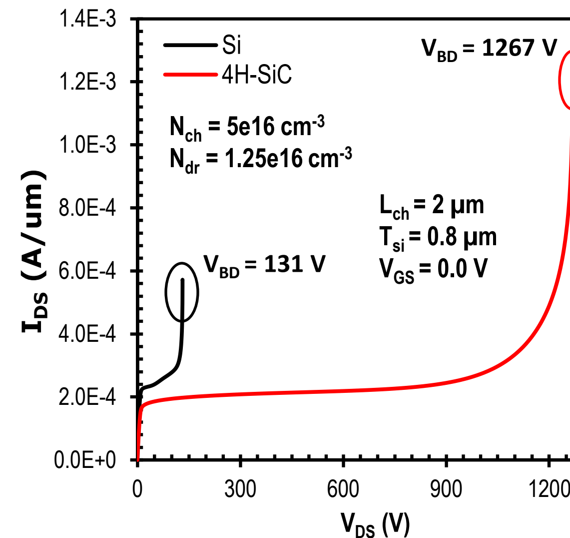


- Normally-on VJFET with channel extension
  - ✓ Improved on-resistance (Ron) with higher Ndr
  - ✓ Almost same breakdown voltage

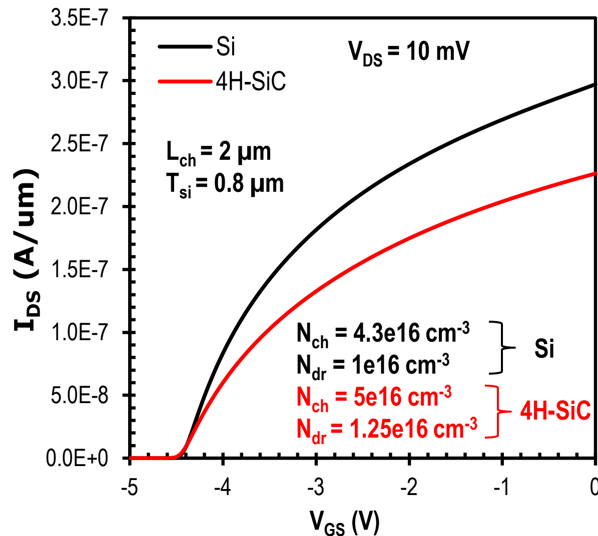
Comparison: Si and 4H-SiC vertical JFET



- Si and 4H-SiC (same physical parameters)
  - ✓ V_T difference ~ 1.0 V
  - ✓ Breakdown field for 4H-SiC (~10 times greater than Si)

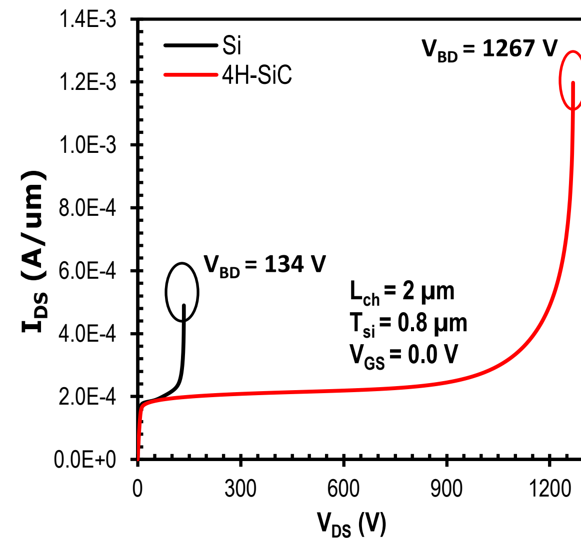


Comparison: Si and 4H-SiC vertical JFET

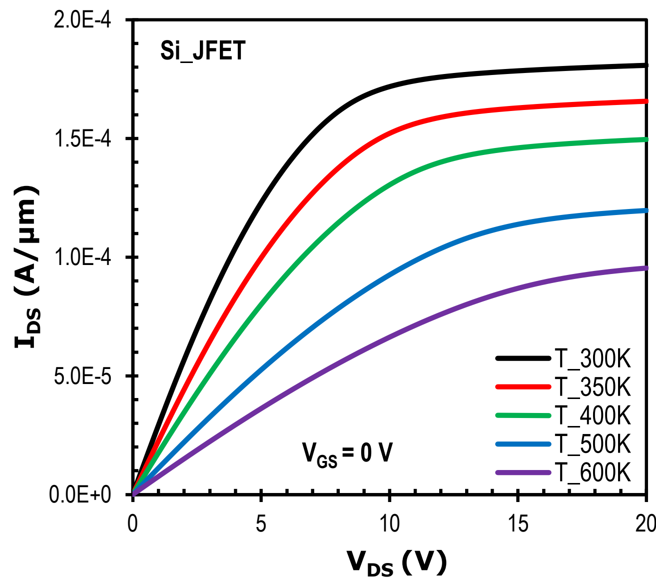


- Si and 4H-SiC
  - ✓ Optimize channel doping of Si JFET for similar V_T
  - ✓ Maintaining the ratio of channel doping (Nch) to drift region doping (Ndr)

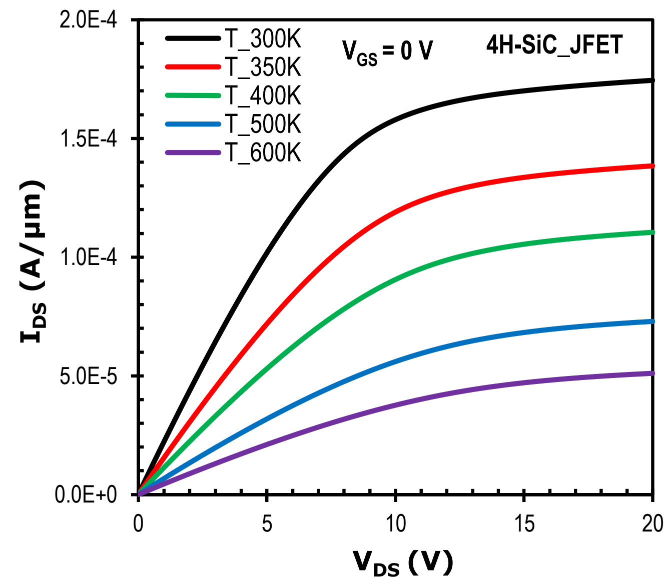
- 30 % higher drain current for Si JFET (higher mobility)



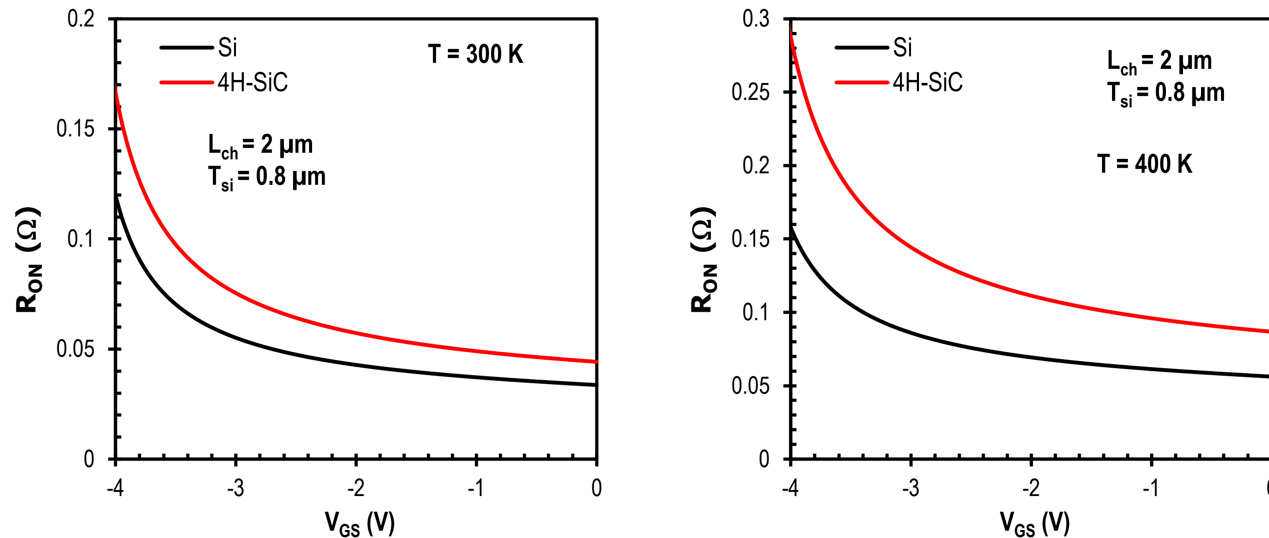
Thermal analysis



- Si and 4H-SiC vertical JFET
  - ✓ Higher drain current for Si JFET
  - ✓ Drain current decreases slightly more for 4H-SiC with temperature

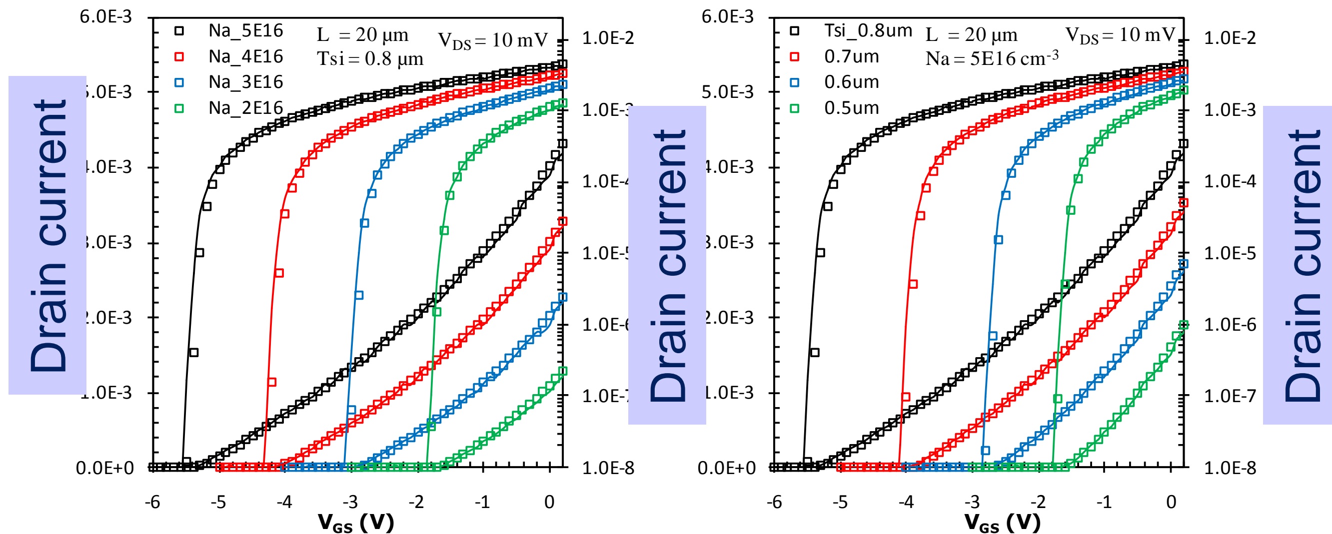


Thermal analysis



- Si and 4H-SiC vertical JFET
  - ✓ Lower R_{on} for Si JFET
  - ✓ R_{on} increases with increasing temperature
  - ✓ The increase in R_{on} with increasing temperature is less for Si JFET

Outlook: compact model development



- First JFET charge-based model presented at MOS-AK 9/2012
- New model development underway
- Full charge-based intrinsic model for channel region
- Short-channel effects, scalability
- Drift extension modelling

Conclusions

- **Optimization**
  - ✓ Channel extension JFET is desirable for better on-resistance vs. breakdown voltage
  - ✓ Channel extension JFET, less sensitive for drift region doping.
  - ✓ Ratio of channel doping-to-drift region doping is very important.
- **TCAD based analysis, Si vs. 4H-SiC JFET**
  - ✓ 4H-SiC JFET – good for very high voltage, high power applications
  - ✓ Si JFET – performs better up to 150 V applications
  - ✓ Si JFET - less sensitive to temperature
- **Full scalable compact model for power JFETs underway.**

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