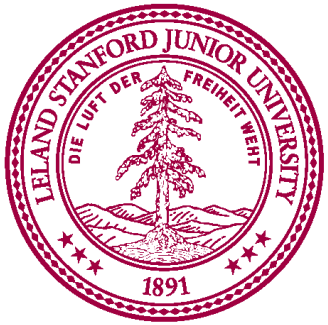
GaN HEMT Electronics for Extreme Environments



Saleh Kargarrazi

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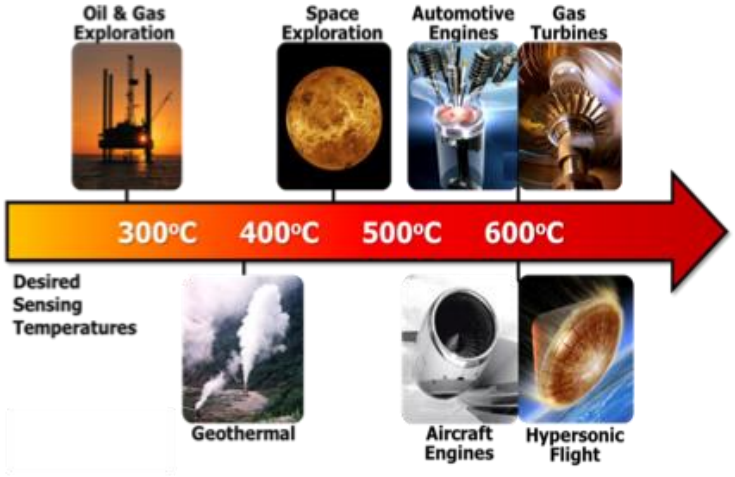
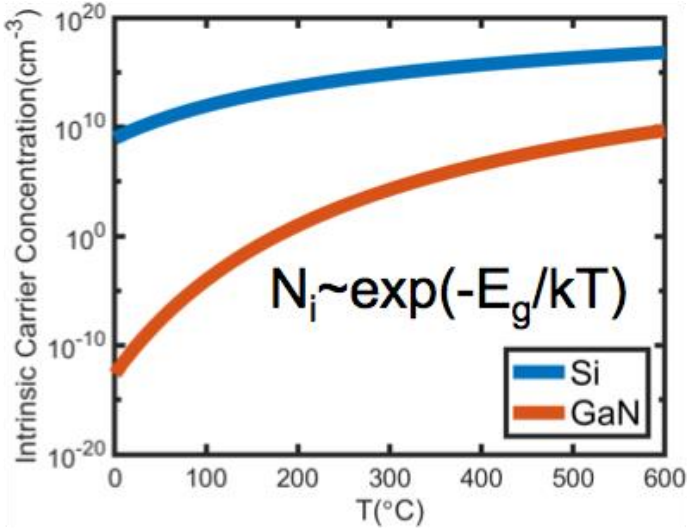
Advisor: Prof. Debbie Senesky

Thu, 21st Jan. 2019

Why wide-bandgap electronics?



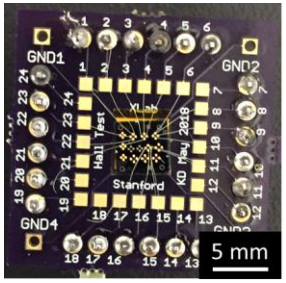


- Sensing in harsh environments require robust transistors

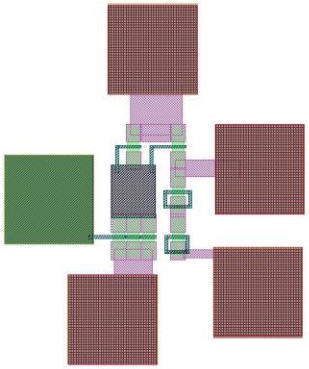
- **Problem:** Silicon device failure at ~125°C due to low bandgap (1.1eV)
- **Solution:** Wide-bandgap (3.4eV) material, Gallium-Nitride (GaN)

An Example of for a Sensor/Electronics system

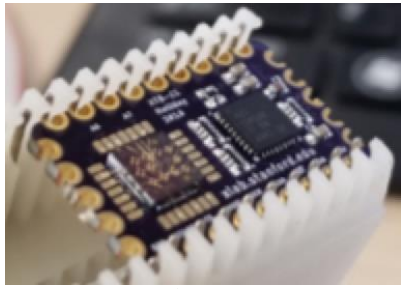
GaN-based Sensor:

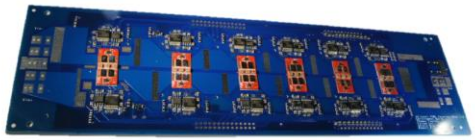


GaN-based IC:



GaN-based Sensor + IC "Surfboard"



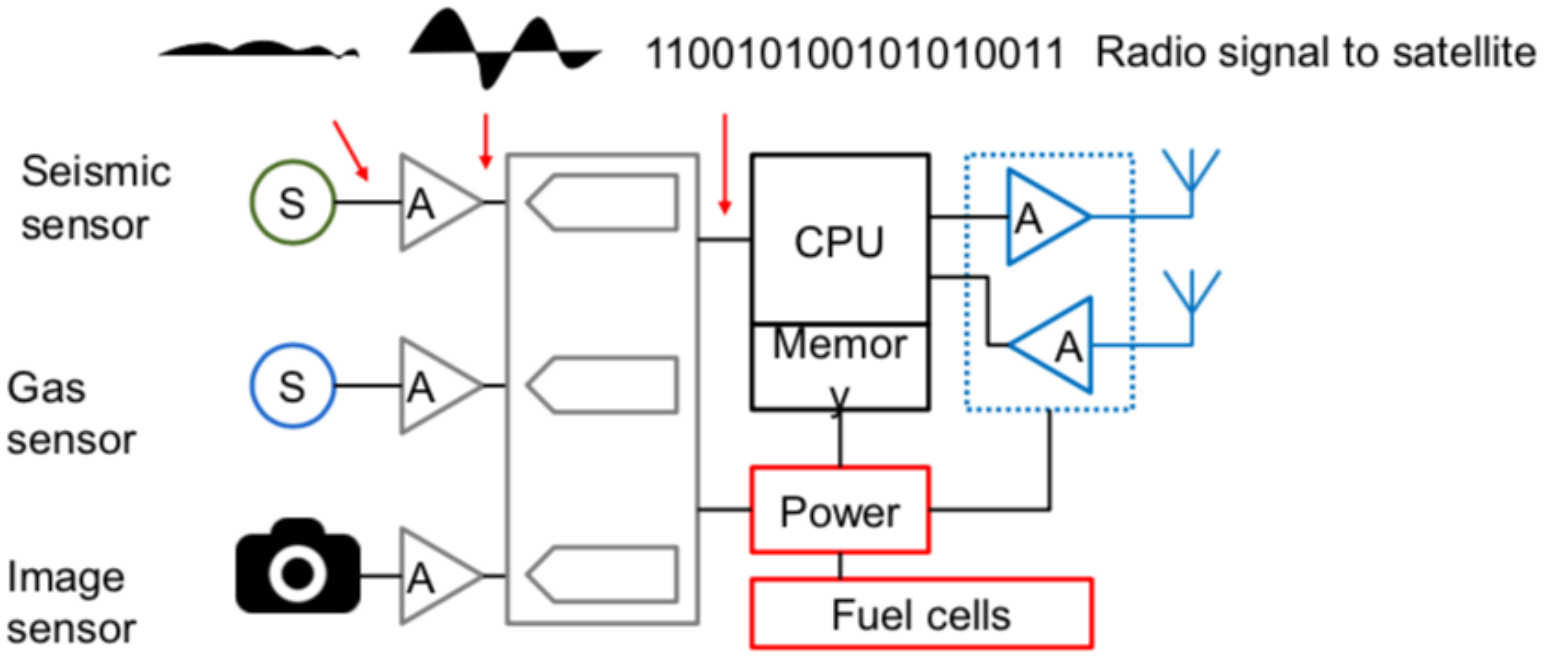


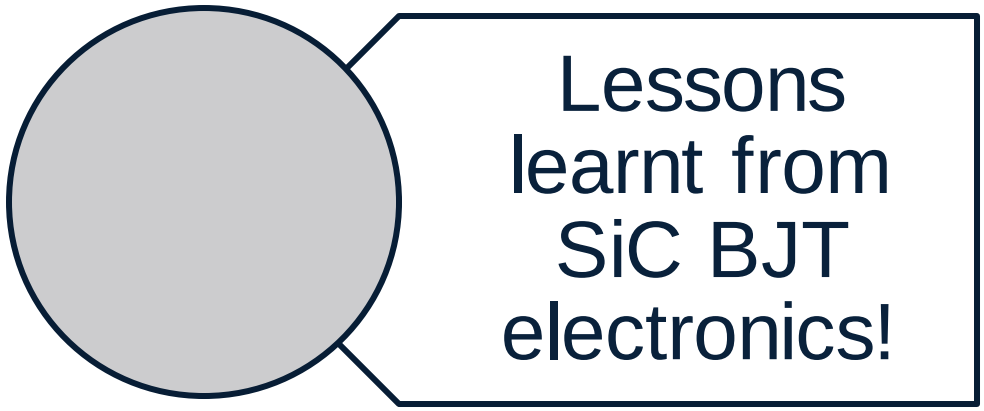
GaN-based Converter Board (R. Pilawa)

Next-generation Aviation

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

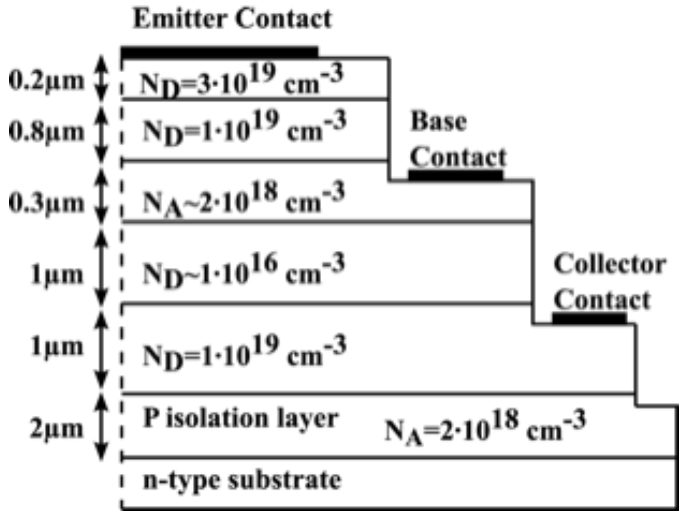
A High-T Electronic System



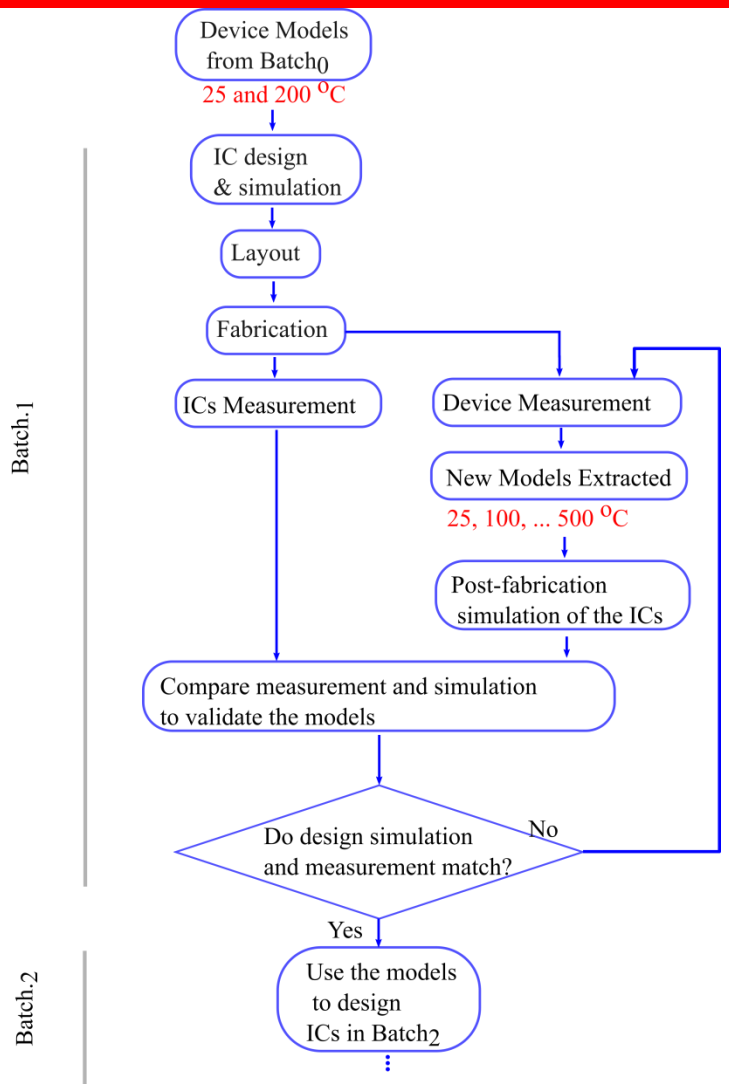

Lessons
learnt from
SiC BJT
electronics!

Lessons learnt from SiC Bipolar Junction Transistors (BJTs)

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

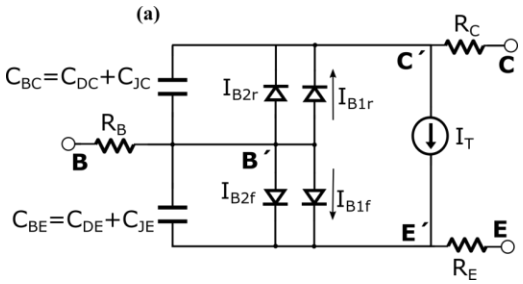


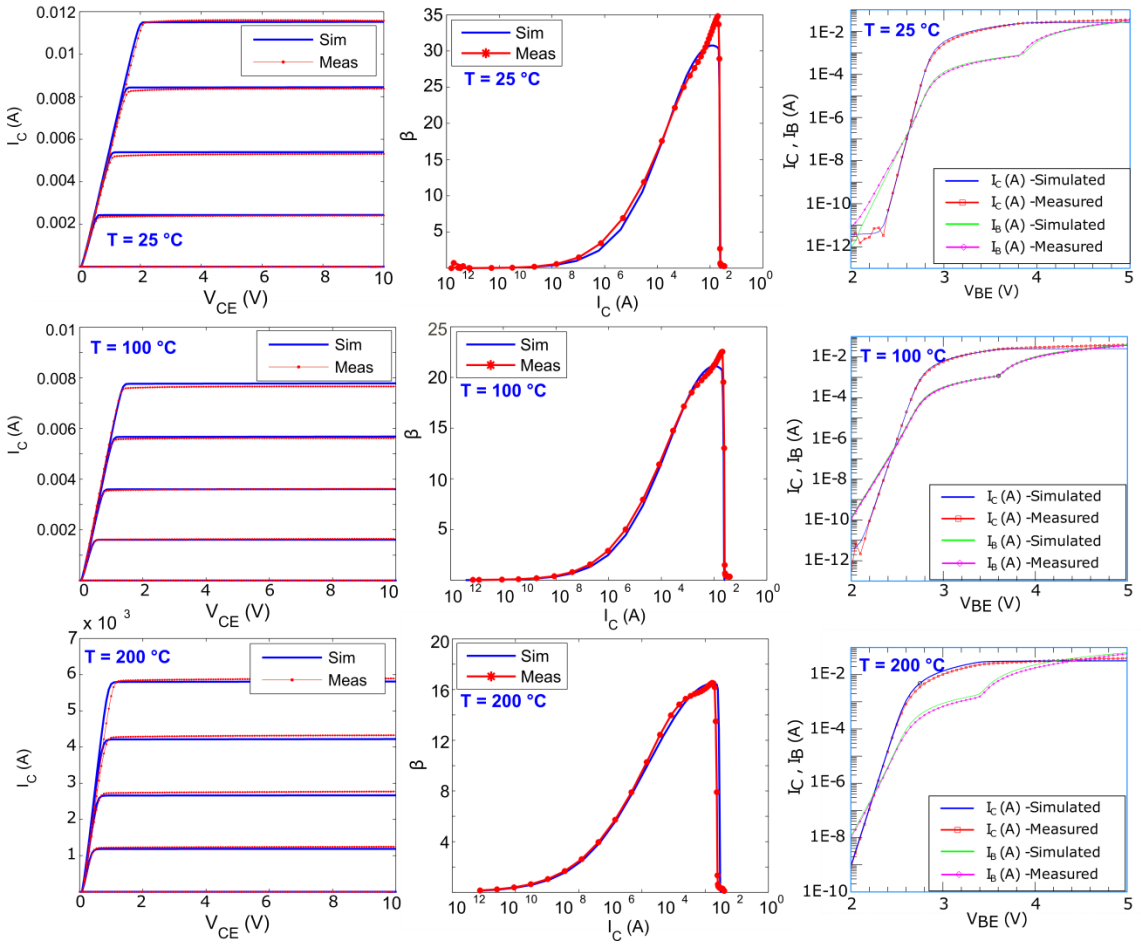
SiC IC Implementation Flowchart



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





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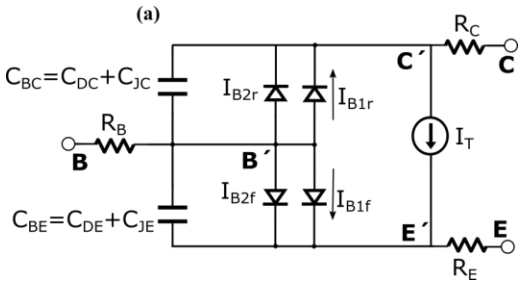
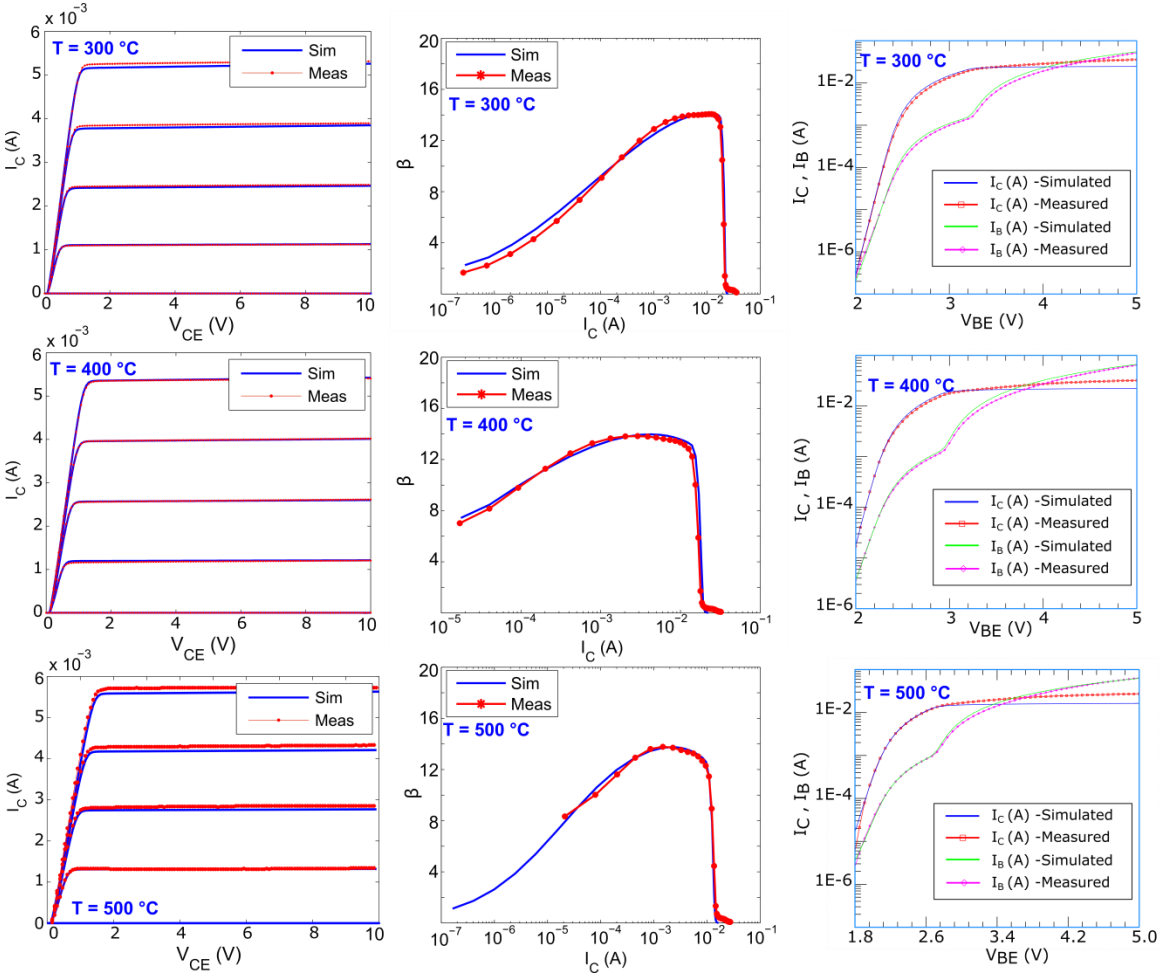
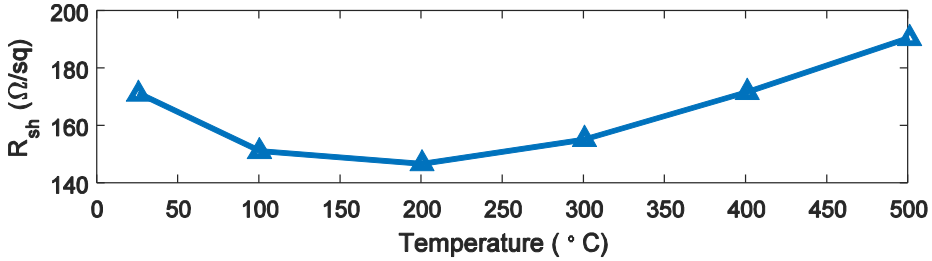


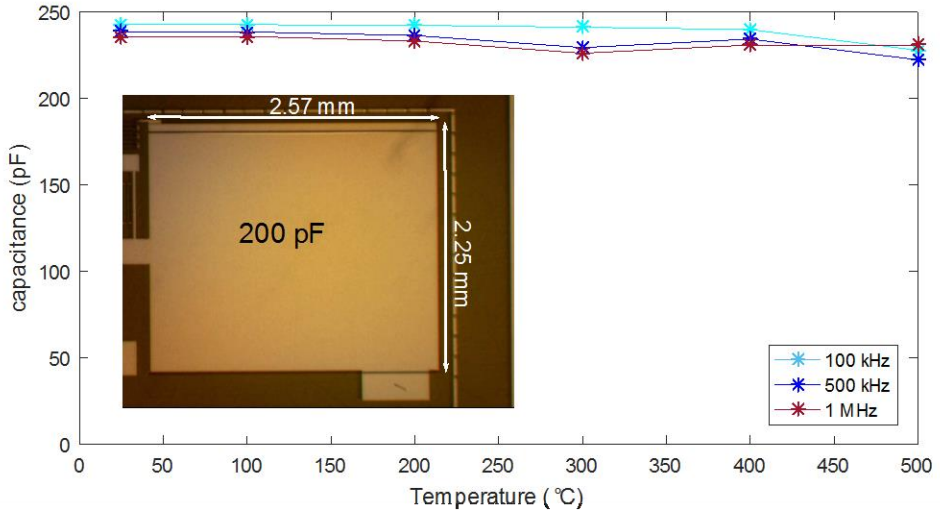


Device Modeling (integrated resistors and capacitors)

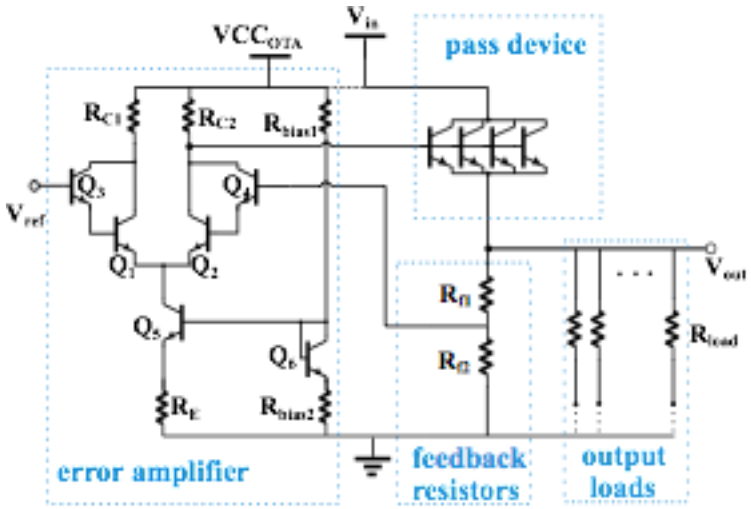
- Resistors on collector highly-doped epi-layer
- Non-monotonous temperature-dependence

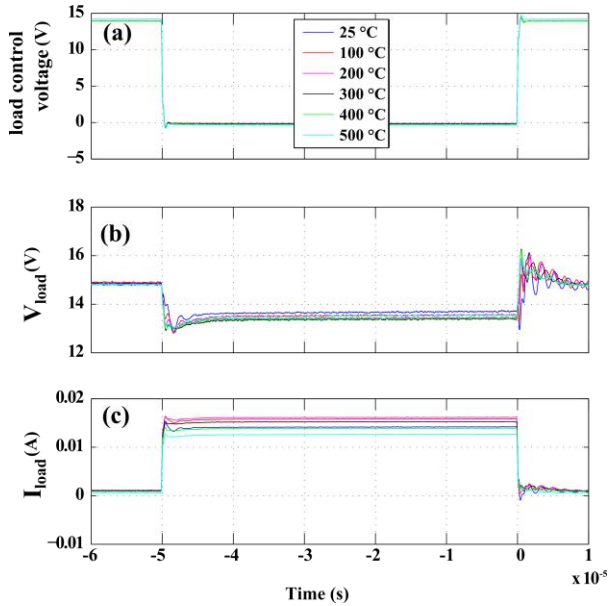


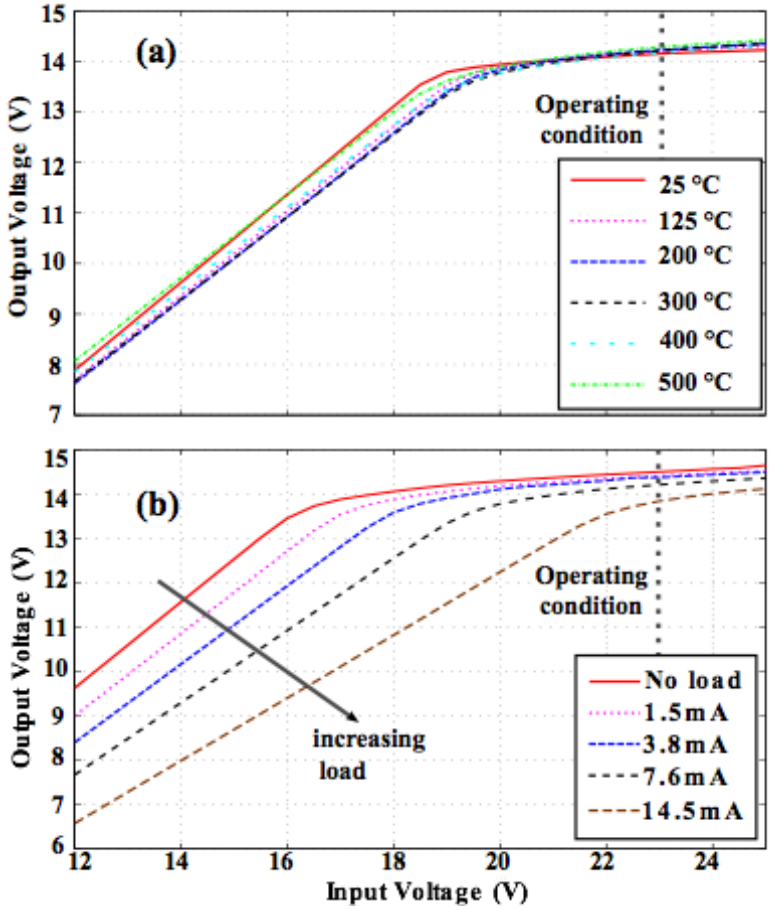
- Parallel plated capacitors
- constant over temperature



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

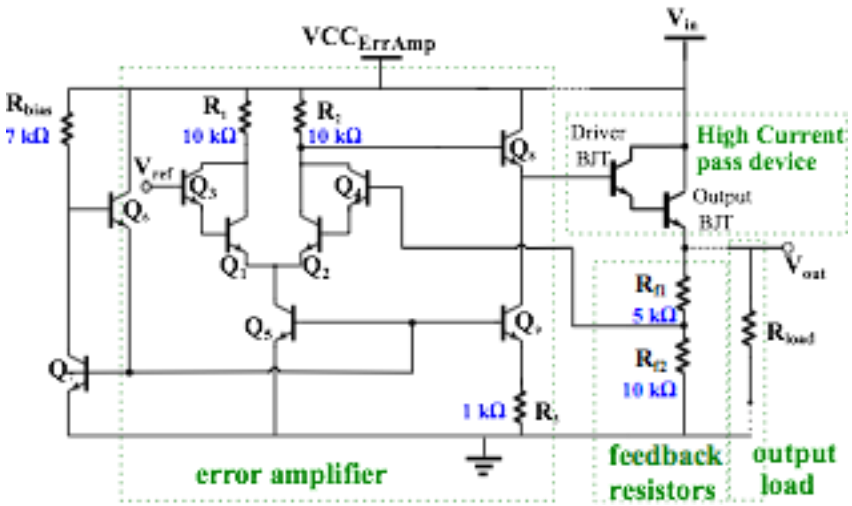


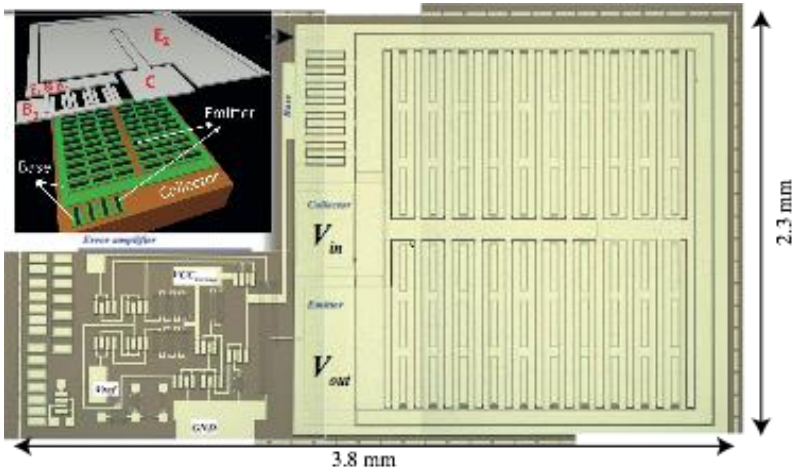


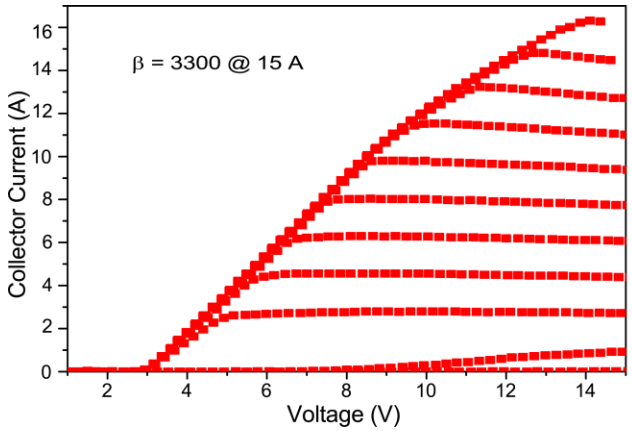


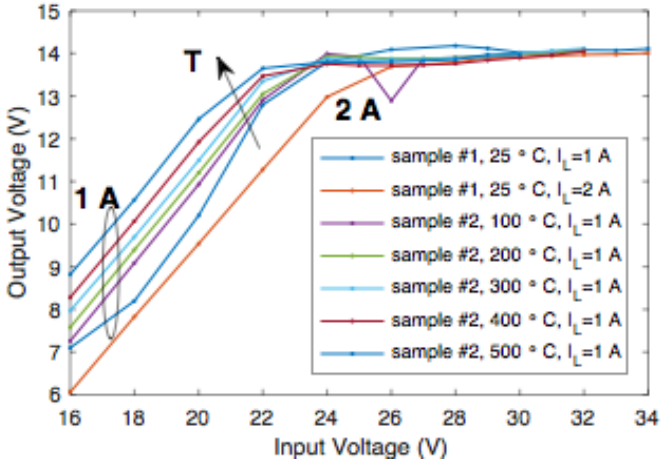
S. Kargarrazi, C.-M. Zetterling, et al., ***IEEE Transactions on Electron Devices*** **(2015)**

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



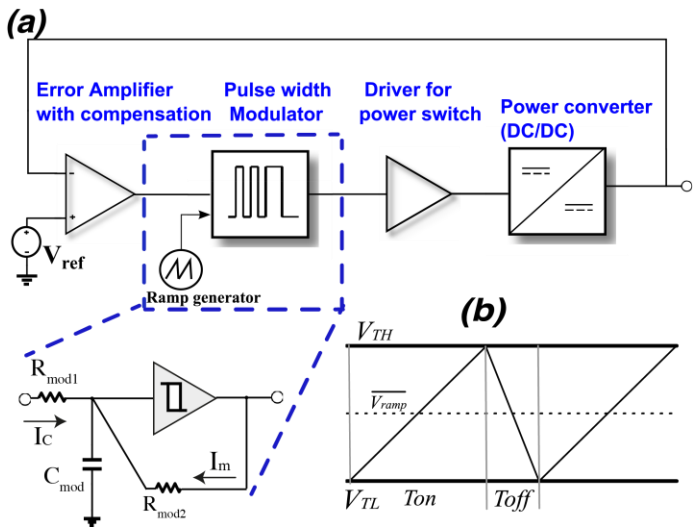


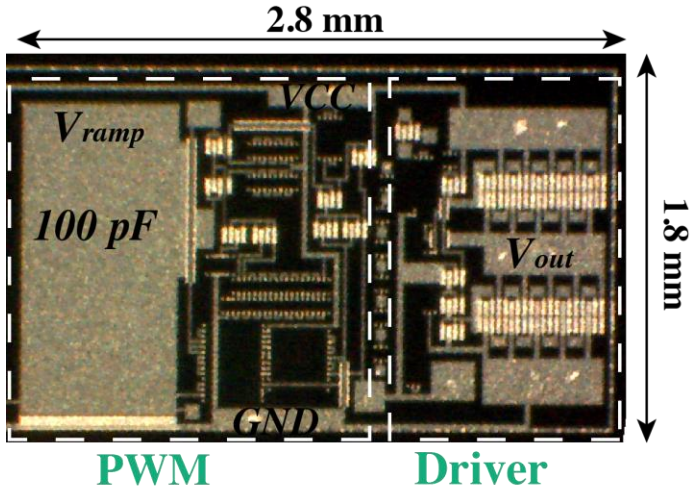


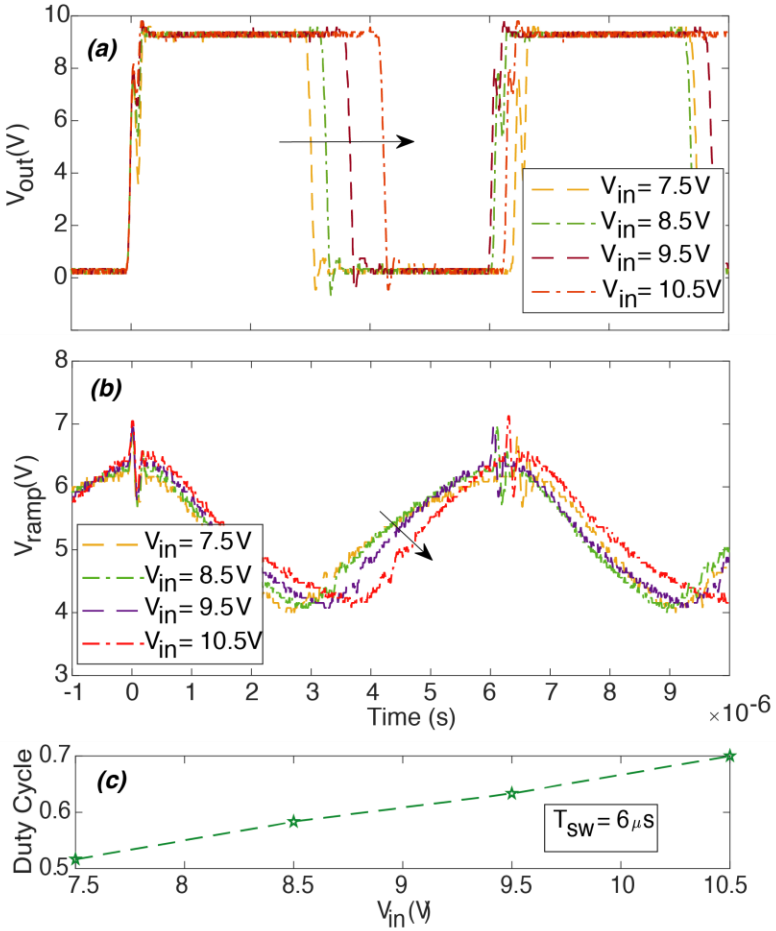


S. Kargarrazi, C.-M. Zetterling, et al., ***IEEE Electron Device Letters (2018)***

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



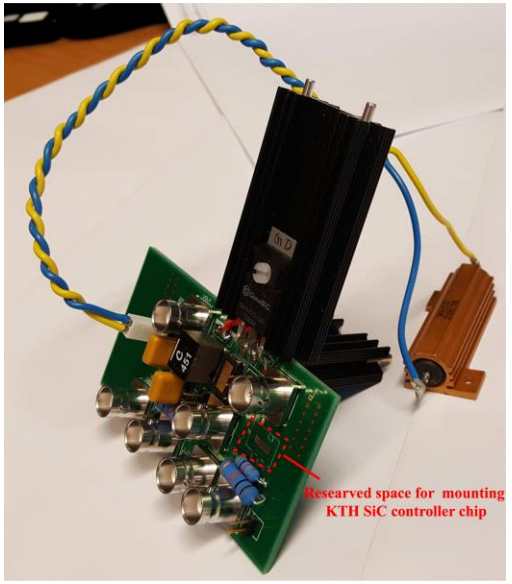


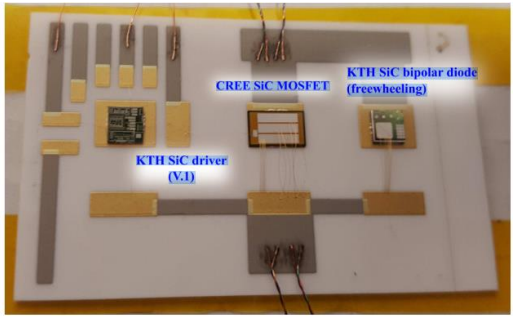


S. Kargarrazi, C.-M. Zetterling, et al., ***IEEE Transactions on Power Electronics*** **(2018)**

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

The PWM was a spin off of a bigger challenge to make controlled power supply for harsh environments!
http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-201618





Presentation Outline

How does GaN HEMT work?

Spontaneous polarization

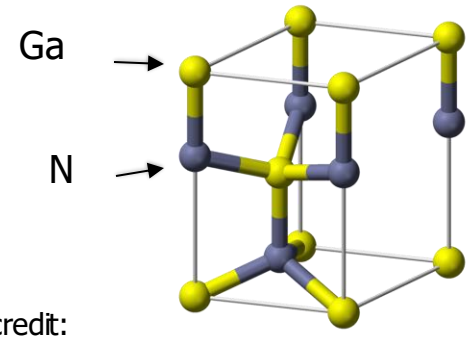
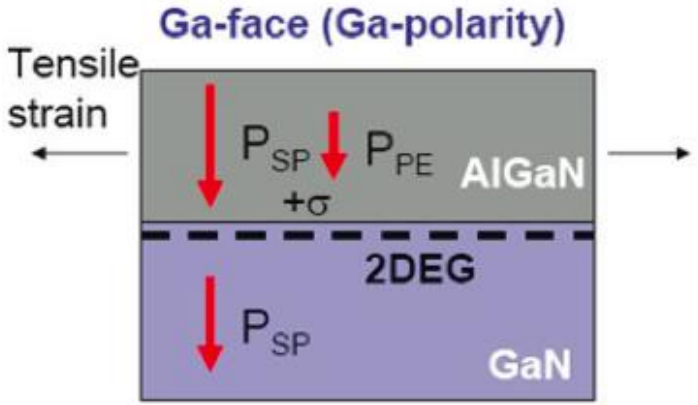


Image credit:
http://en.wikipedia.org/wiki/Wurtzite_crystal_structure



Piezoelectric polarization

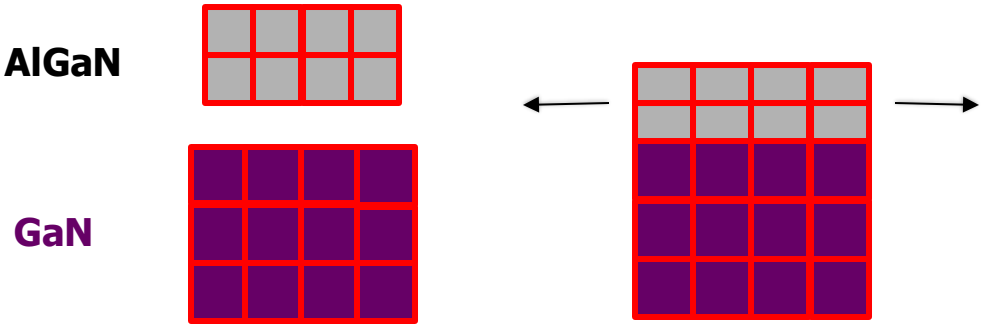


Image credit:
C. Chapin, Stanford University, 2015.

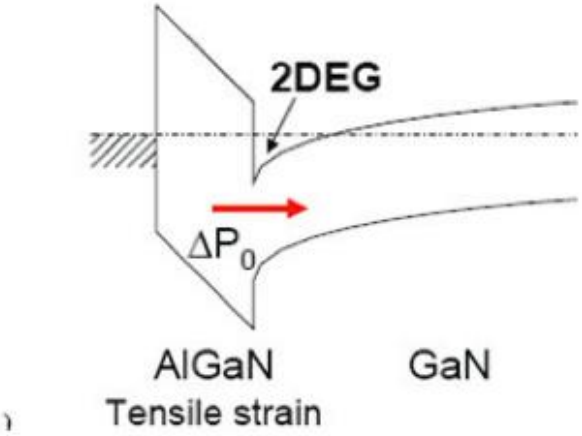


Image credit: M. Lindeborg et al., UCSB, 2011.

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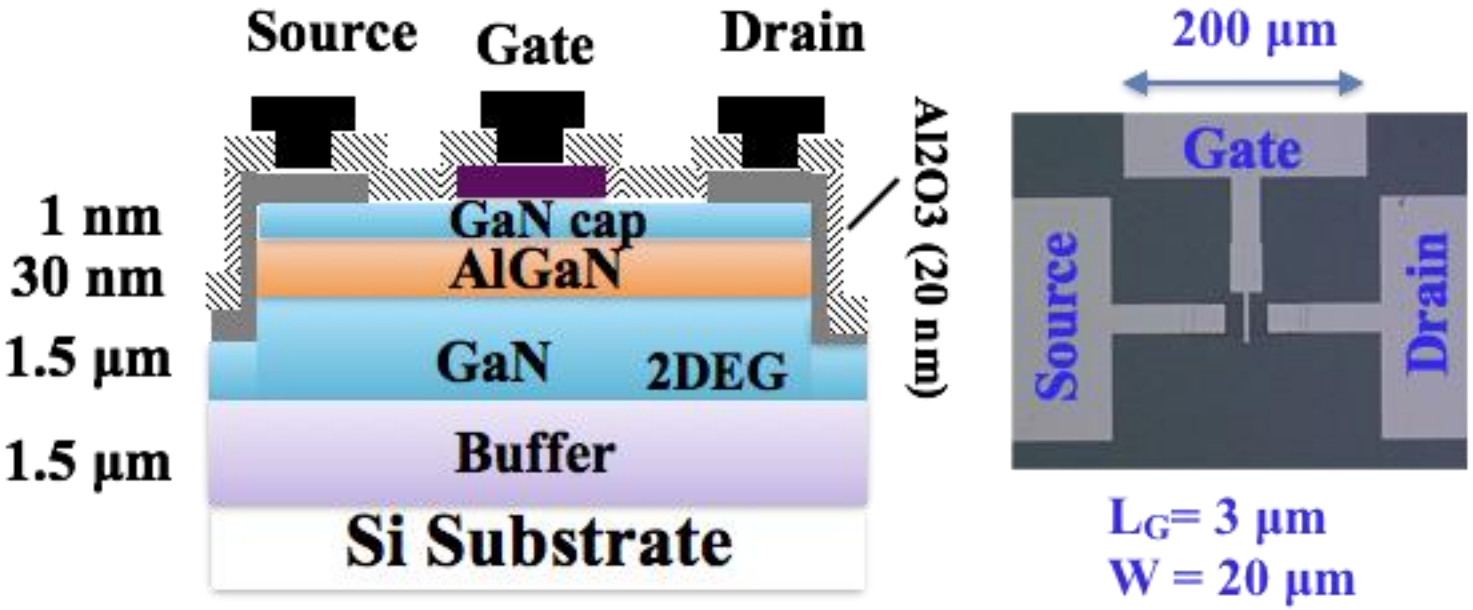
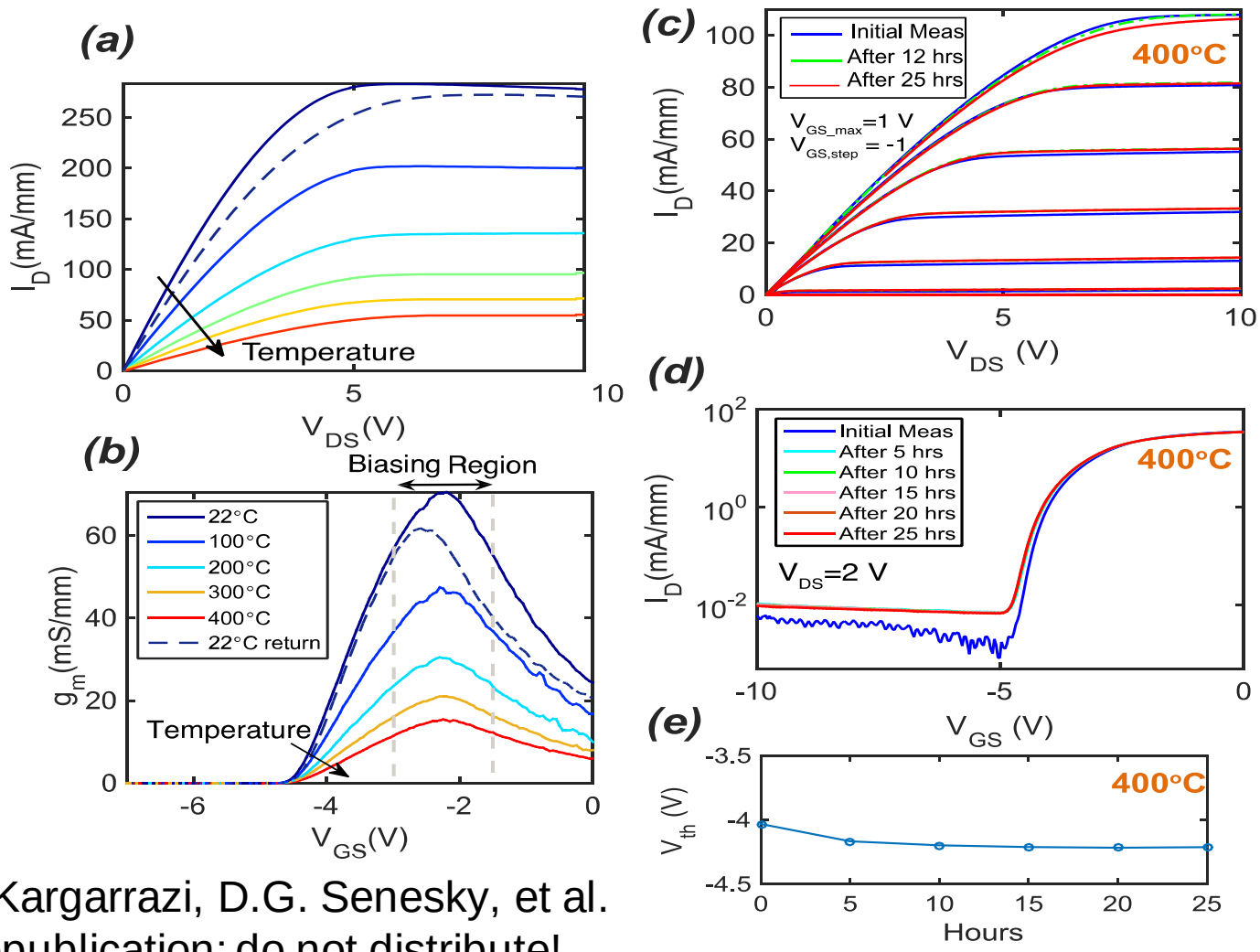
GaN HEMT



- MOCVD grown AlGaN/GaN HEMTs on Si/SiC/Sapphire substrates
- Device geometry optimization
- Depletion-mode (Normally-on), but we also work on enhancement-mode (Normally-off).

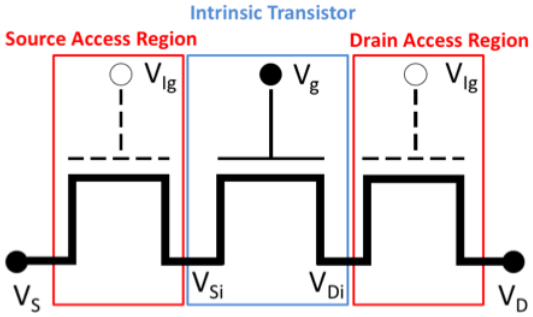
High-T Operation of the HEMTs over 25 Hours!



S. Kargarrazi, D.G. Senesky, et al.
prepublication: do not distribute!

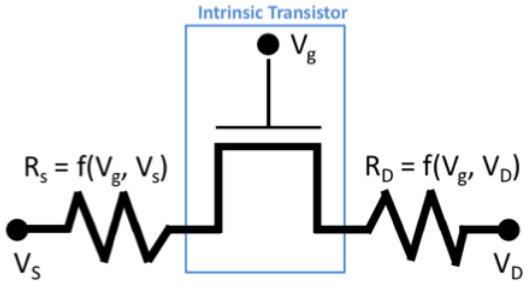
GaN HEMT compact Models

MIT MVSG MODEL

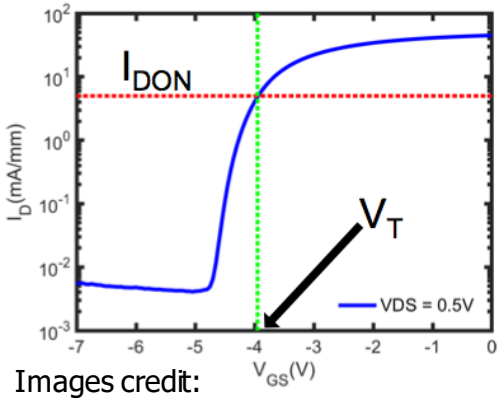


- Charge based model
- Implicit Gate transistors

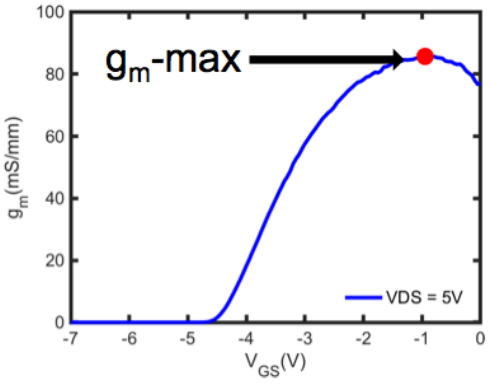
ASM MODEL



- Potential based model
- Non-linear resistors



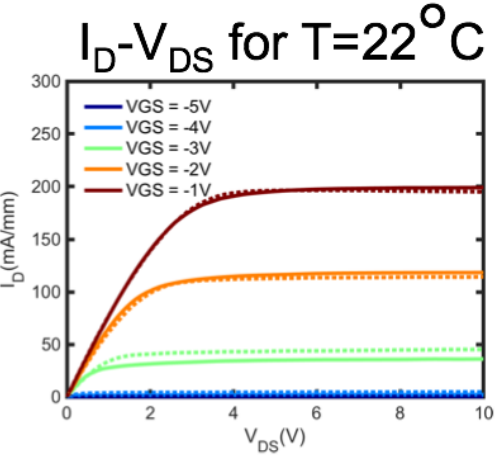
- V_T determines where the transistor turns on
- Important to have stable V_T across temperature

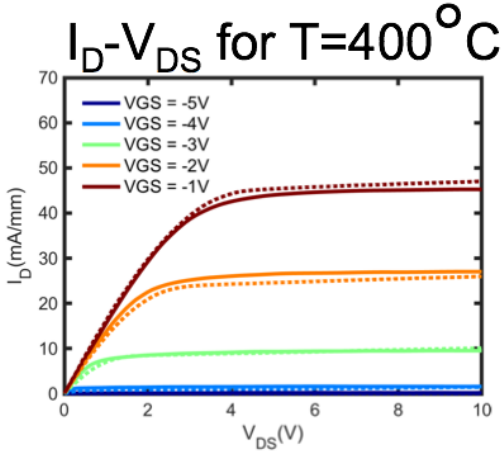


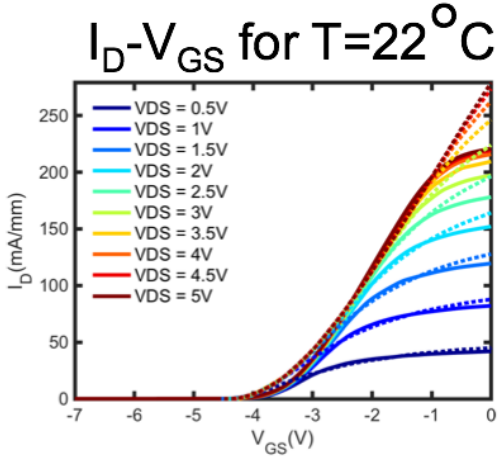
- g_m determines how much a signal can be amplified
- Bias circuit in region where g_m is large

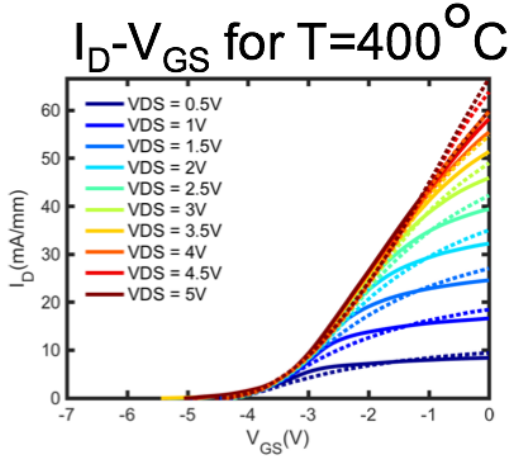
Images credit:
S. Blankenberg, summer REU, Stanford University, 2018.

Extraction of ASM parameters





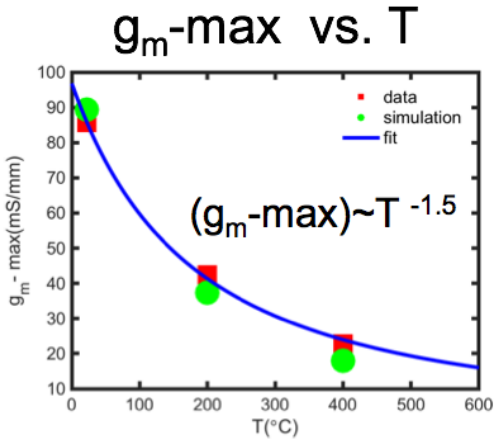


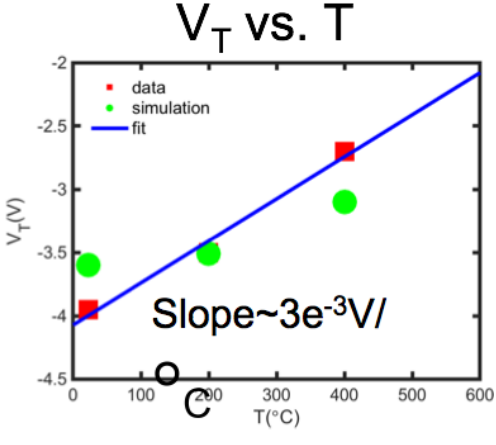


Simulated ▬▬

Measured ▬ ▬ ▬

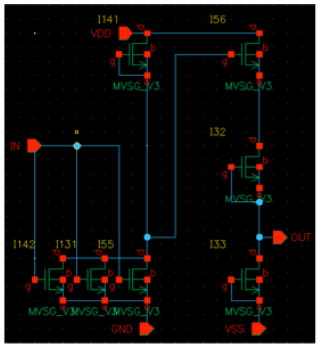
- Heated transistors up to 500°C
- IC-CAP to obtain fit
- Model captures g_m-max, R_{on}, I_{SAT}, and general trends in V_T
- V_T fairly stable ($\Delta V_T \sim 1V$)

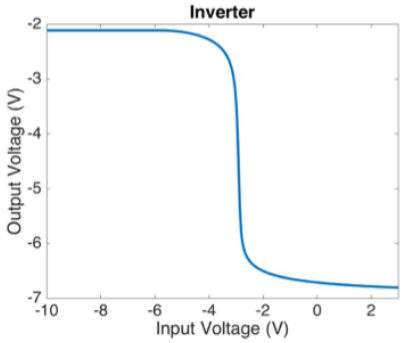


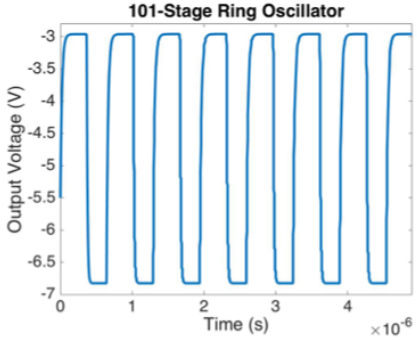


Images credit:
S. Blankenberg, summer REU, Stanford University, 2018.

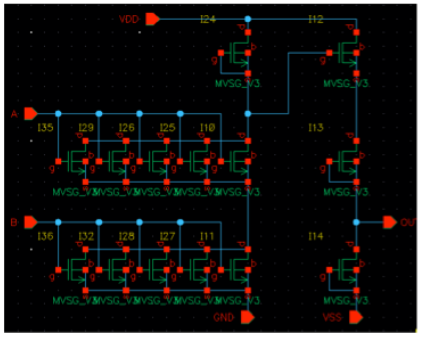
Circuit Design and Simulation

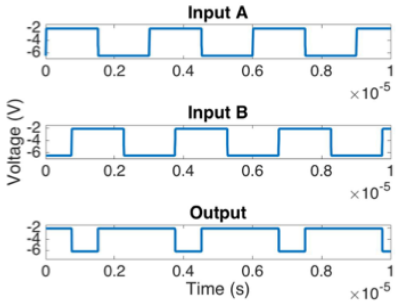


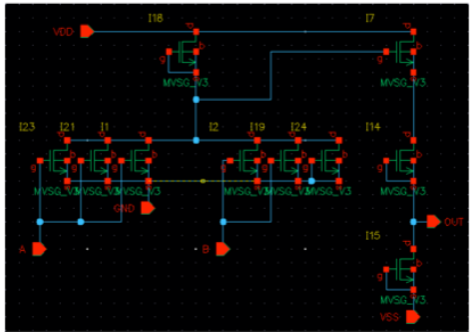


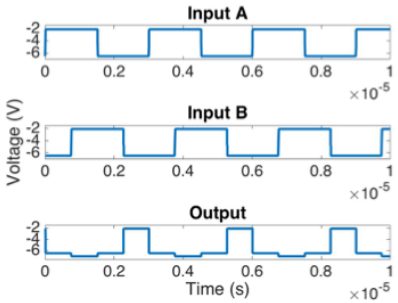


NAND and NOR Gates

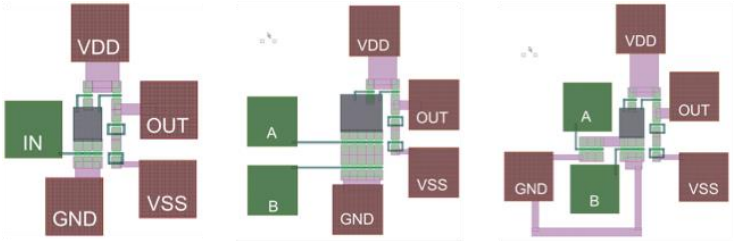






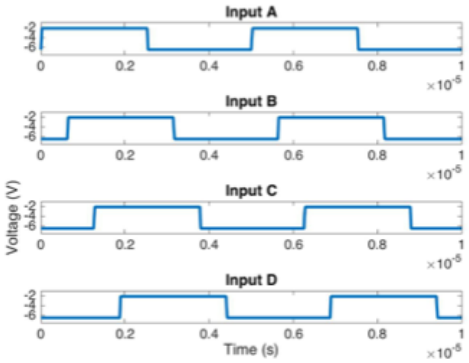


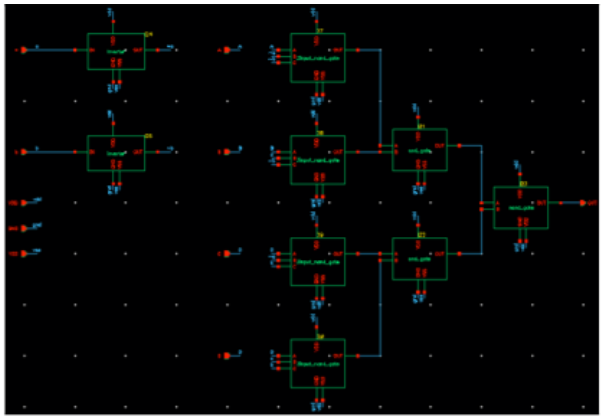
Images credit:
D. Mendoza, summer REU, Stanford University, 2018.
(Pre-publication material)

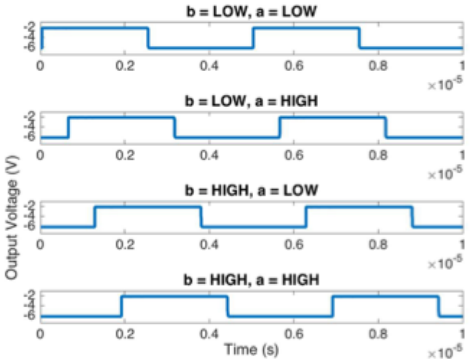


more Circuit Design and Simulation

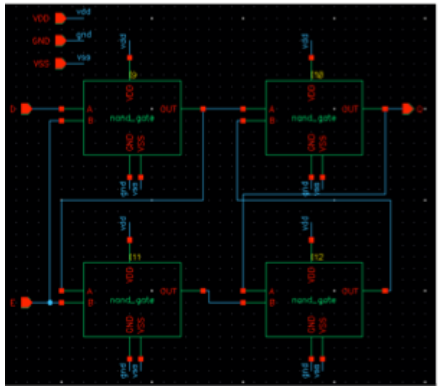
4-to-1 Multiplexer

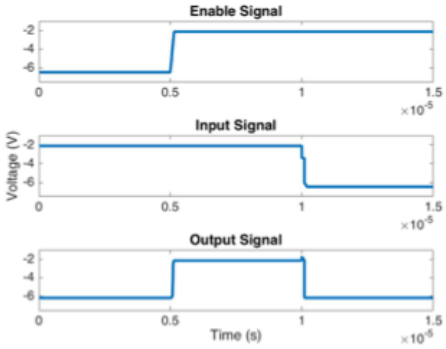




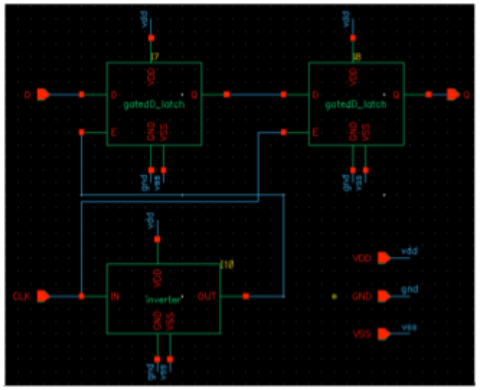


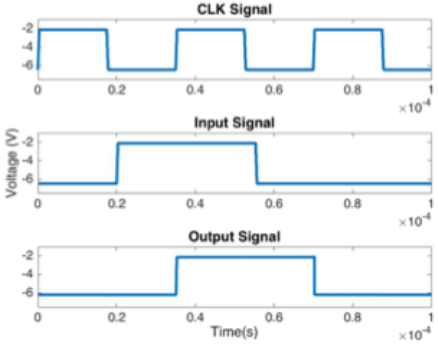
Gated Latch





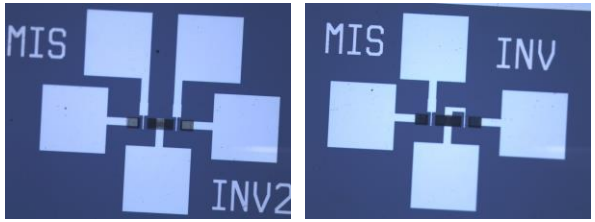
Gated Flip-Flop



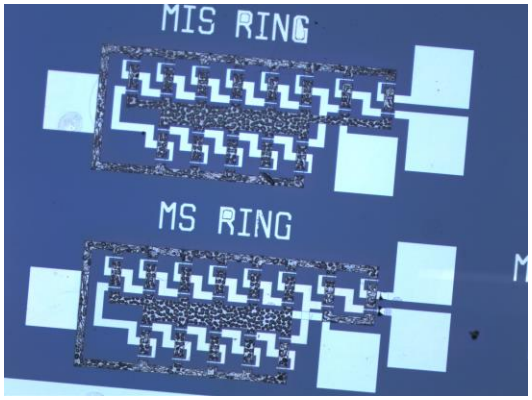


Images credit:
D. Mendoza, summer REU, Stanford University, 2018. (Pre-publication material)

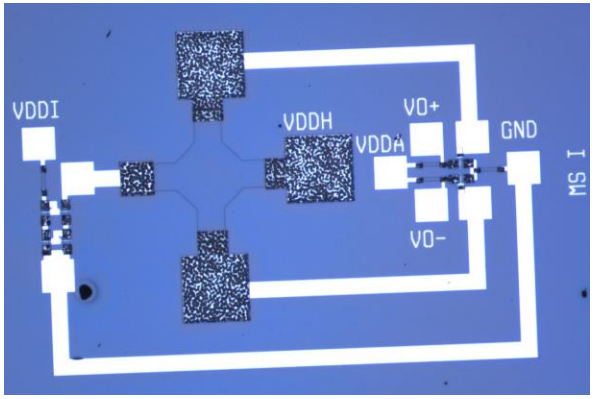
GaN HEMT Integrated Circuits *(Batch.1)*



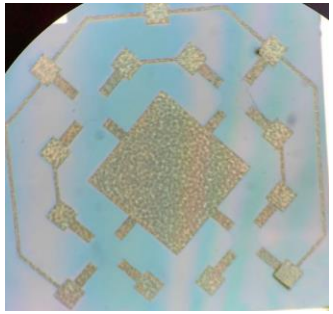
D-mode Inverters



11-stages ring oscillator



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



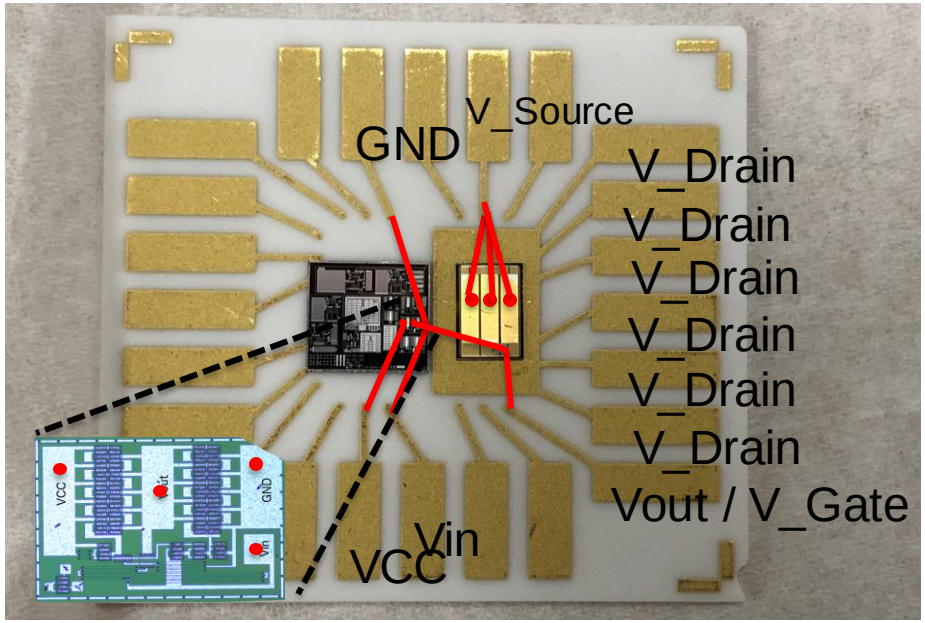
An offset-reduced magnetic hall-effect sensor

S. Kargarrazi, D.G.Senesky, et al.,pre-*publication material* (2019)

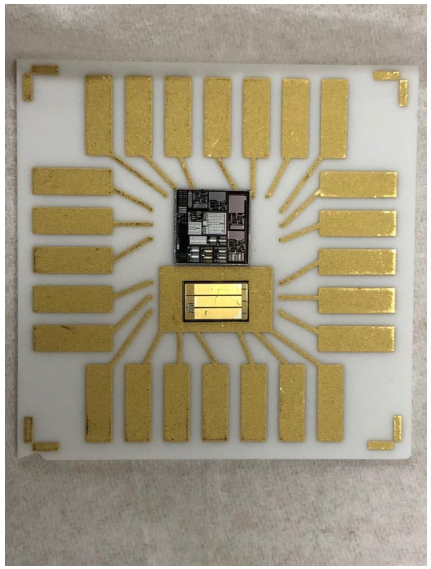
High-T Substrate (High-temperature co-fired Ceramic)

“ No, you didn’t really make high-T electronics, unless.…”

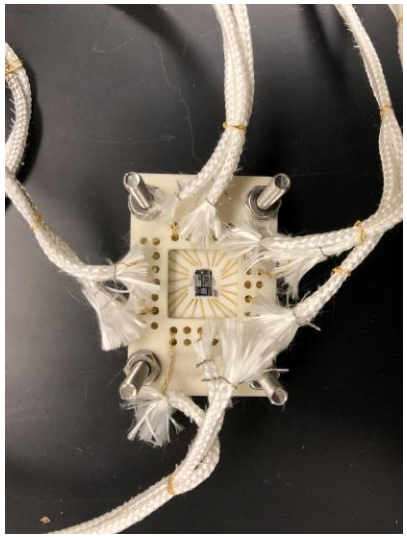
An audience in ISPSD 2015



High-T mounting, bonding, packaging



HTCC board

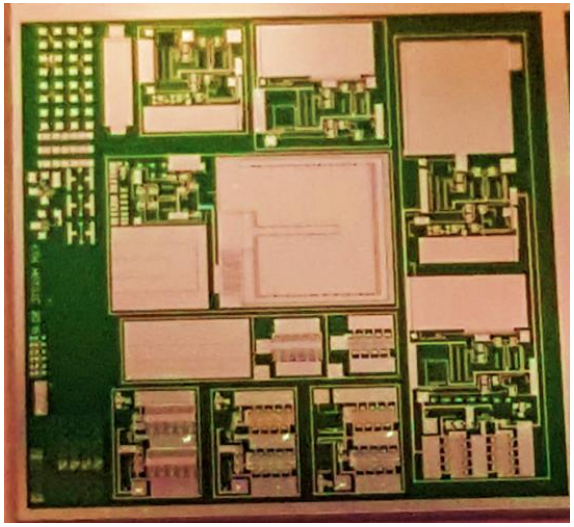


HT- Wirebonding
HT- Wires/mounting

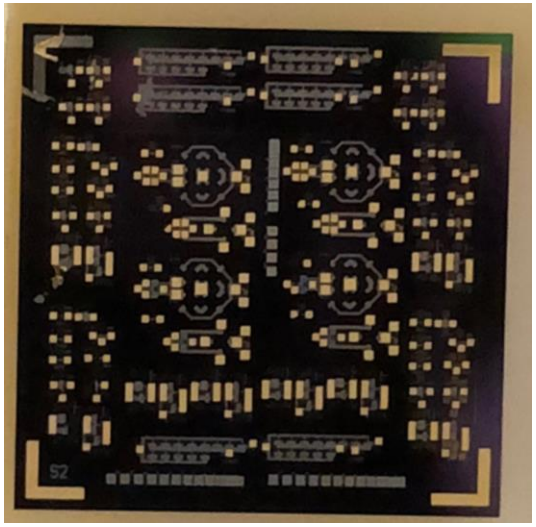
Prolonged measuremnnts
in the oven

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 (2018)



Thanks

Special Thanks to all my colleagues at XLab