GaN HEMT Devices and Modeling for Operational Electronics within Harsh Environments

Saleh Kargarrazi

Postdoc | Aeronautics and Astronautics Department

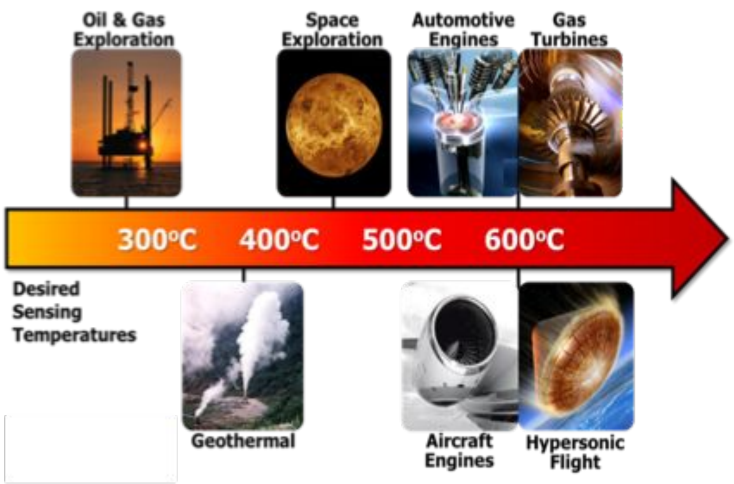
EXtreme Environment Microsystems Lab (XLab)

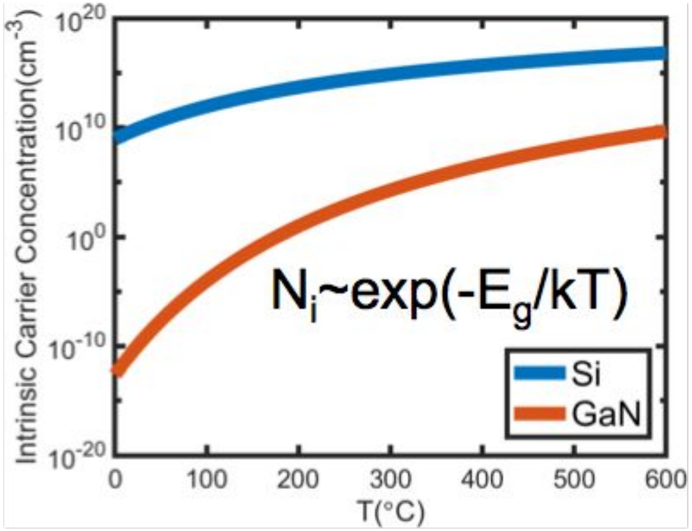
xlab.stanford.edu | +1.669.273.9990

Advisor: Prof. Debbie Senesky

Wed, 5th Dec. 2018

Why wide-bandgap electronics?

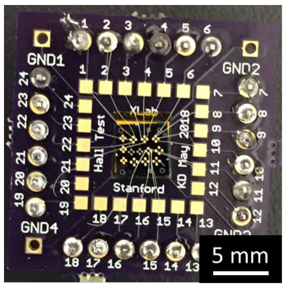




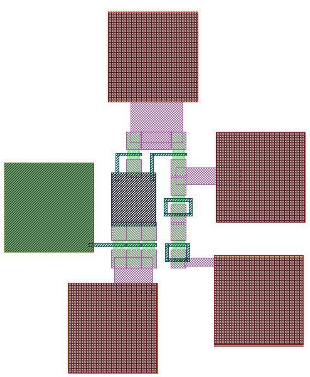
- Sensing in harsh environments require robust transistors
- **Problem:** Silicon device failure at ~125°C due to low bandgap (1.1eV)
- **Solution:** Wide-bandgap (3.4eV) material, Gallium-Nitride (GaN)

An Example of for a Sensor/Electronics system

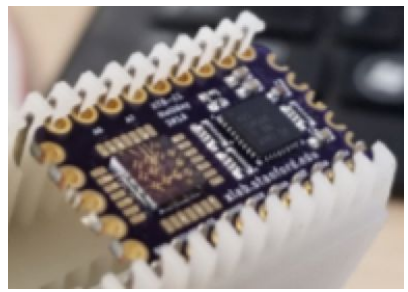
GaN-based Sensor:

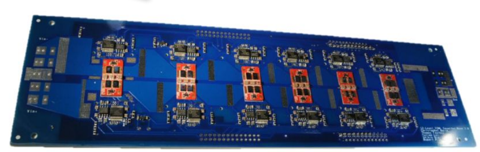


GaN-base d IC:



GaN-based Sensor + IC "Surfboard"



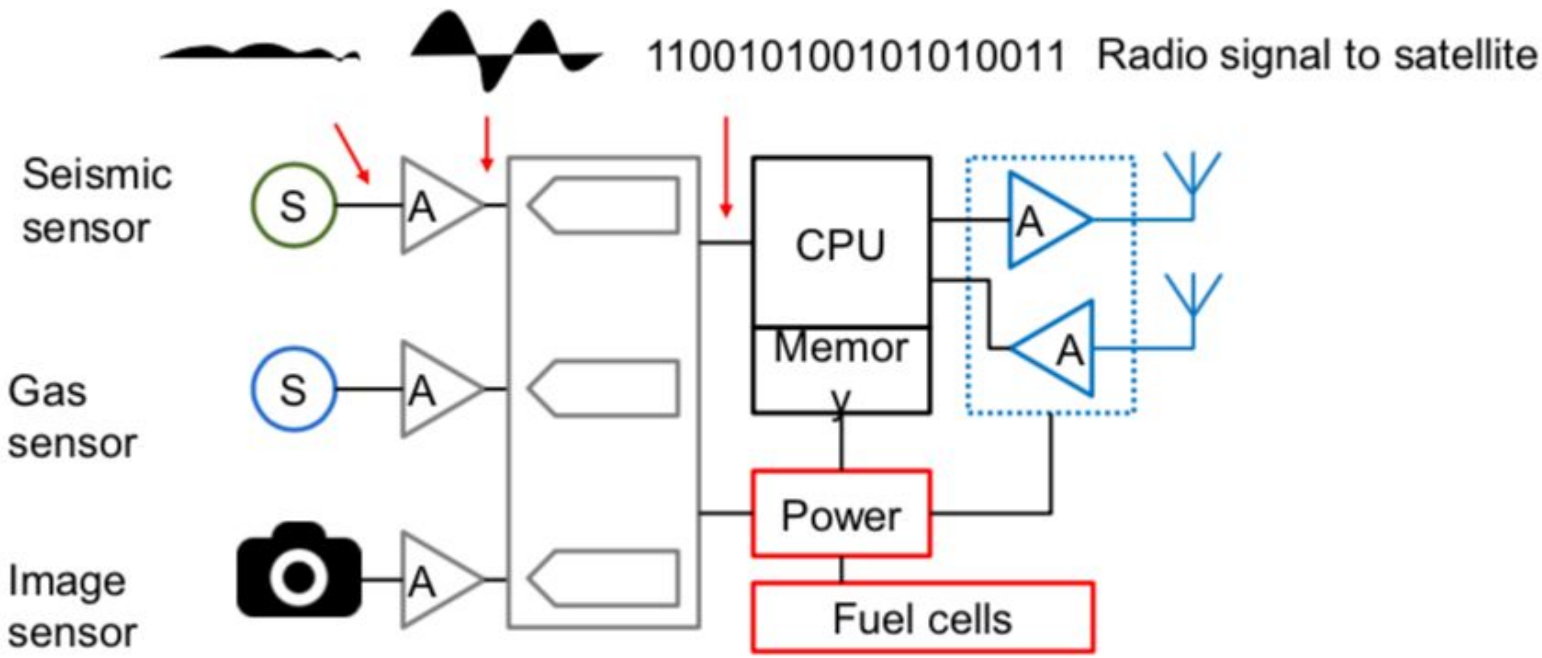


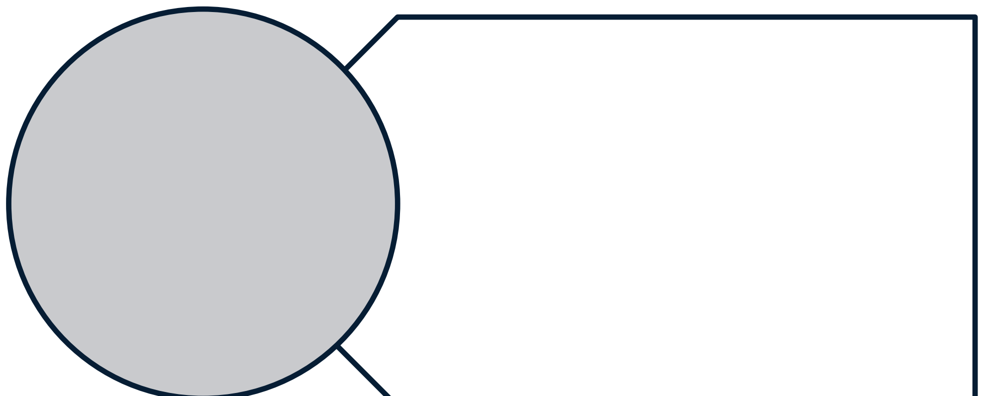
GaN-based Converter Board (R. Pilawa)

Next-generation Aviation

Collaborations:
Profs. Mantooth, Ang, Salamo, and Pop

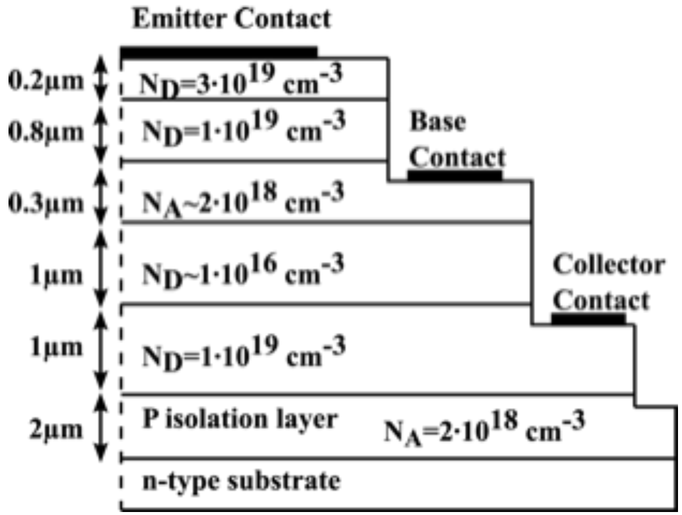
A High-T Electronic System



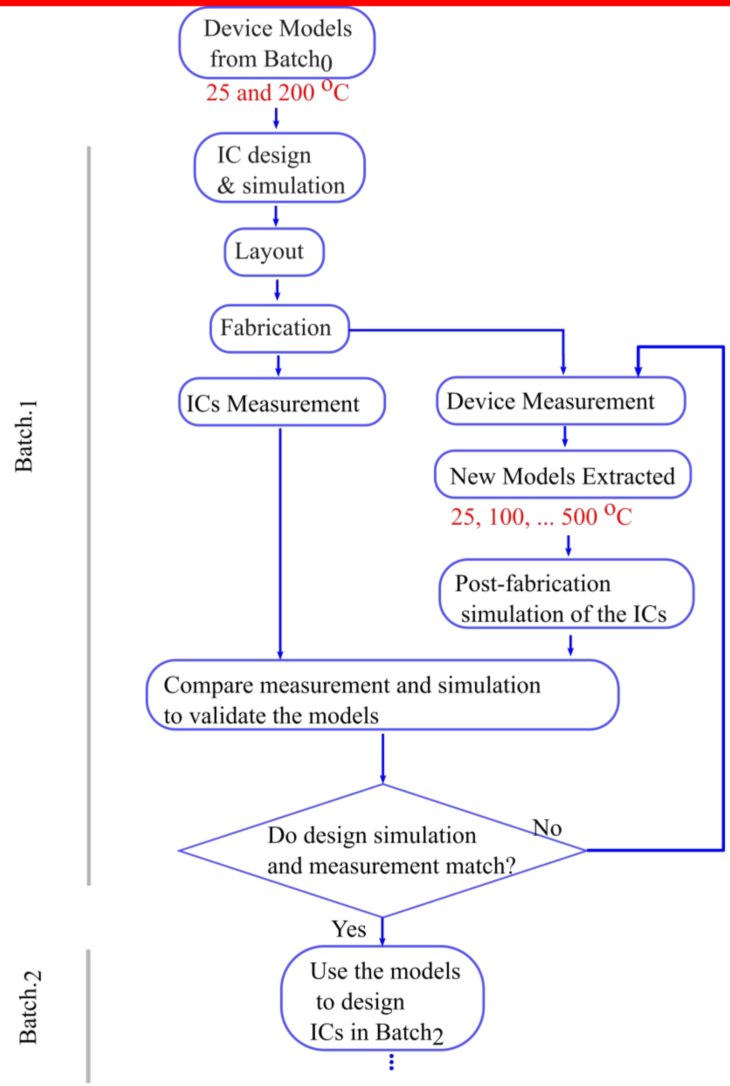


SiC Bipolar Junction Transistors (BJTs)

- 4H-SiC substrate
- Epitaxial Emitter, Base and Collector layers
- Plasma etching
- Metallization and Passivation

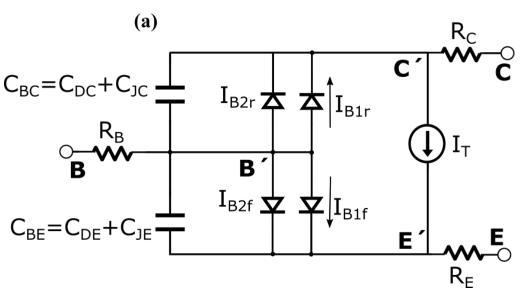


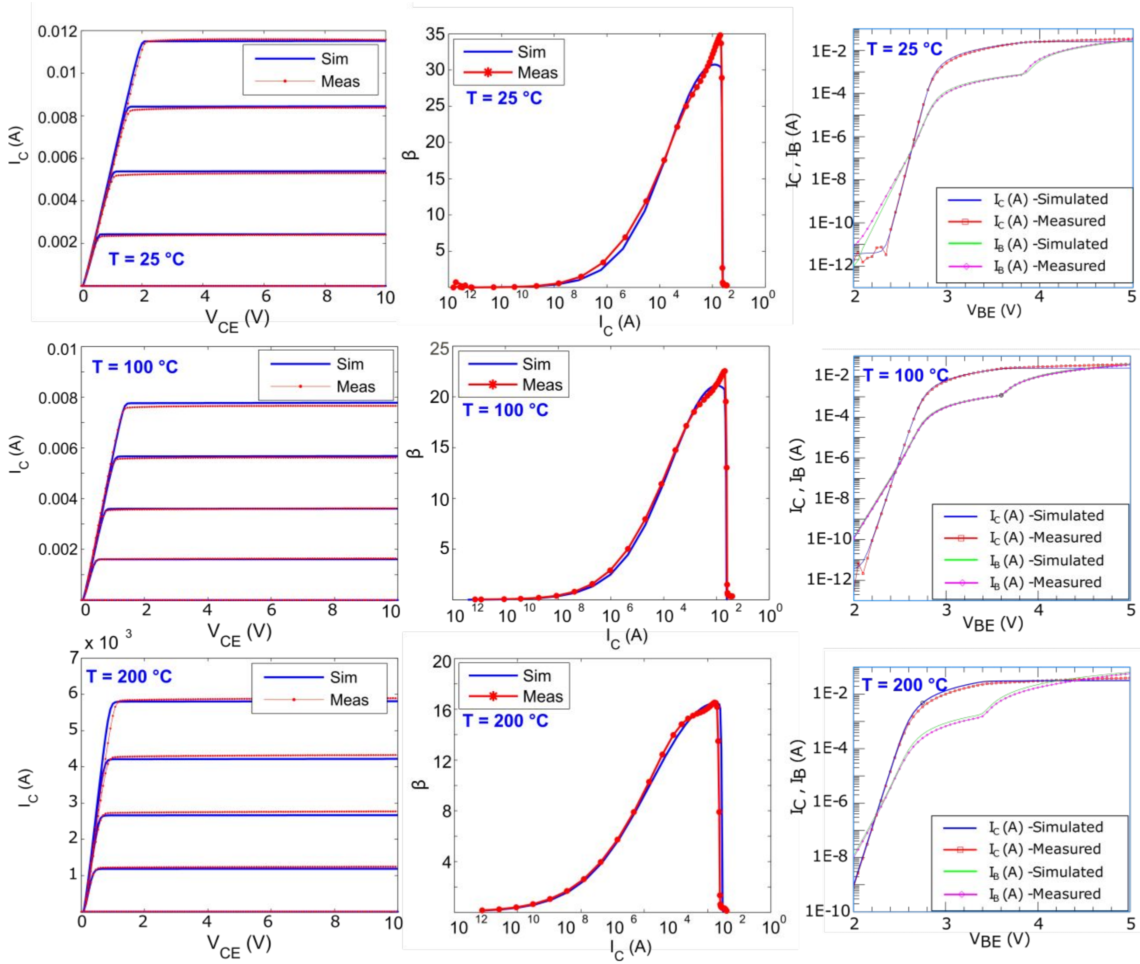
SiC IC Implementation Flowchart



Device modeling for SiC IC design (NPN BJTs)

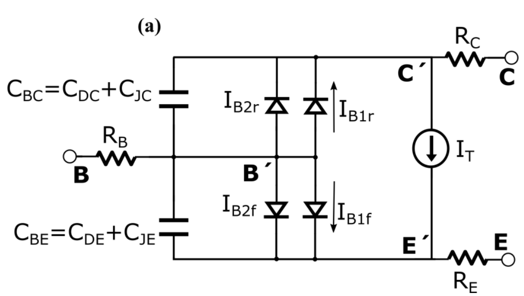
- SPICE Gummel-Poon model
- Batch.0 models as the start
- Measurement of Batch.1 BJTs
- Fitting and parameters extraction Using ICCAP

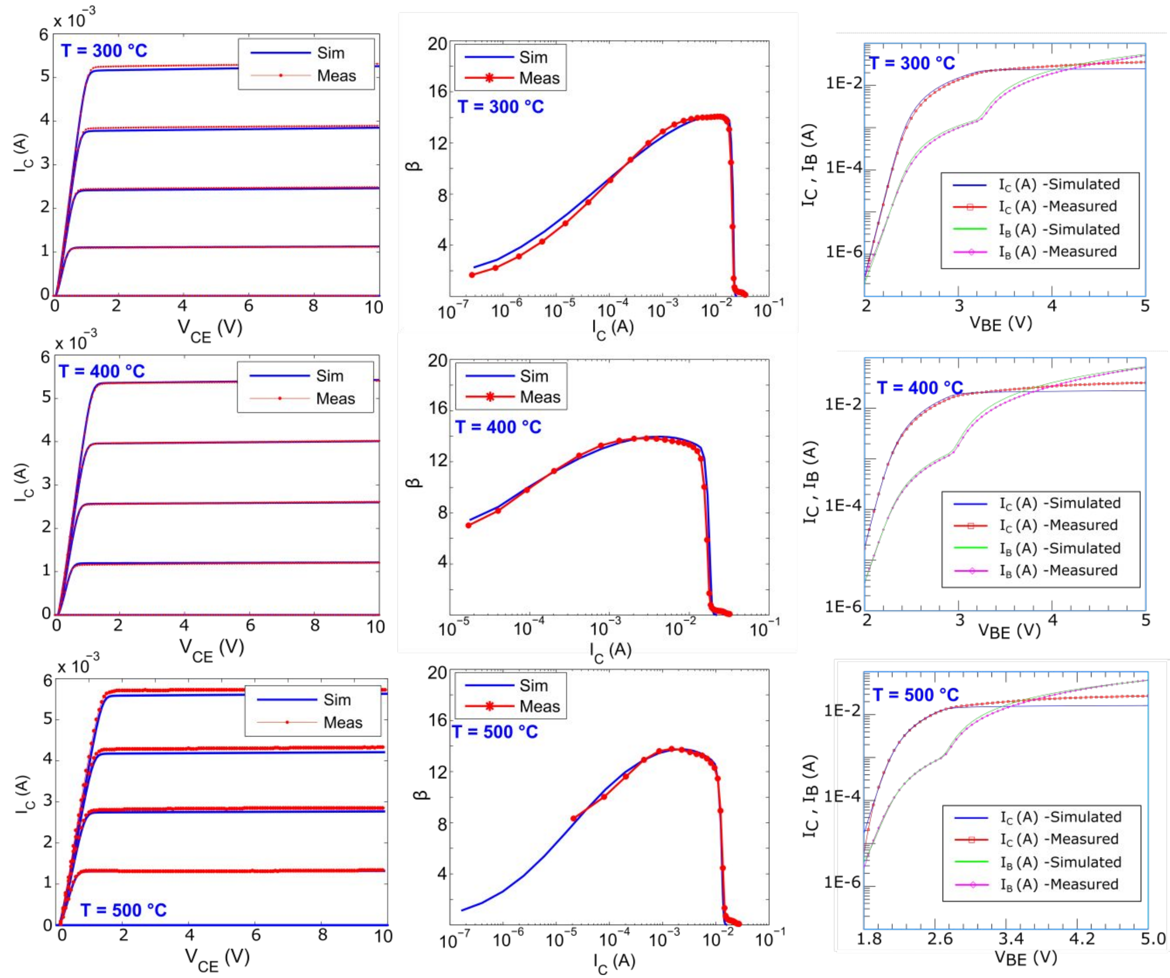




Device modeling for SiC IC design (NPN BJTs)

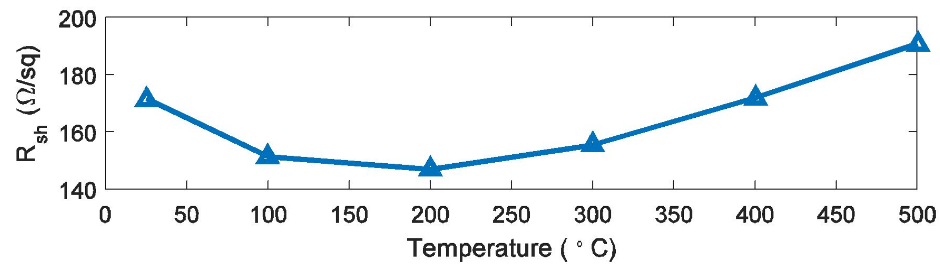
- SPICE Gummel-Poon model
- Batch.0 models as the start
- Measurement of Batch.1 BJTs
- Fitting and parameters extraction Using ICCAP



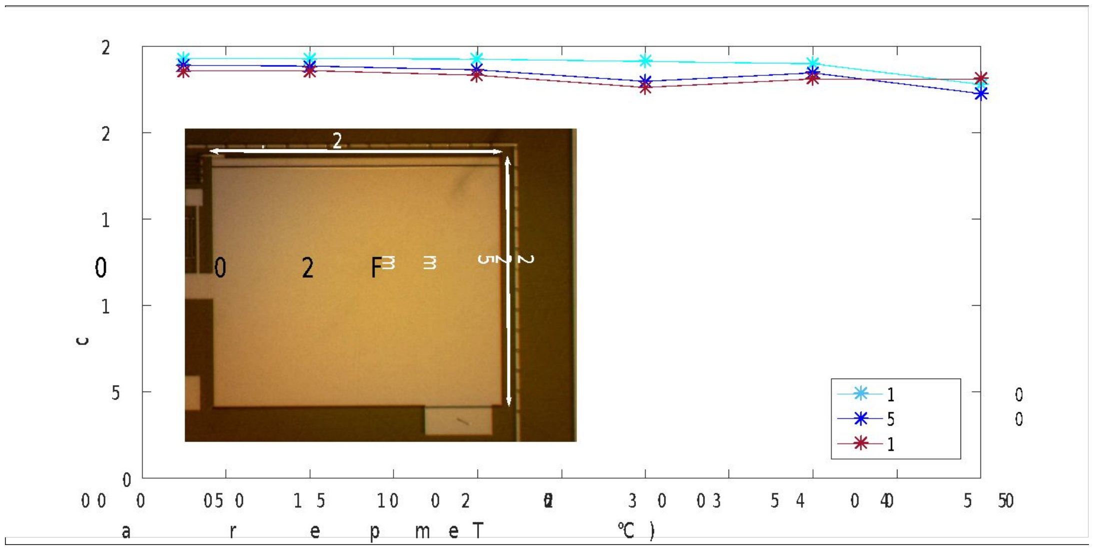


Device Modeling (integrated resistors and capacitors)

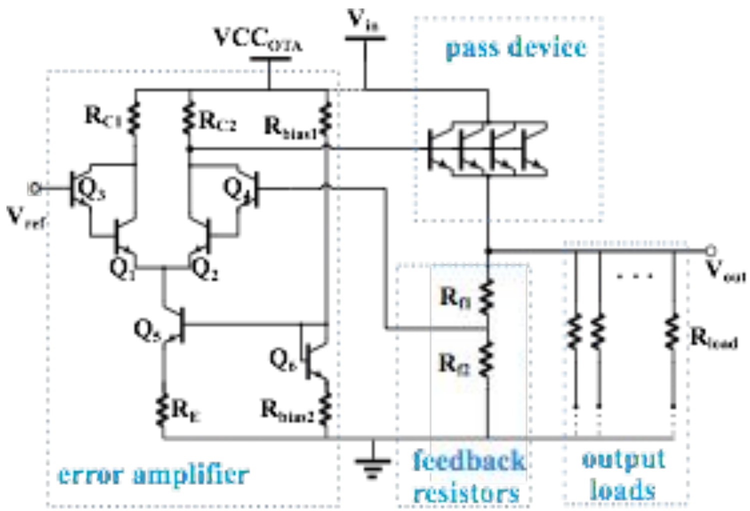
- ❖ Resistors on collector highly-doped epi-layer
- ❖ Non-monotonous temperature-dependence

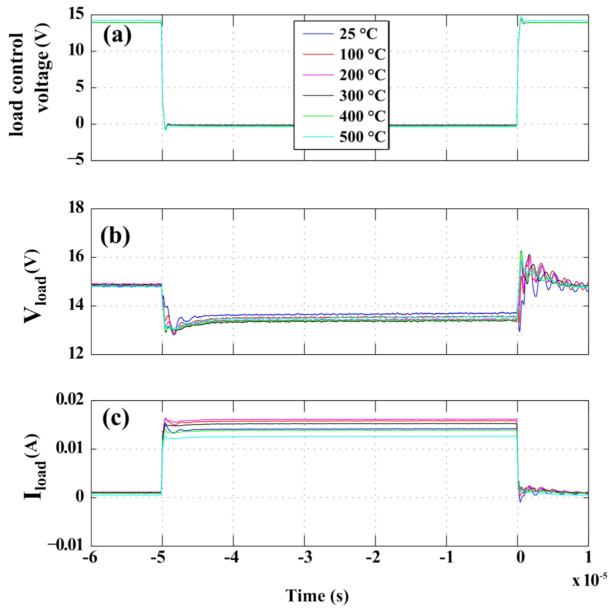


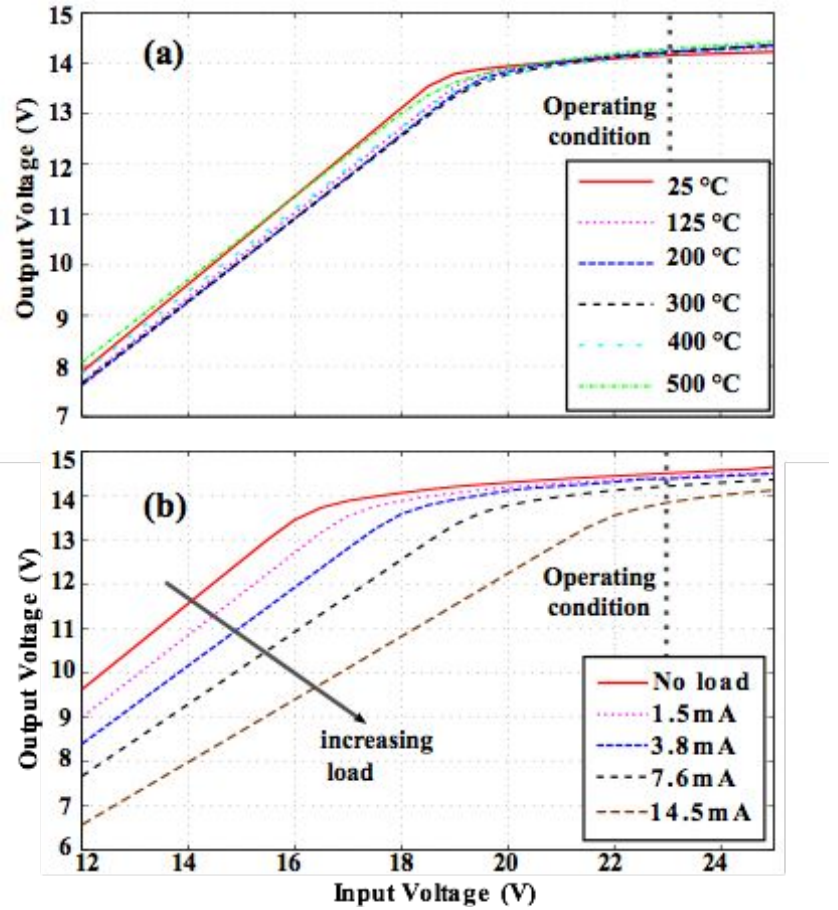
- ❖ Parallel plated capacitors
- ❖ constant over temperature



SiC-based Integrated Circuits
Example I (Linear voltage regulator)

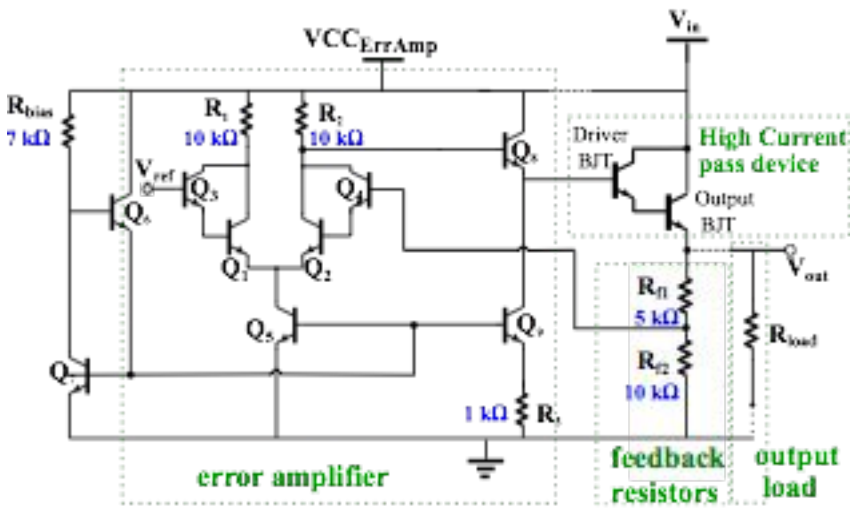


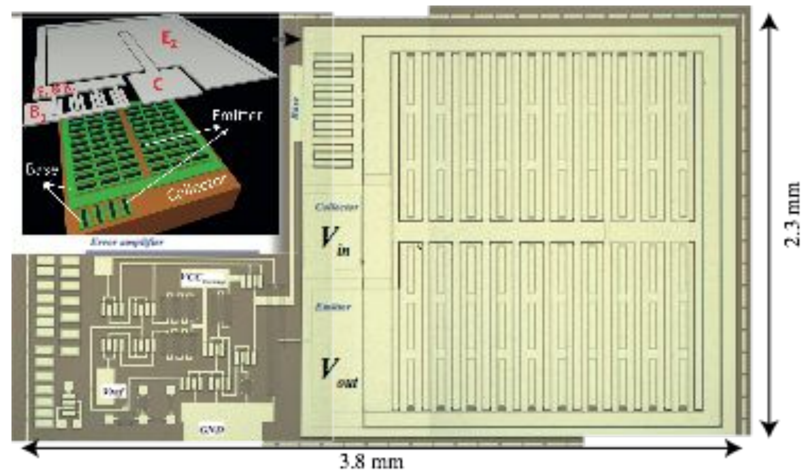


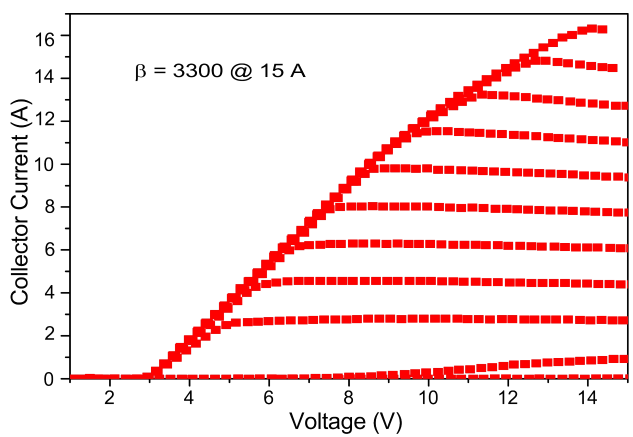


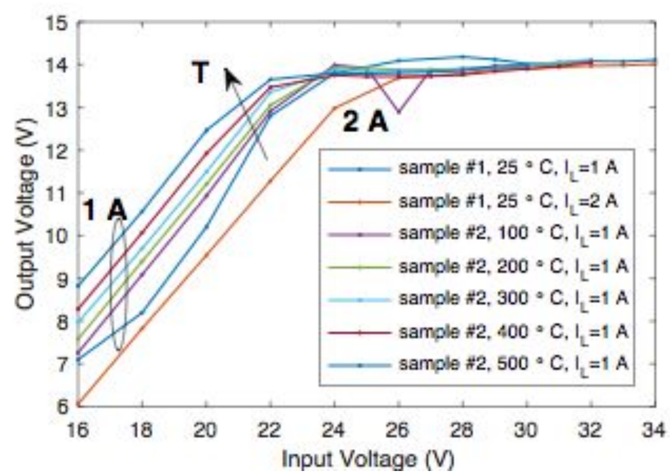
S. Kargarrazi, C.-M. Zetterling, et al., ***IEEE Transactions on Electron Devices*** **(2015)**

SiC-based Integrated Circuits
Still Example II (Linear voltage regulator)



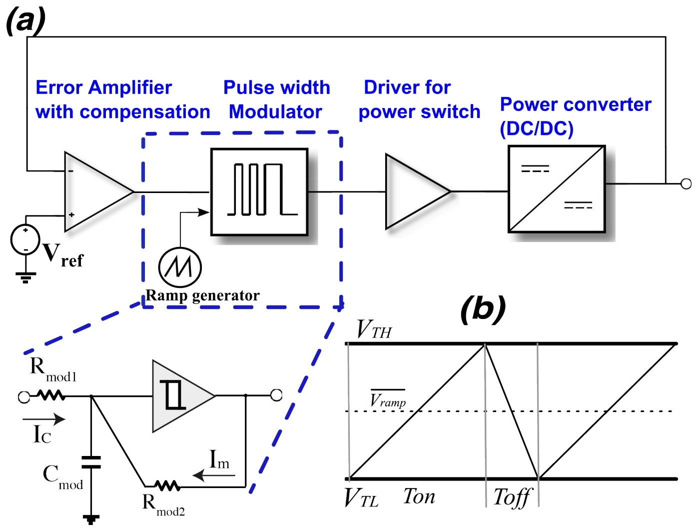


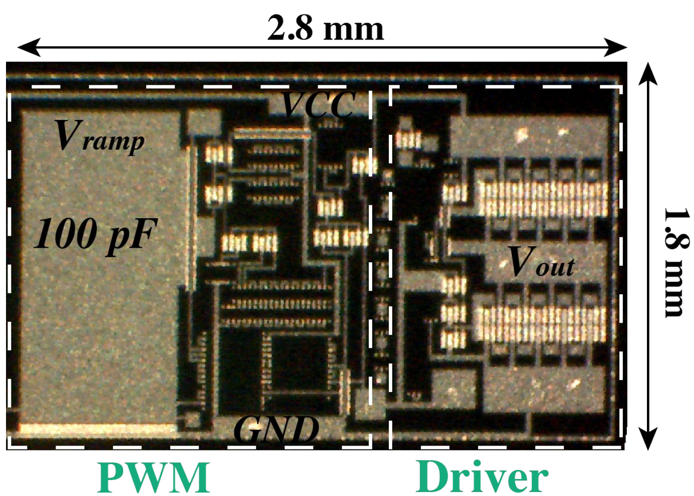


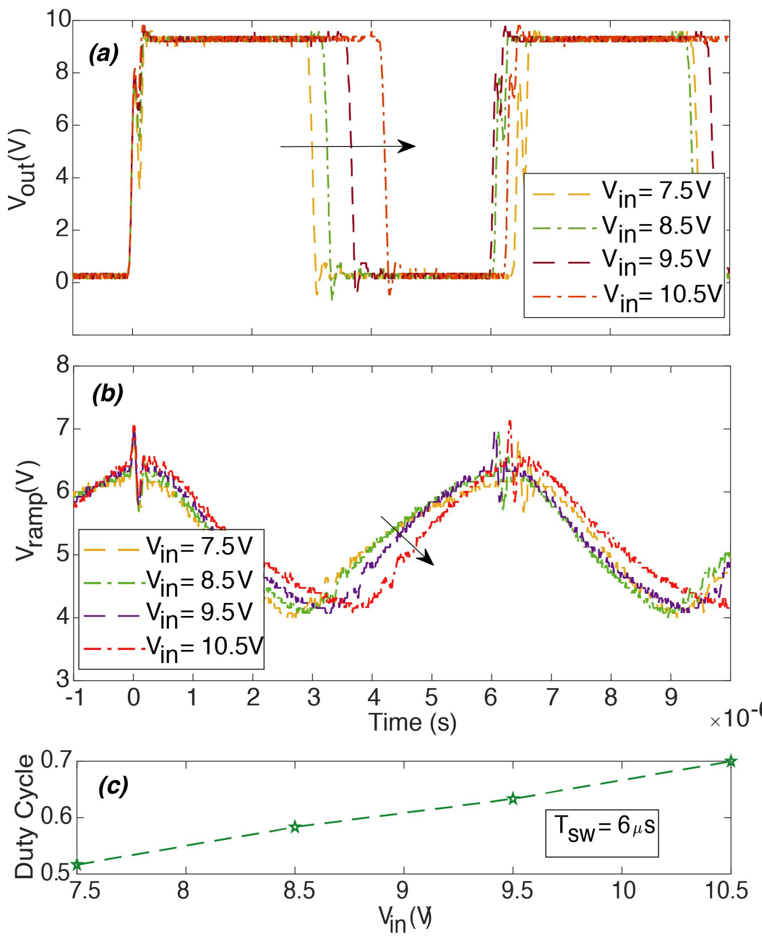


S. Kargarrazi, C.-M. Zetterling, et al., ***IEEE Electron Device Letters (2018)***

SiC-based Integrated Circuits
Example III (Pulse-width Modulator)



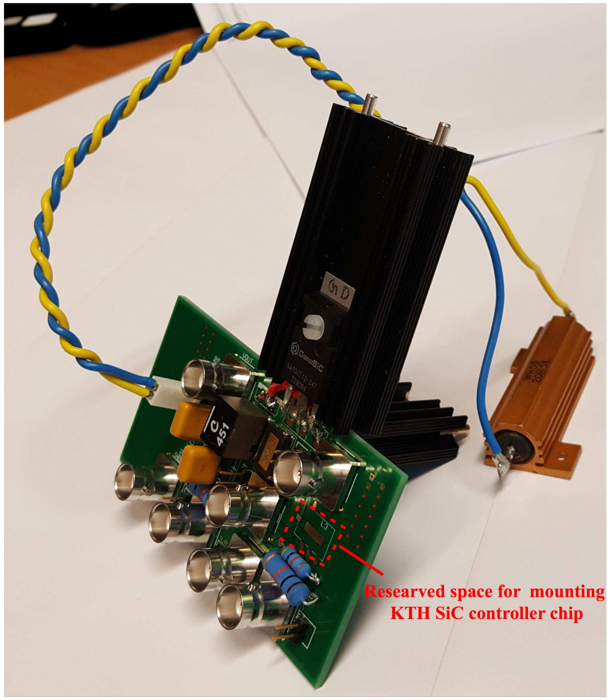




S. Kargarrazi, C.-M. Zetterling, et al., ***IEEE Transactions on Power Electronics*** **(2018)**

SiC-based Integrated Circuits
Still Example III (Pulse-width Modulator)

The final goal was not the PWM but a controlled
Power supply for harsh environments.
http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-201618



How does GaN HEMT work?

Spontaneous polarization

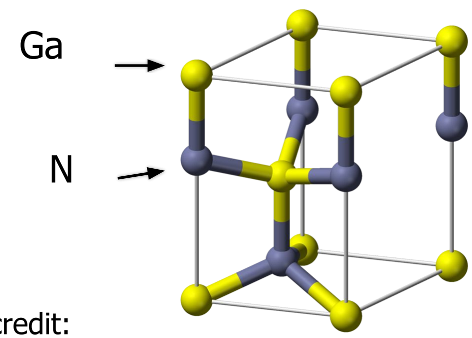
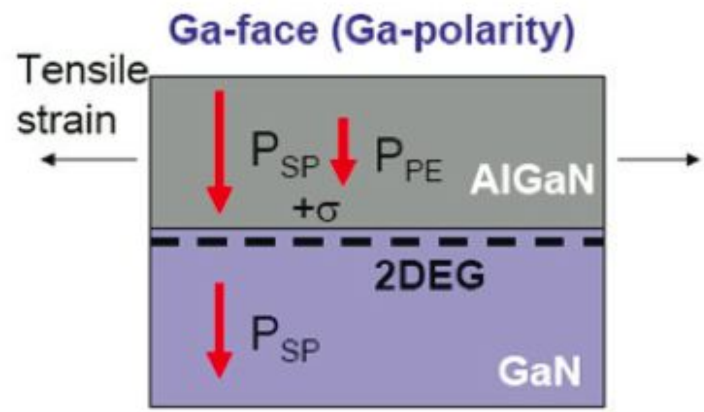


Image credit:
http://en.wikipedia.org/wiki/Wurtzite_crystal_structure



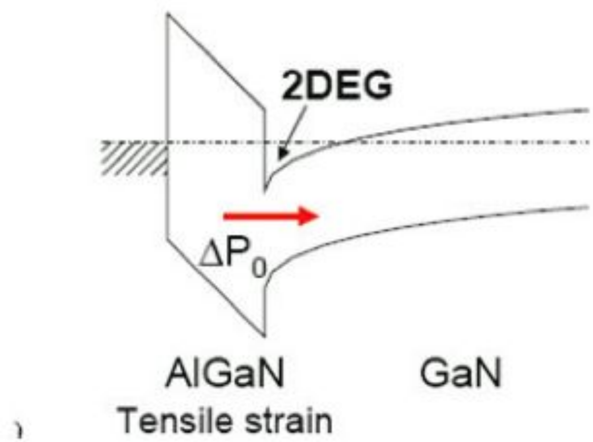


Image credit: M. Lindeborg et al., UCSB, 2011.

Piezoelectric polarization

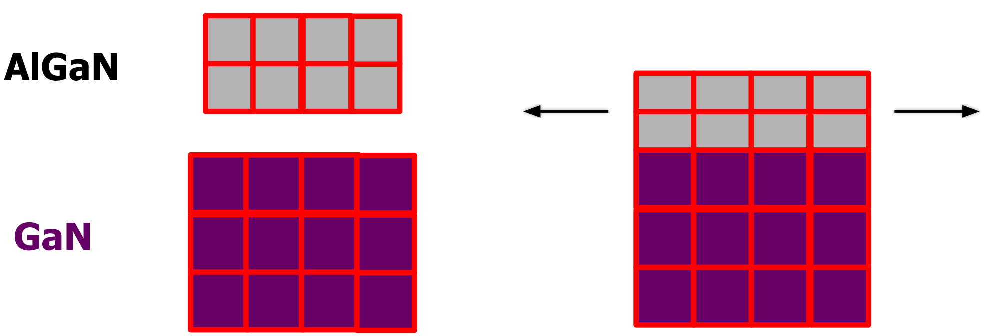
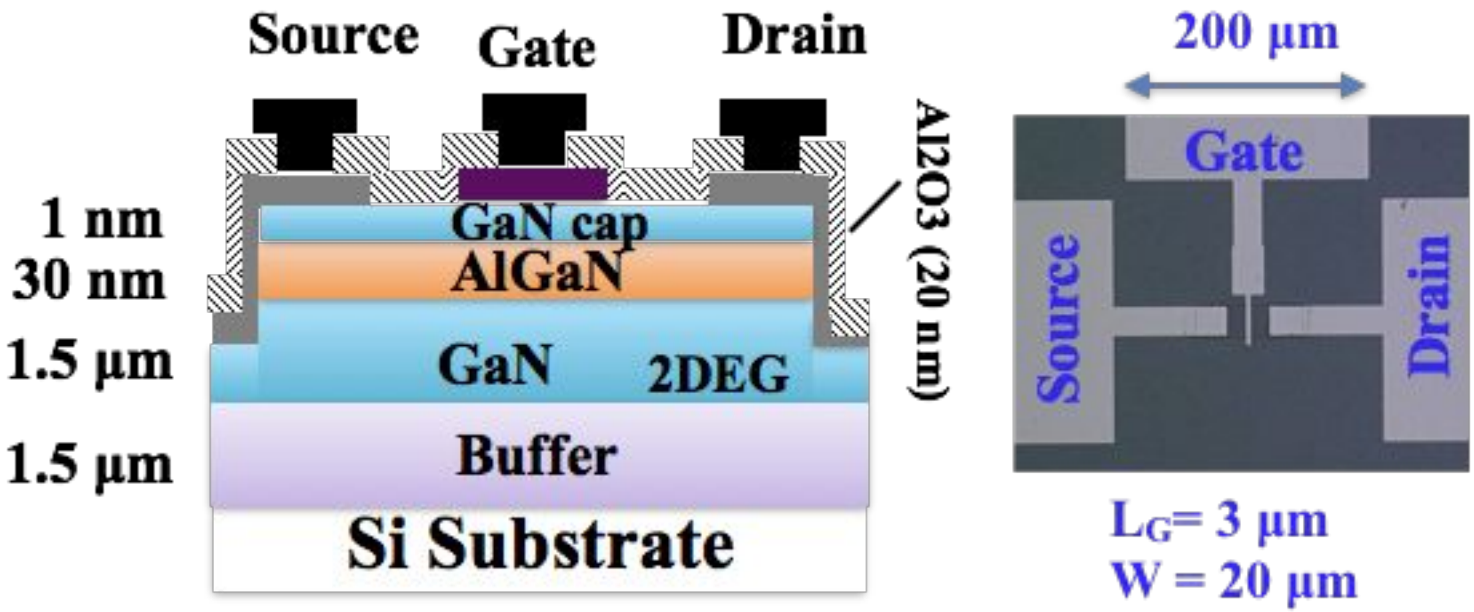


Image credit:
C. Chapin, Stanford University, 2015.

Image credit: M. Lindeborg et al., UCSB, 2011.

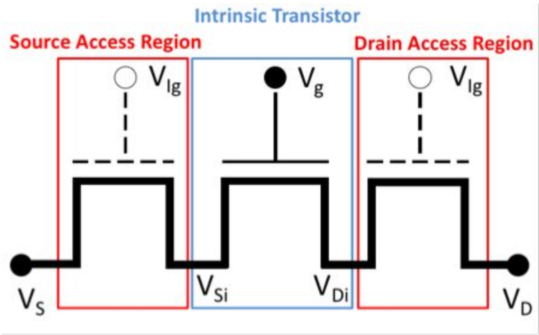
GaN HEMT



- ❖ MOCVD grown AlGaN/GaN HEMTs on Si/SiC/Sapphire substrates
- ❖ Device geometry optimization
- ❖ Depletion-mode (Normally-on), but Enhancement-mode (Normally-off) are coming too.

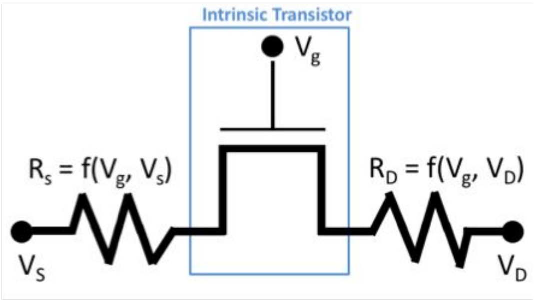
GaN HEMT compact Models

MIT MVSG MODEL

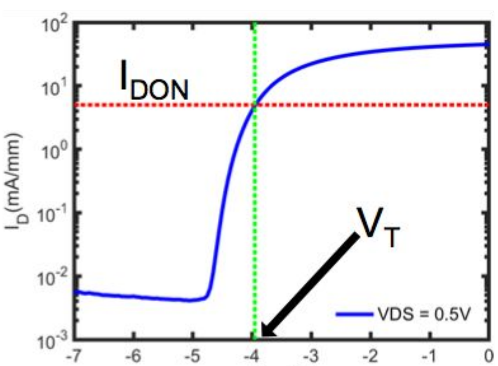


- Charge based model
- Implicit Gate transistors

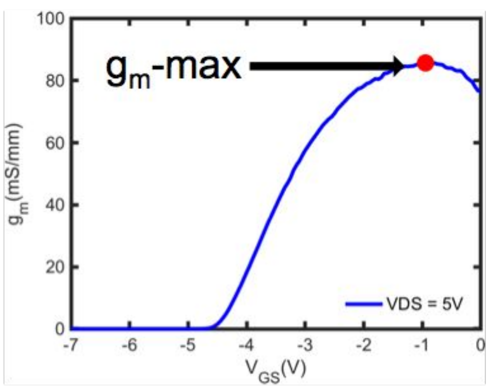
ASM MODEL



- Potential based model
- Non-linear resistors



- V_T determines where the transistor turns on
- Important to have stable V_T across temperature

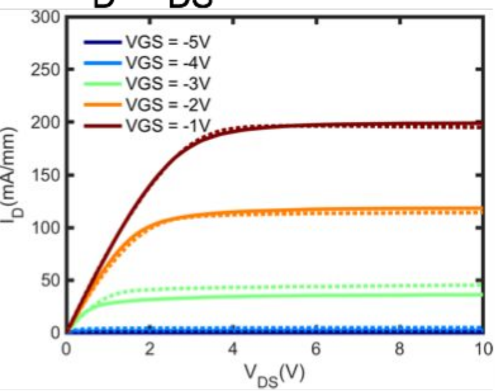


- g_m determines how much a signal can be amplified
- Bias circuit in region where g_m is large

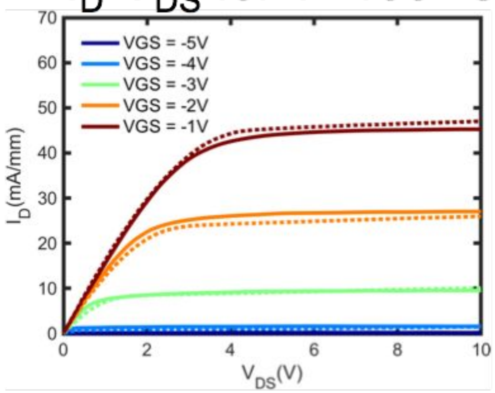
Images credit:
S. Blankenberg, summer REU, Stanford University, 2018.

Extraction of ASM parameters

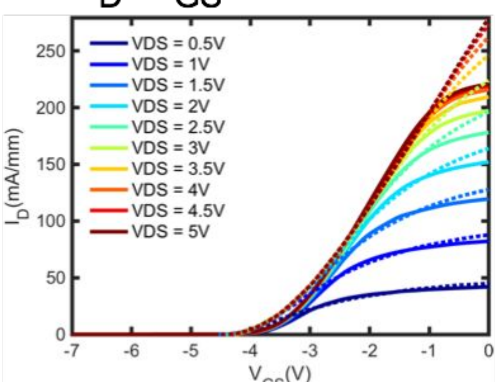
I_D-V_{DS} for T=22°C



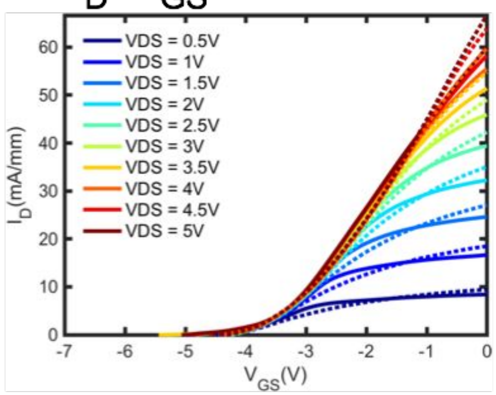
I_D-V_{DS} for T=400°C



I_D-V_{GS} for T=22°C



I_D-V_{GS} for T=400°C

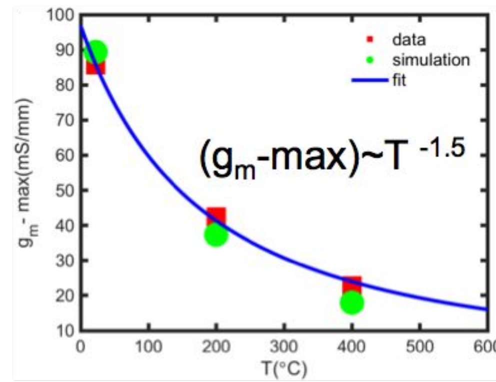


Simulated ▬▬

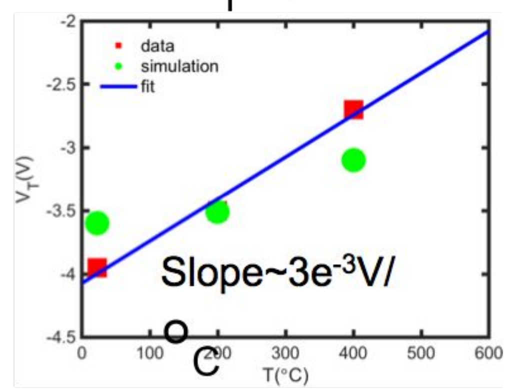
Measured ▪ ▪ ▪

- Heated transistors up to 500°C
- IC-CAP to obtain fit
- Model captures g_m-max, R_{on}, I_{SAT}, and general trends in V_T
- V_T fairly stable (ΔV_T ~ 1V)

g_m-max vs. T

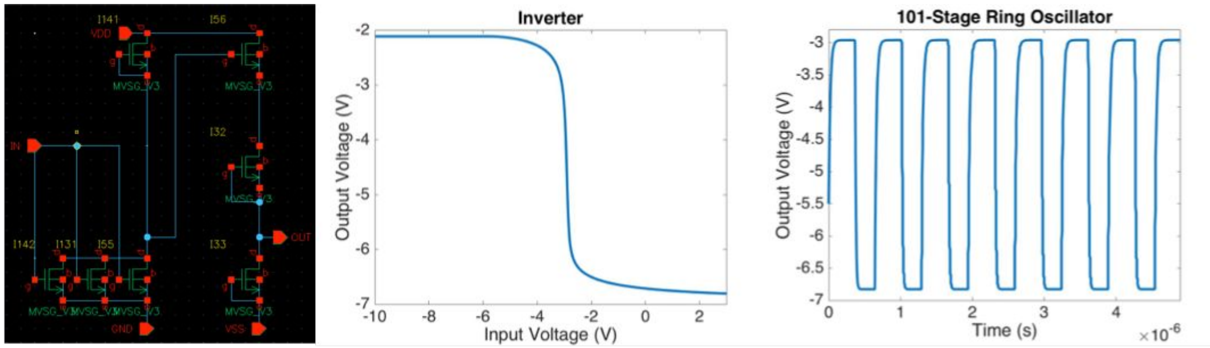


V_T vs. T

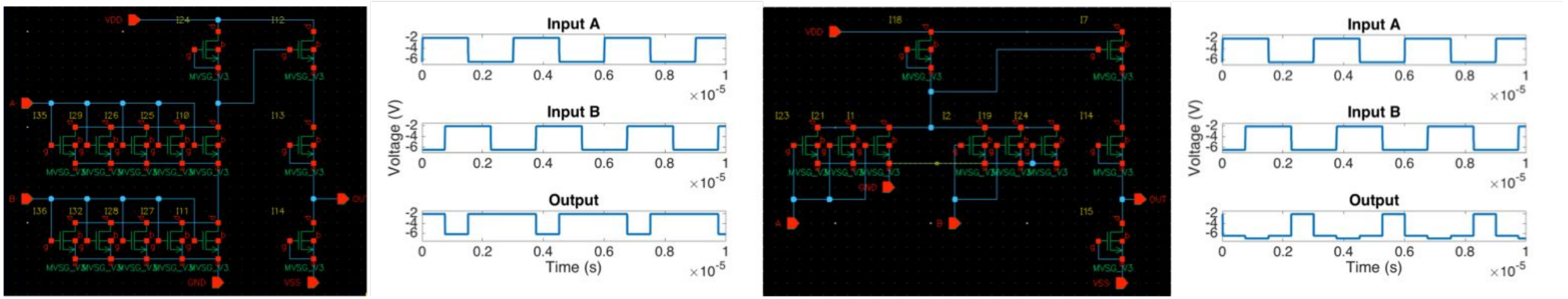


Images credit:
S. Blankenberg, summer REU, Stanford University, 2018.
(Pre-publication material)

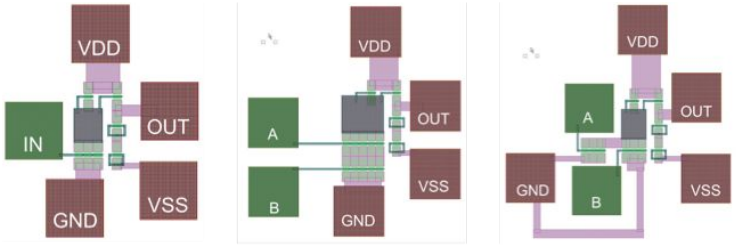
Circuit Design and Simulation



NAND and NOR Gates

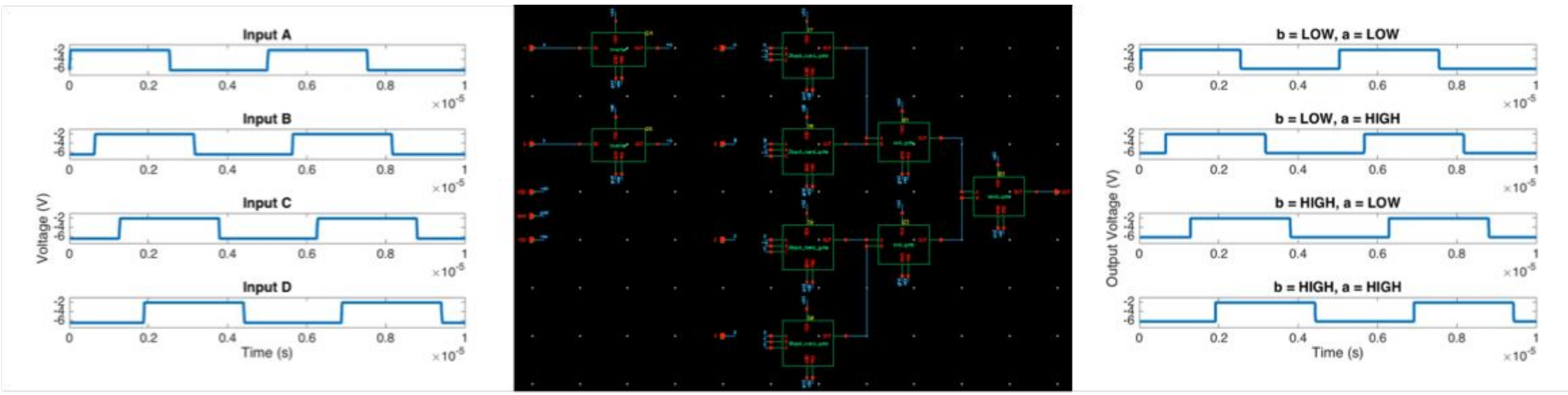


Images credit:
D. Mendoza, summer REU, Stanford University, 2018.
(Pre-publication material)

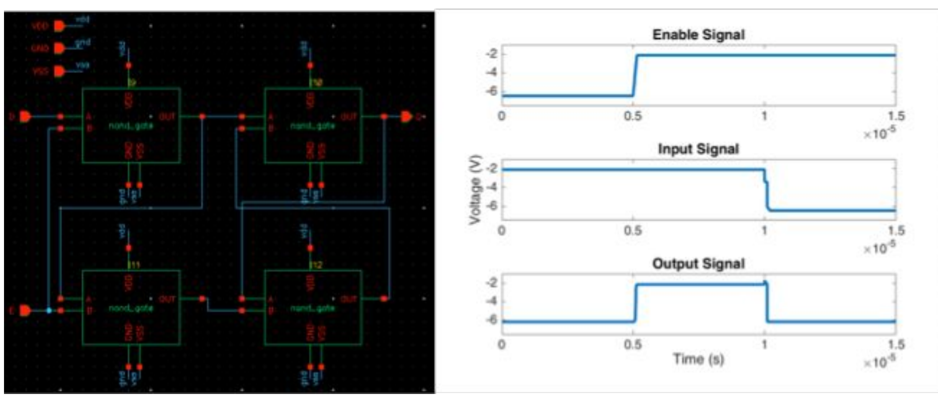


more Circuit Design and Simulation

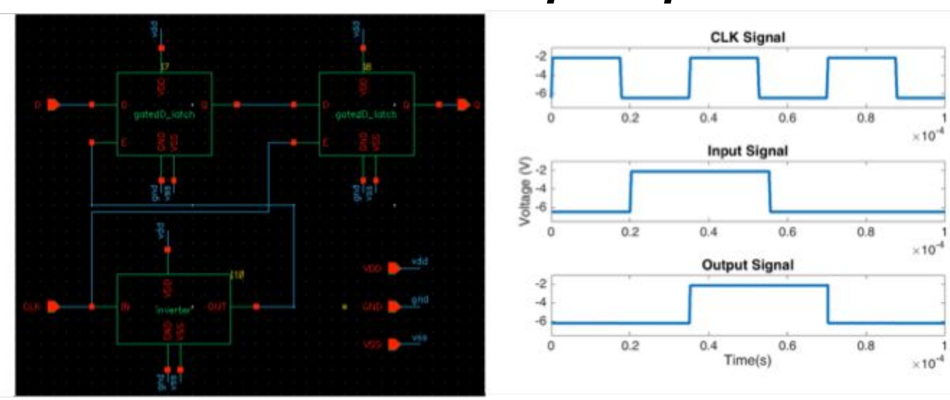
4-to-1 Multiplexer



Gated Latch

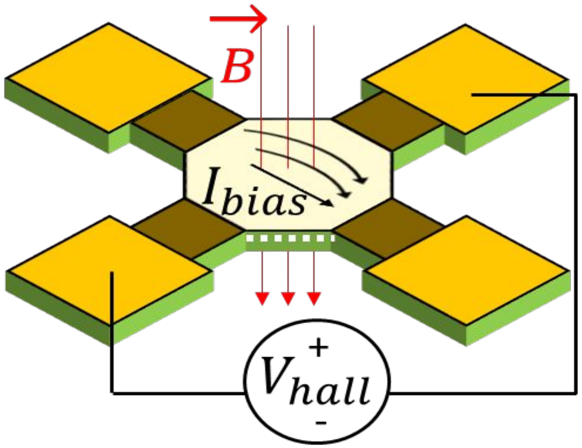


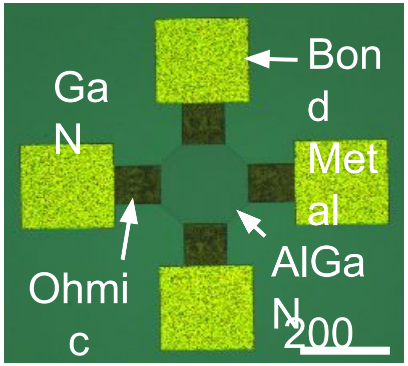
Gated Flip-Flop

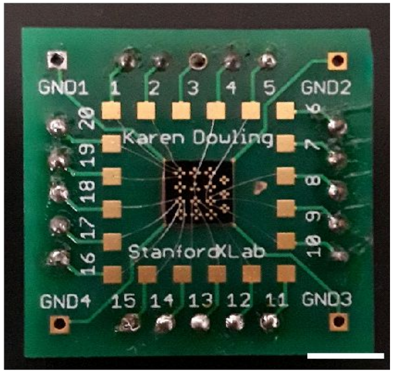


Images credit:
D. Mendoza, summer REU, Stanford University, 2018. (Pre-publication material)

GaN-based Hall-effect Plates for B-field Sensing







K. Dowling, D.G. Senesky et al., *Hilton Head Workshop* (2018)

GaN Sensor Device Characterization

GaN Sensor Specifications:

Field Range: -5 to 5 mT

Temperatures:

-200ºC to 200 ºC

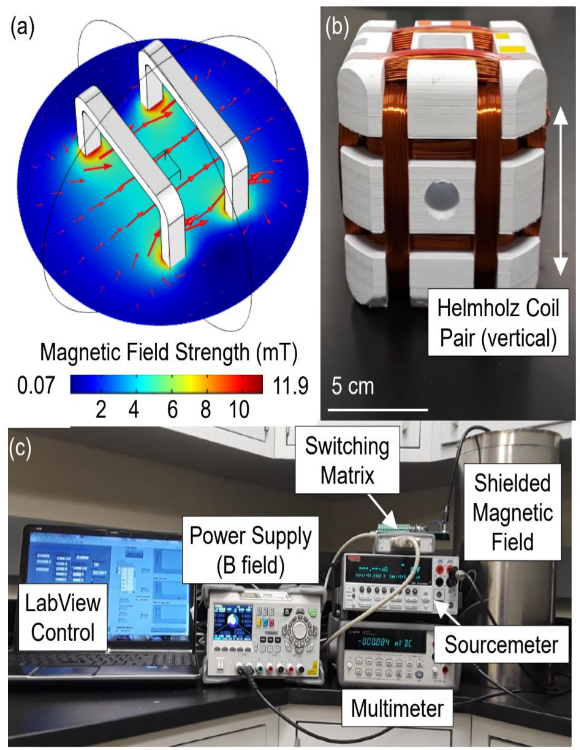
Temp Drift (Current Mode)

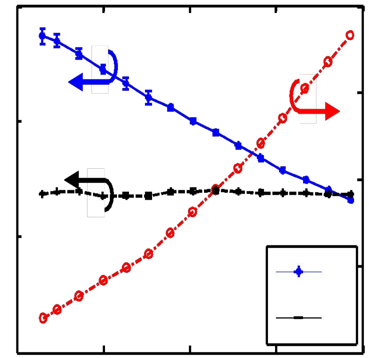
0.3 ppm/ºC

Power: < 1 mW

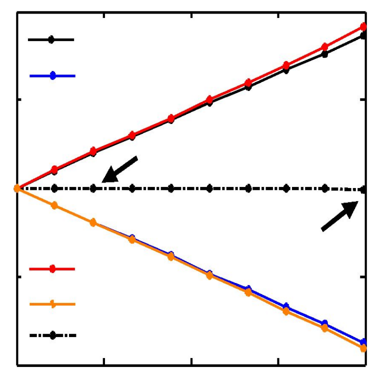
Accuracy: < 10 µT

Size: 0.9 mm^2



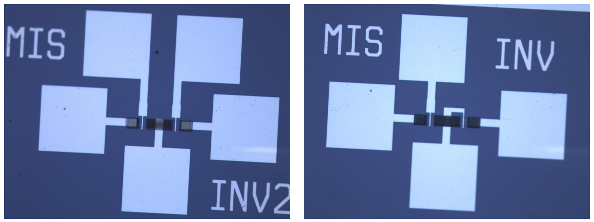


$$S_V \sim \frac{W}{l} \cdot \mu \qquad S_I \sim \frac{1}{q \cdot n \cdot t}$$

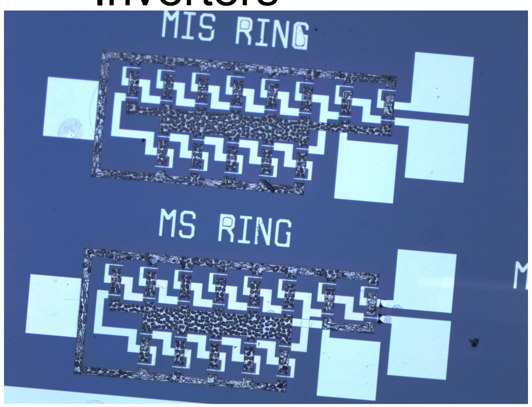


K. Dowling, D.G. Senesky, et al, *in preparation* (2018)

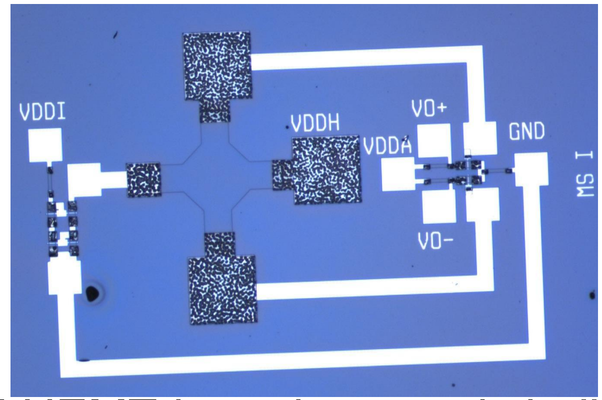
GaN HEMT Integrated Circuits (Cyrus-I fab run)



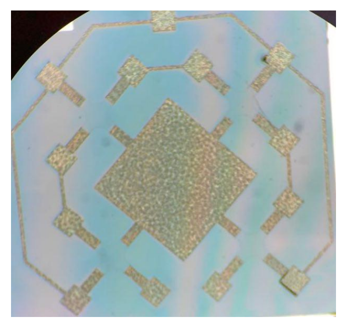
D-mode Inverters



11-stages ring oscillator



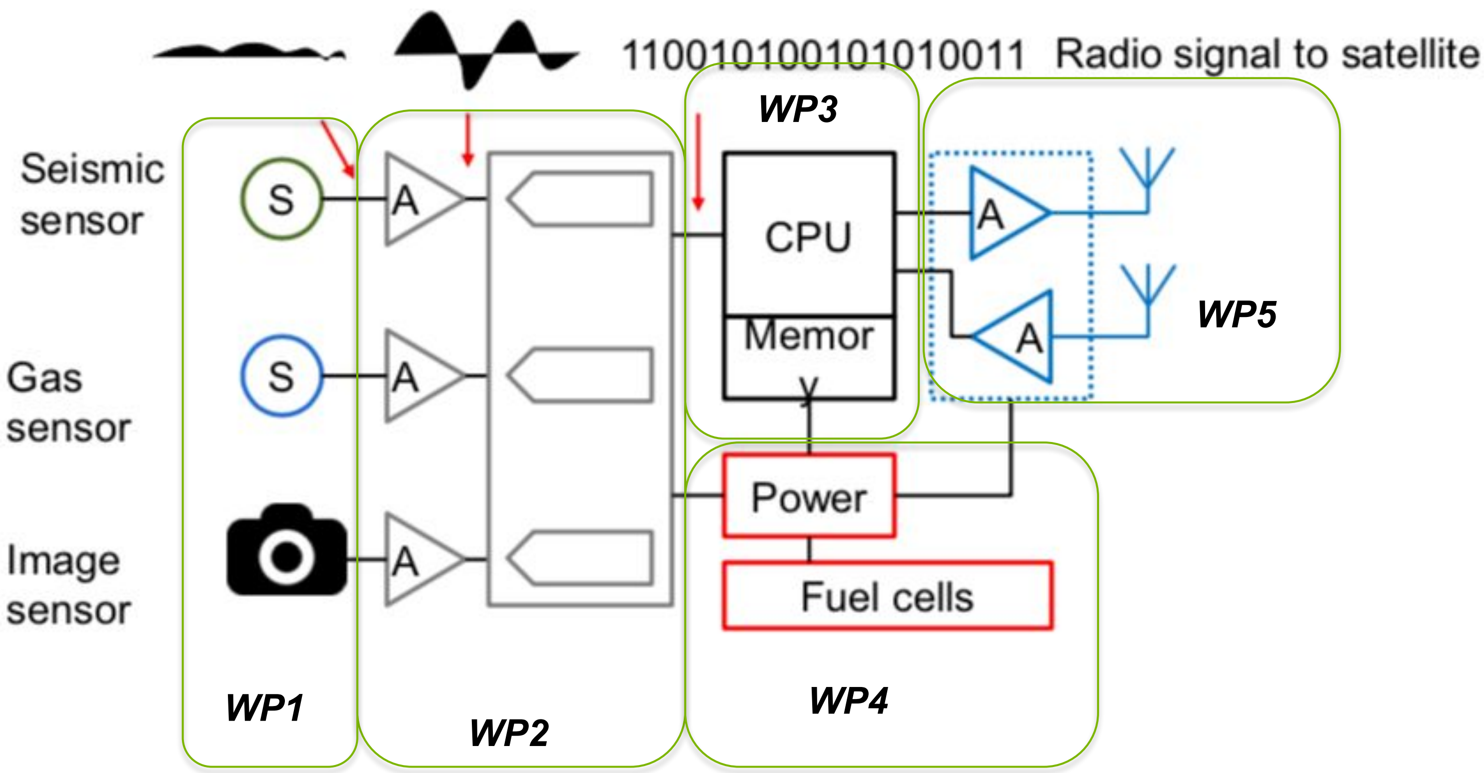
GaN HEMT-based magnetic hall-effect sensor accompanied with a current source and differential amplifier ICs.



An offset-reduced magnetic hall-effect sensor

S. Kargarrazi, D.G.Senesky, et al.,pre-*publication material* (2018)

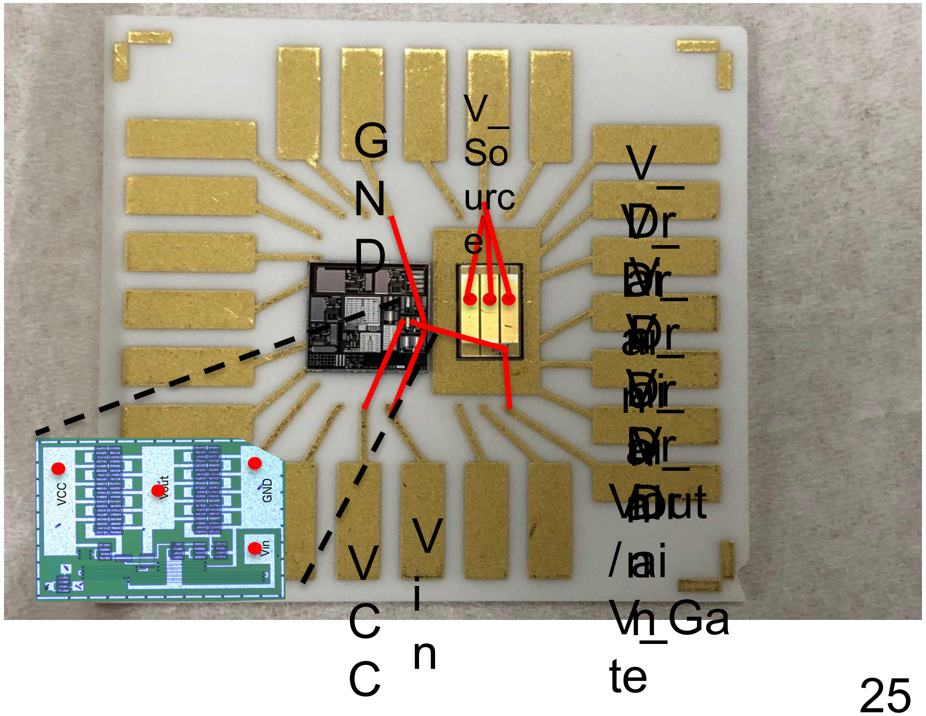
High-T GaN Integrated Circuits Opportunities!



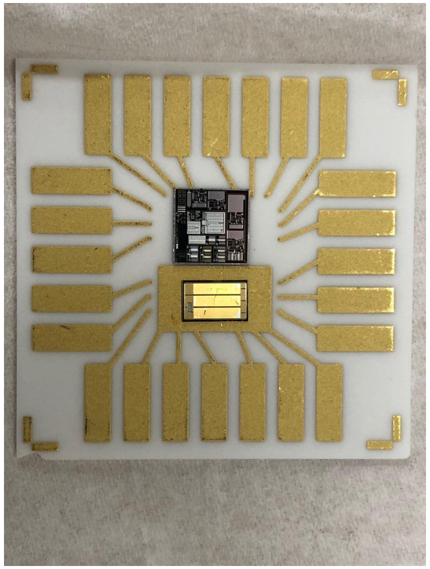
High-T Substrate (High-temperature co-fired Ceramic)

“ No, you didn’t make high-T electronics, because…”

An audience in ISPSD 2015



High-T mounting, bonding, packaging



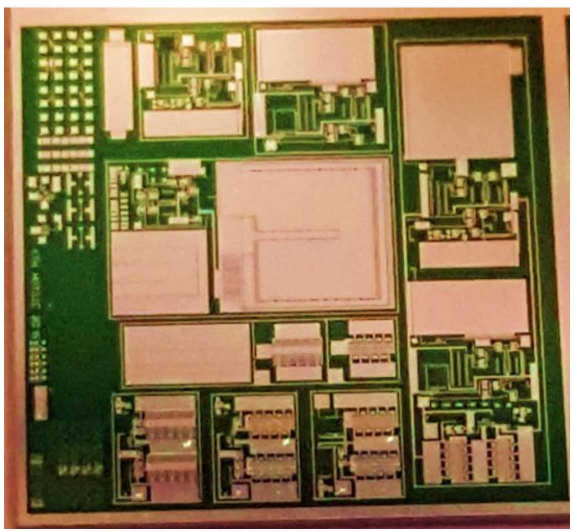
HTCC board

HT- Wirebonding
HT- Wires/mounting

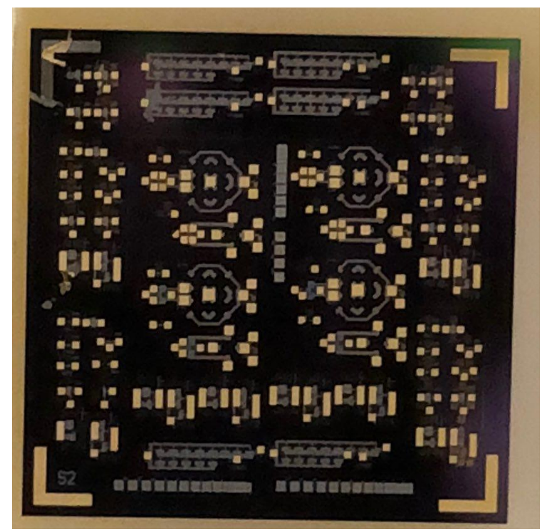
Prolonged measuremnnts
in the oven

R. Chen, S.Kargarrazi, D.G.Senesky, et al.,pre-*publication material* (2018)

SiC BJT IC fab run, EKT, KTH (2016)



GaN HEMT IC fab run, XLab, Stanford (2017)



Thanks

Special Thanks to all my colleagues at XLab