Temperature-accelerated Degradation of GaN HEMTs under High-power Stress: Activation Energy of Drain Current Degradation

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Acknowledgement: DRIFT-MURI, TriQuint Semiconductor

Outline

1. Motivation
2. High-power and high-temperature stress experiments
3. An improved approach
4. Conclusions

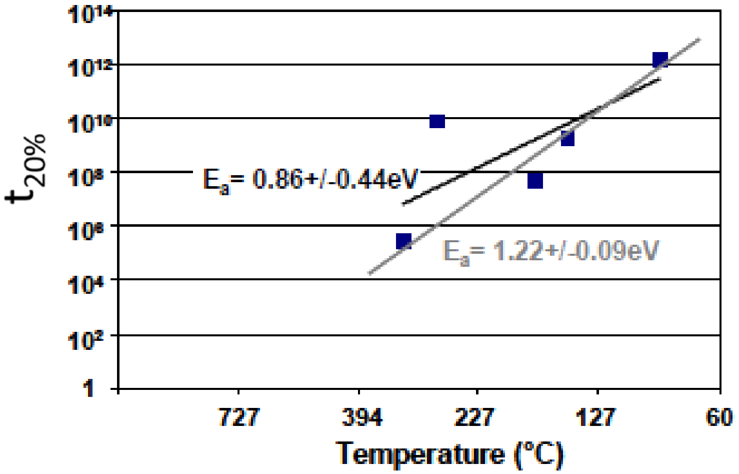
Motivation

- Activation energy, E_a :

  essential in predicting lifetime
- Conventionally:

  high temperature accelerated life test

N. Malbert, IRPS 2010



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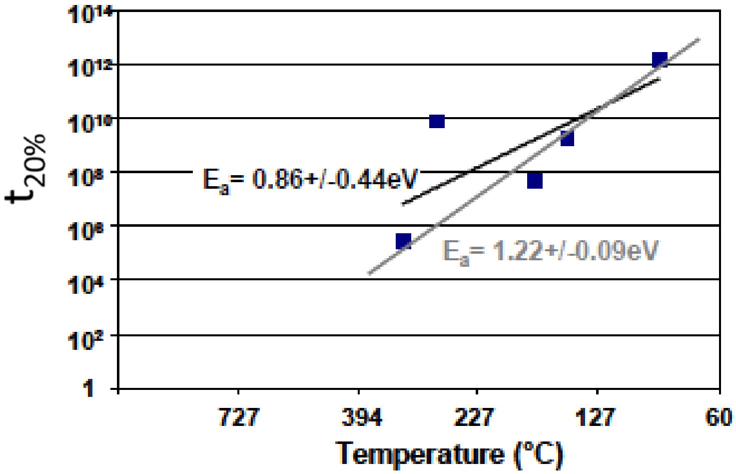
N. Malbert, IRPS 2010

Problems:

- Requires multiple devices
- Carrier trapping not properly dealt with
- Different degradation mechanisms can emerge at different temperatures

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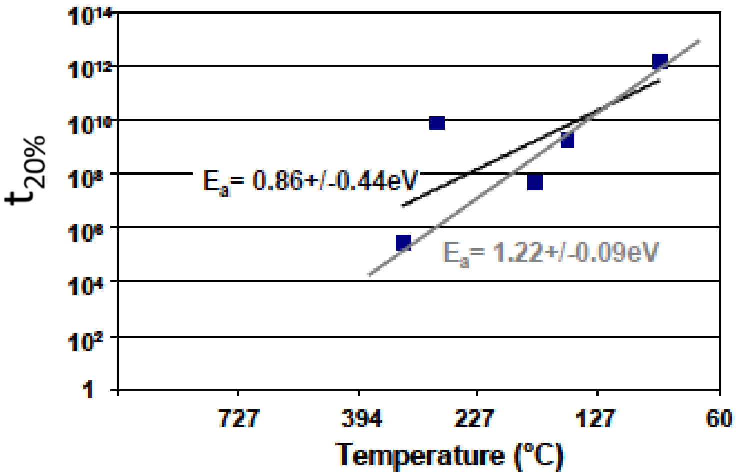
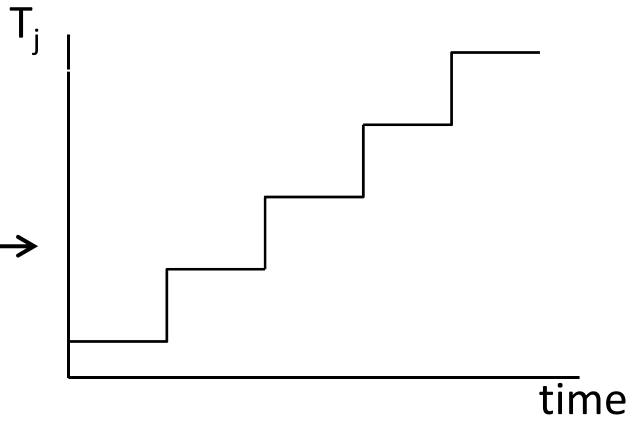


Desirable: E_a extraction from measurements on a ***single device***

Step-temperature stress →



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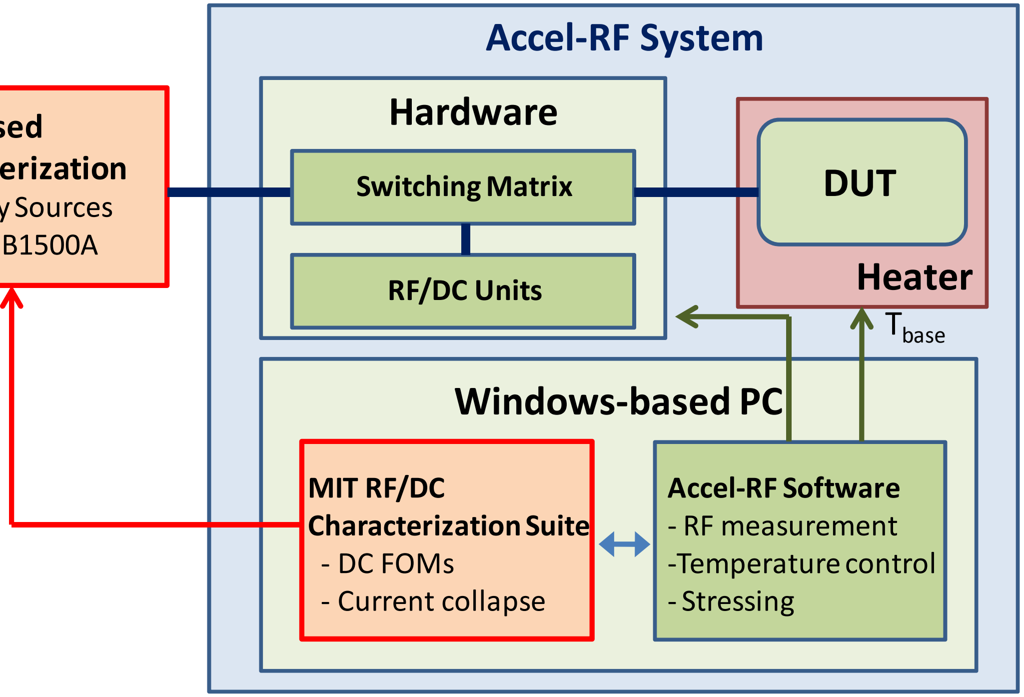
Setup for DC reliability studies

Devices: Prototype GaN Power Amplifier MMIC from industry



DC/Pulsed Characterization
- Keithley Sources
- Agilent B1500A

Accel-RF System

Hardware

Switching Matrix

RF/DC Units

DUT

Heater

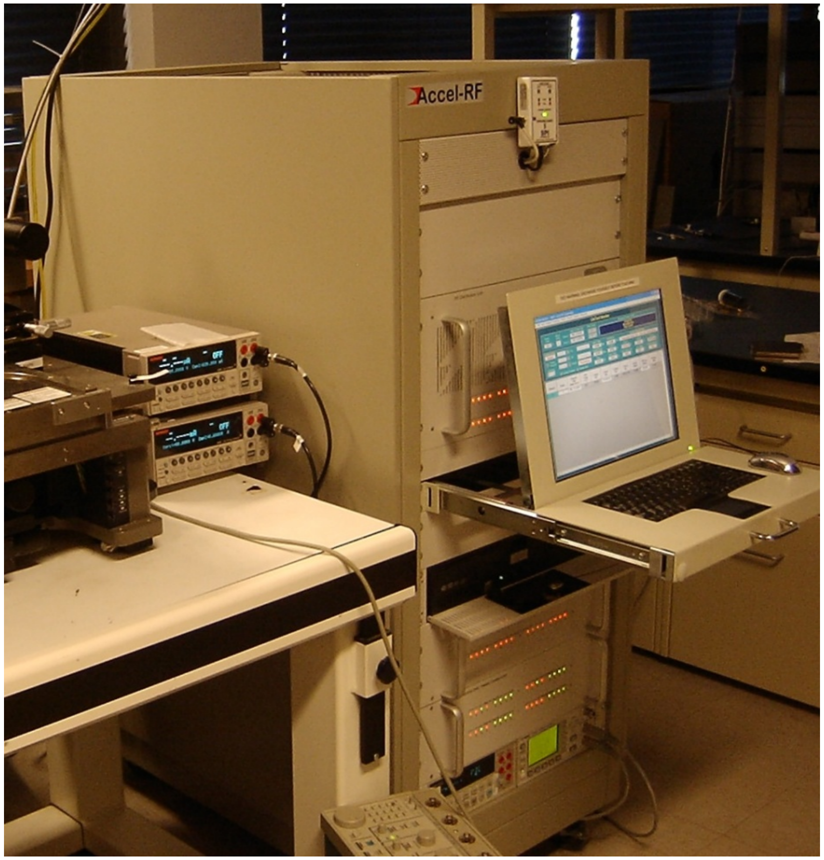
T_{base}

Windows-based PC

MIT RF/DC Characterization Suite
- DC FOMs
- Current collapse

Accel-RF Software
- RF measurement
- Temperature control
- Stressing

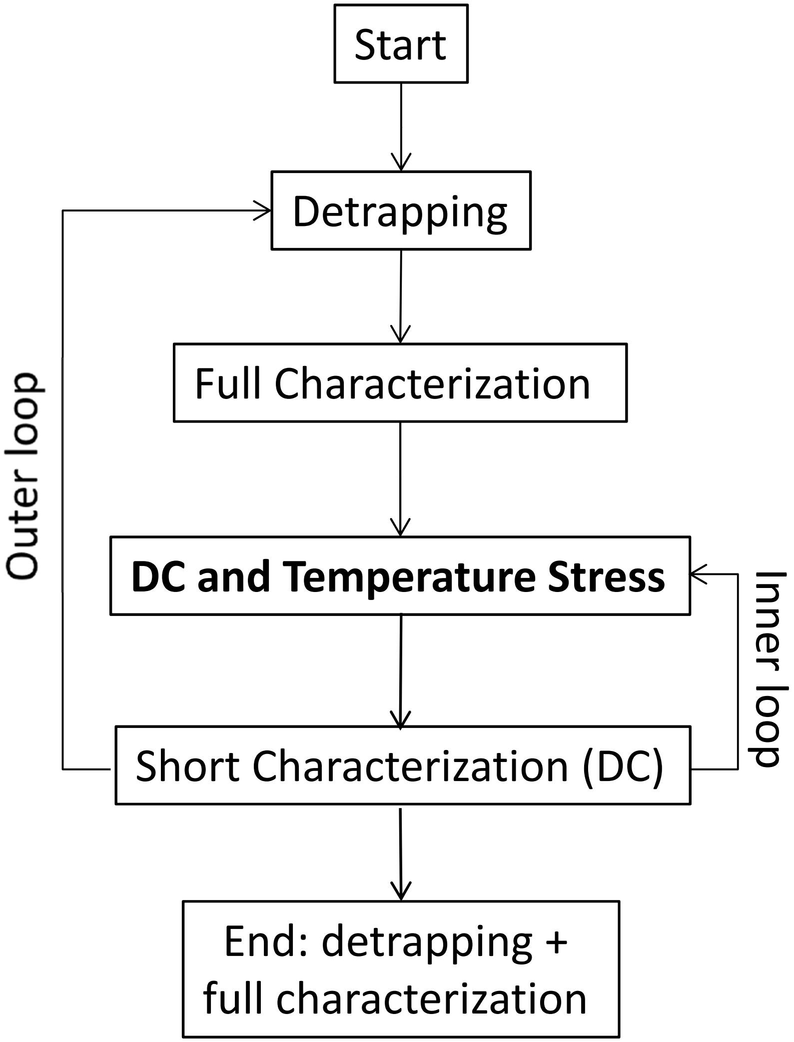
Accel-RF AARTS RF10000-4/S system



Augmented with:

- external instrumentation for DC/pulsed characterization
- software to control external instrumentation and extract DC FOMs

High-power DC Experiment Flowchart



Start

Detrapping

Full Characterization

DC and Temperature Stress

Short Characterization (DC)

End: detrapping +
full characterization

Outer loop

Inner loop

- **Detrapping**: T_{base} = 250 °C for 7.5 hours
- **Full characterization**
  - At T_{base} = 50 °C
  - Full DC I-V sweep
  - Current collapse

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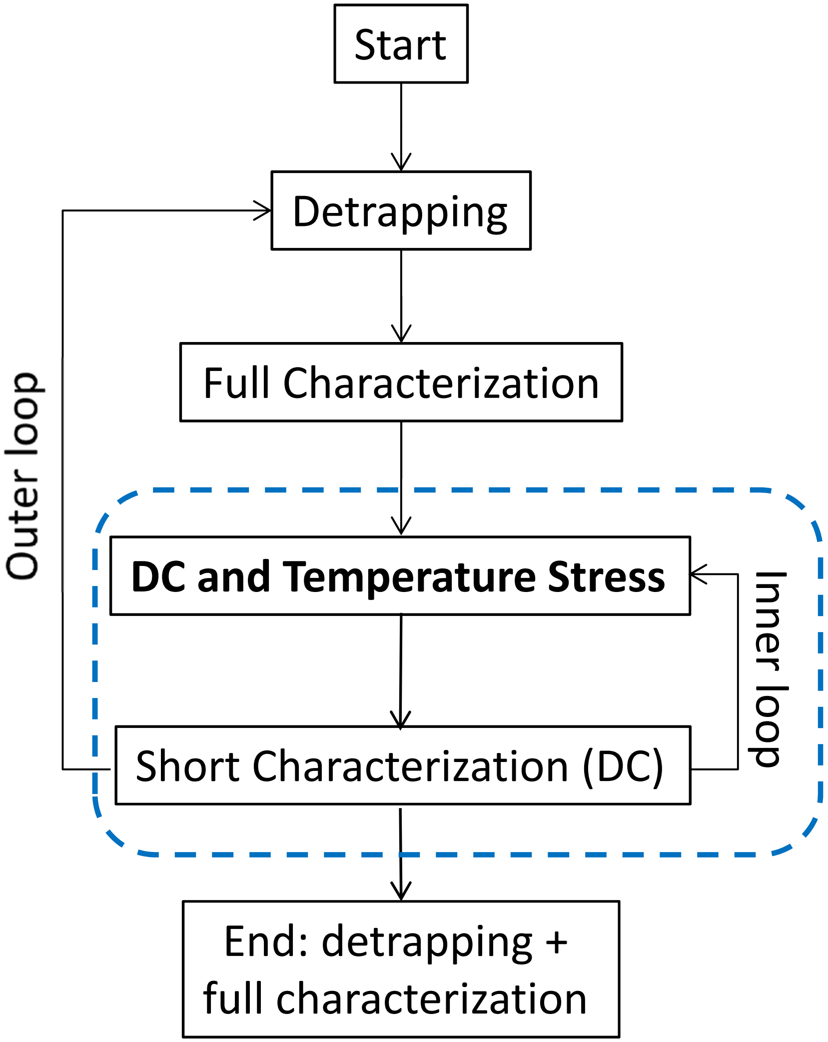

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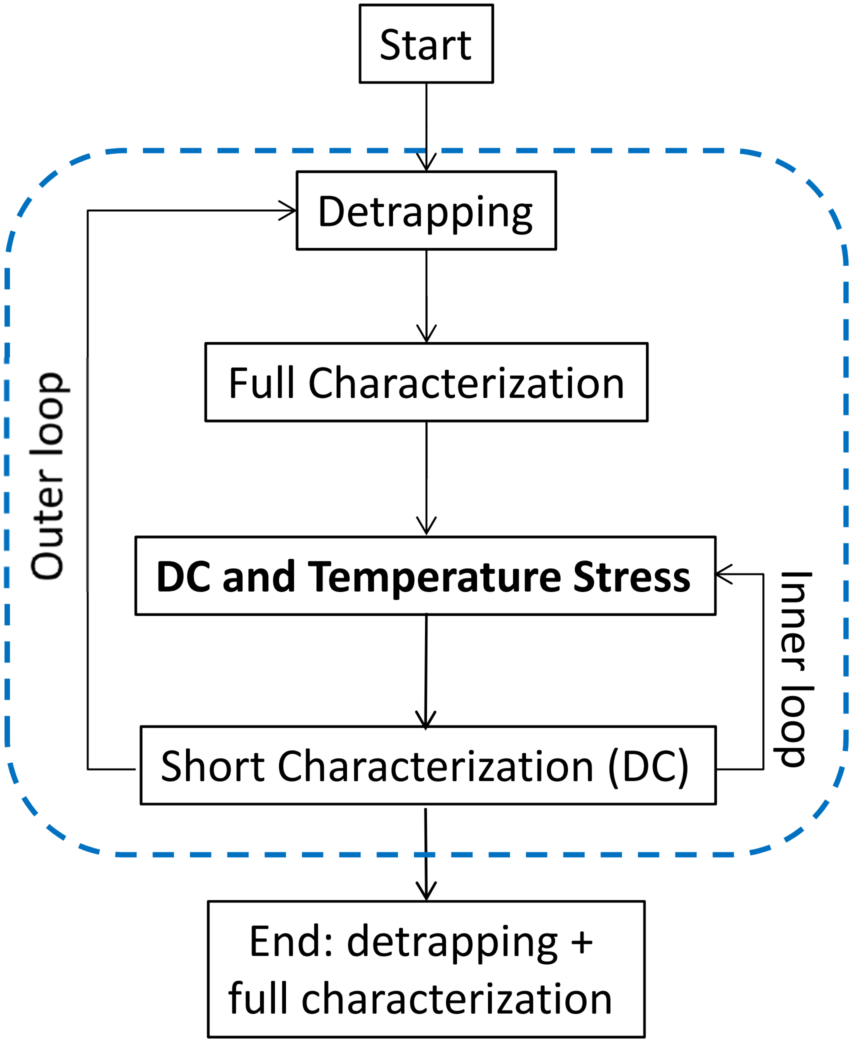
- **Full characterization**
  - At T_{base} = 50 °C
  - Full DC I-V sweep
  - Current collapse
- **Stress:**
  - High-power condition
  - Base temperature stepped up
- **Short characterization**
  - Every 30 minutes at T_{base} = 50 °C
  - DC FOMs: I_{Dmax}, I_{Goff}, R_D, R_S, V_T, …

High-power DC Experiment Flowchart



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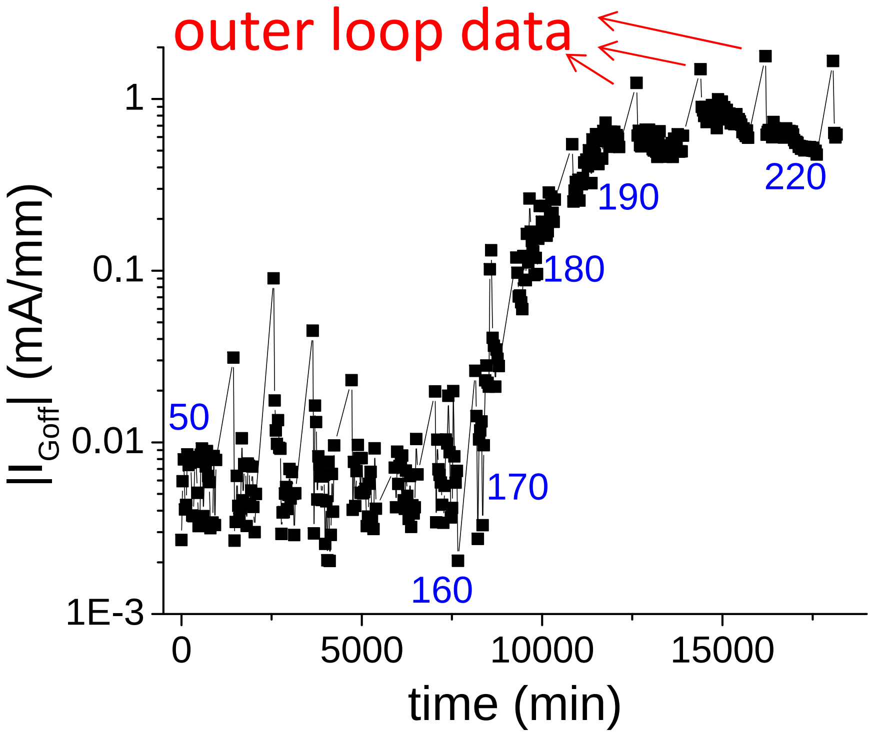
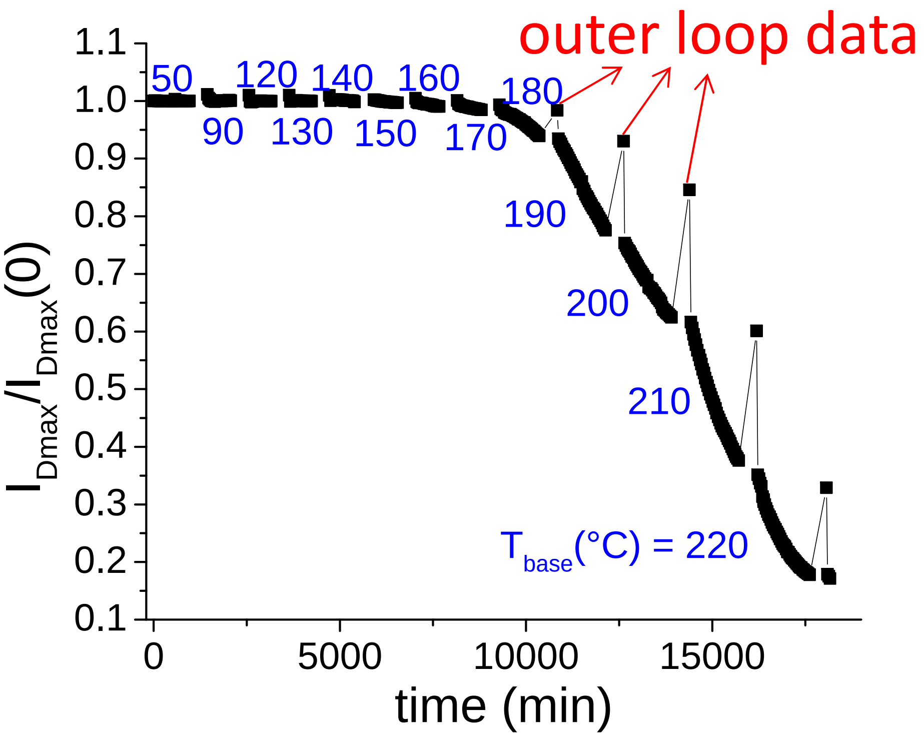
Definitions of Various Figures of Merit

Parameter	Definition
I_{Dmax}	I_D at V_{GS} =2 V, V_{DS} =5 V
I_{Goff}	I_G at V_{GS} =-5 V, V_{DS} =0.1 V
R_D	Drain resistance measured with I_G = 20 mA/mm
R_S	Source resistance measured with I_G = 20 mA/mm
V_T	V_{GS} – 0.5V_{DS} when I_D = 1 mA/mm at V_{DS} = 0.1 V
Current Collapse	Percentage change in I_{Dmax} after 1 sec. V_{DS} = 0 V, V_{GS} = -10 V pulse

High-power DC Experiment

High-power stress: V_{DS} = 40 V, I_D = 100 mA/mm, T_{base} = 50 °C – 230 °C, 600 min/step





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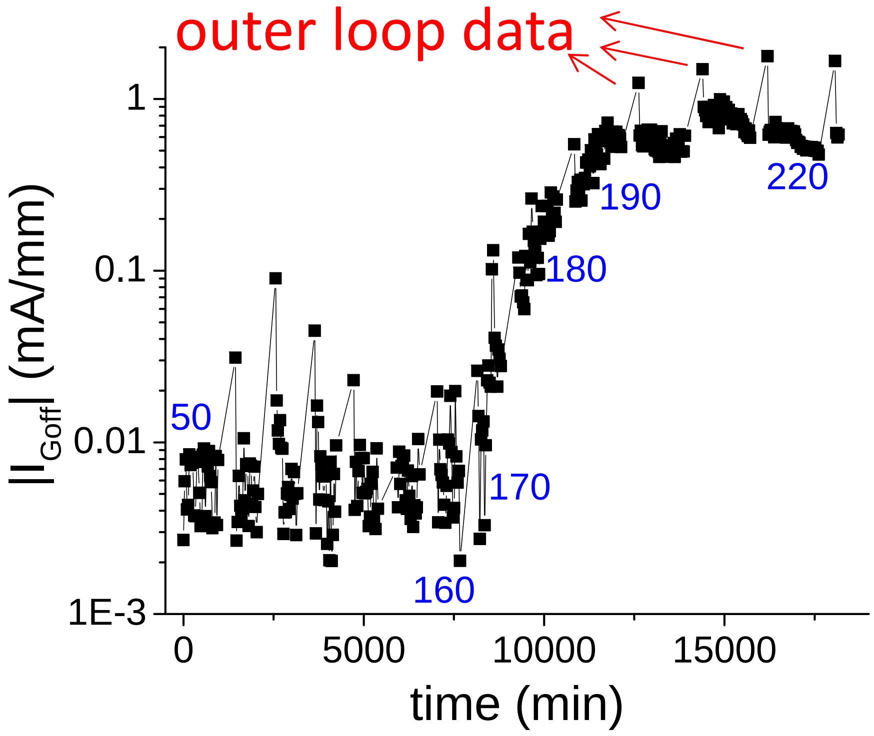
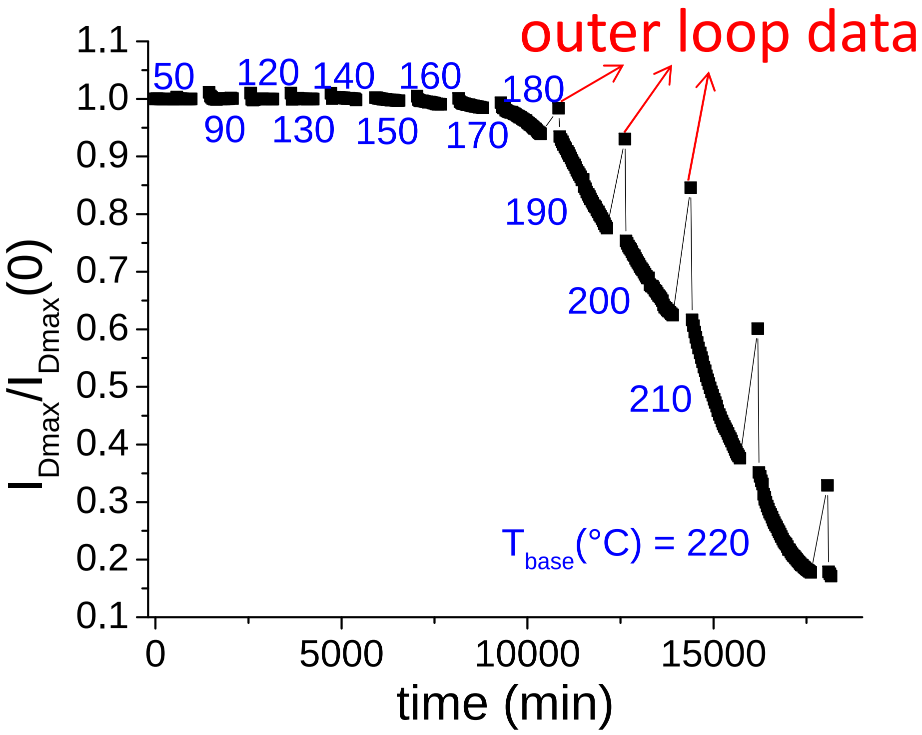
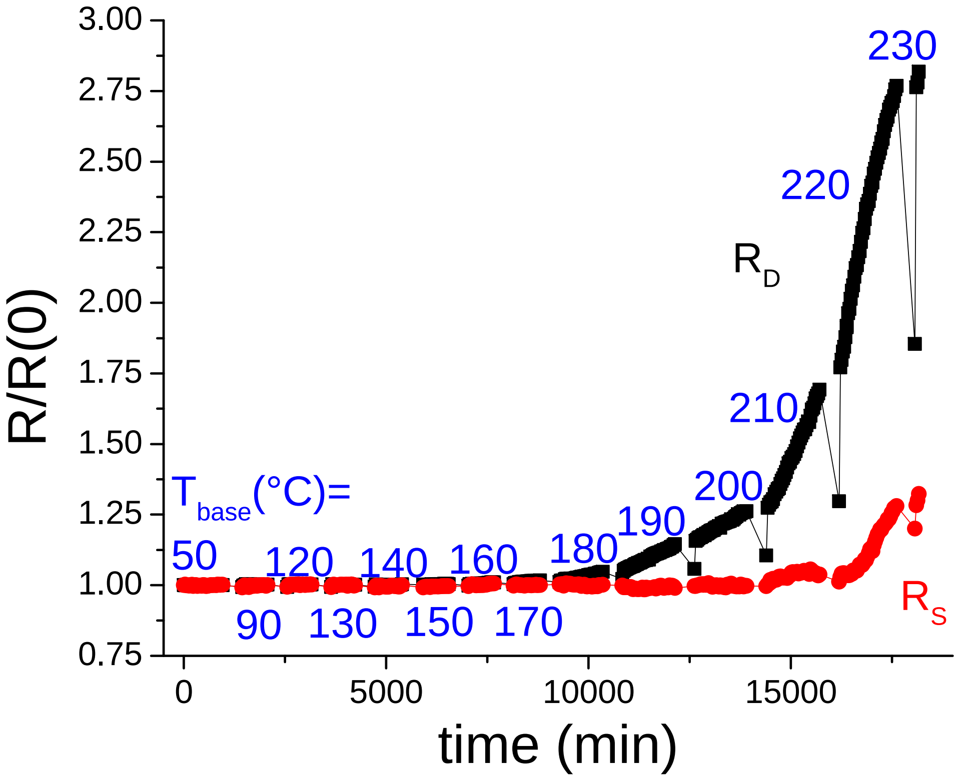




- $|I_{Goff}|$ increases from T_{base}=170 to 190°C; then saturates
- Significant I_{Dmax} degradation for T_{base} > 180 °C
- Thermally activated I_{Dmax} degradation rate shown

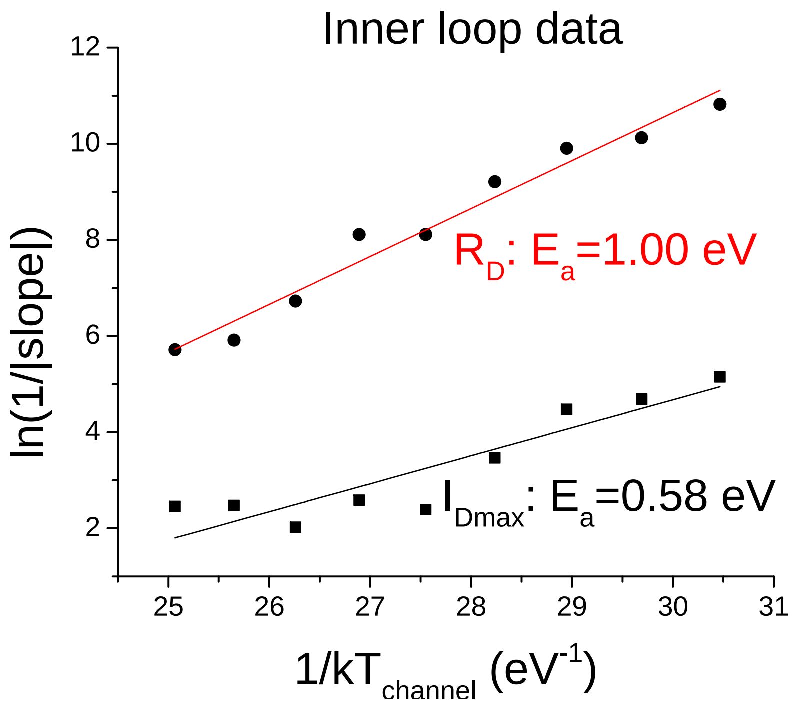
High-power DC Experiment

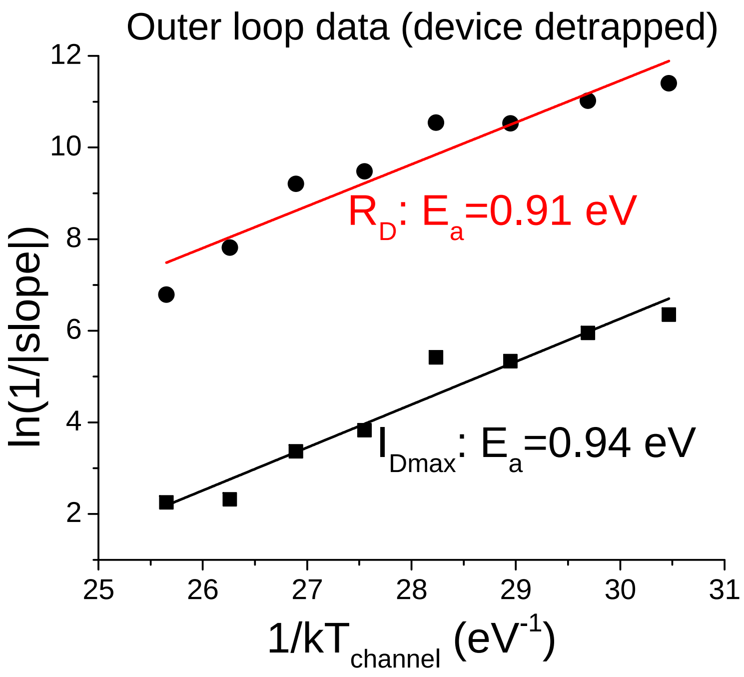
High-power stress: V_{DS} = 40 V, I_D = 100 mA/mm, T_{base} = 50 °C – 230 °C, 600 min/step



- R_D increases significantly, consistent with I_{Dmax} decrease
- R_S increases much less

Activation Energies of Degradation Rates


Inner loop data


Outer loop data (device detrapped)

$T_{channel}$ obtained from thermal model of MMICs

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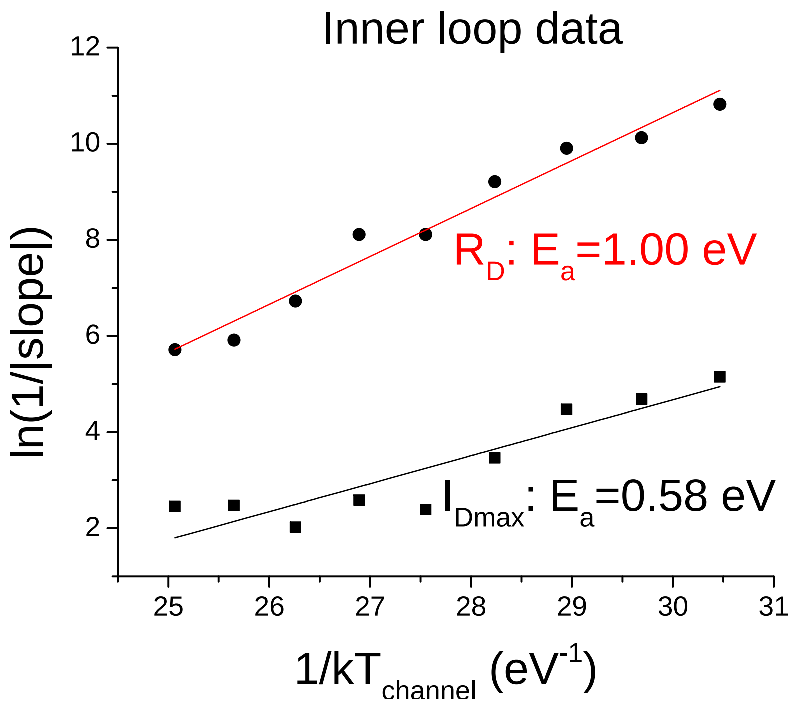
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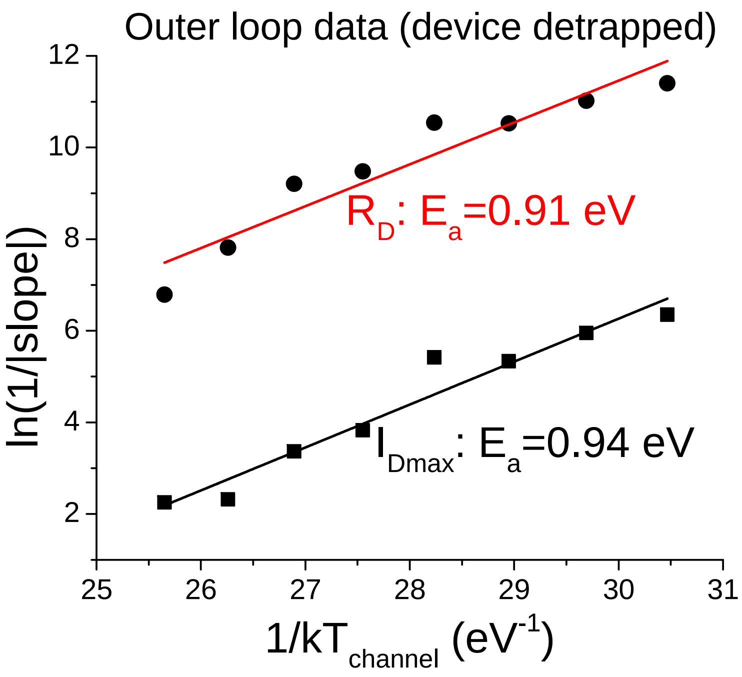
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$T_{channel}$ obtained from thermal model of MMICs

- Inner loop data :

  Large difference between E_a for I_{Dmax} and R_D

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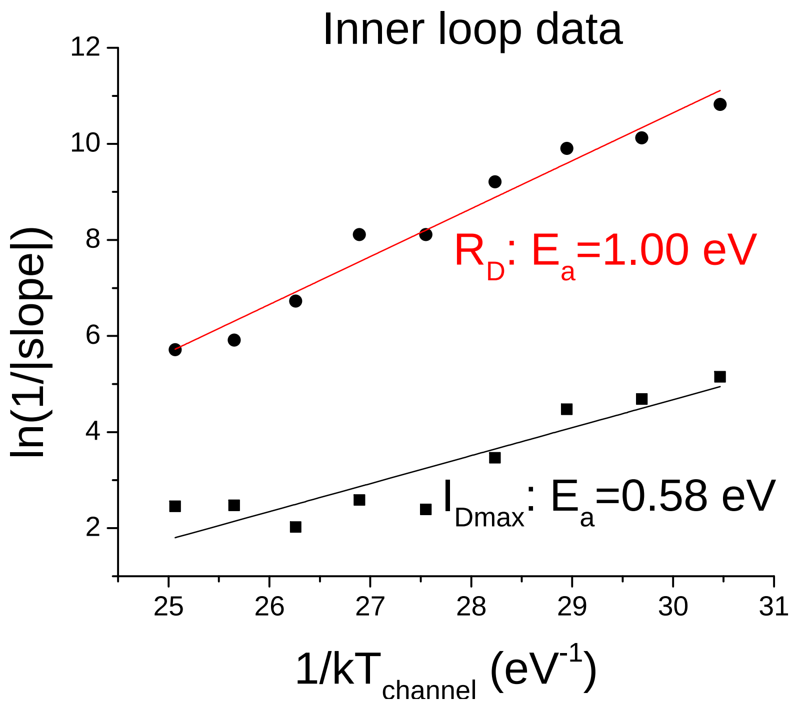
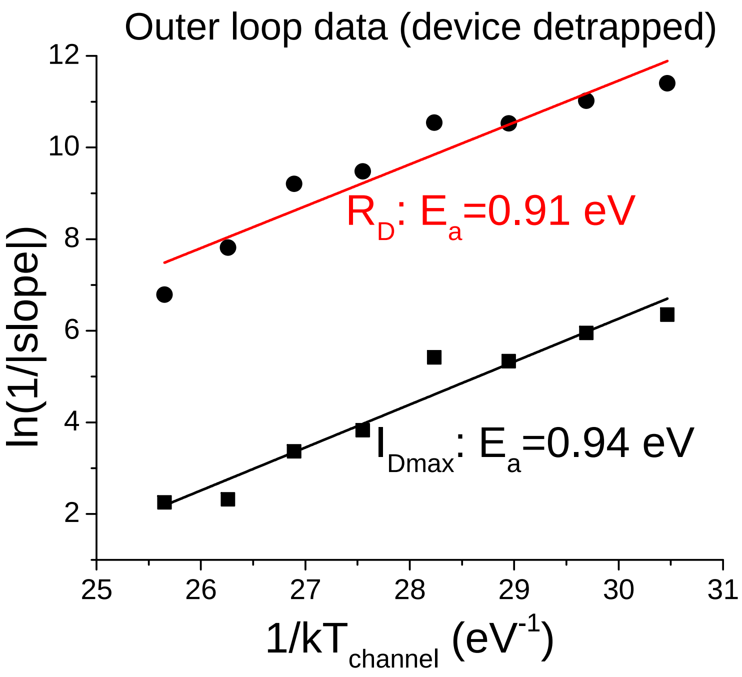




$T_{channel}$ obtained from thermal model of MMICs

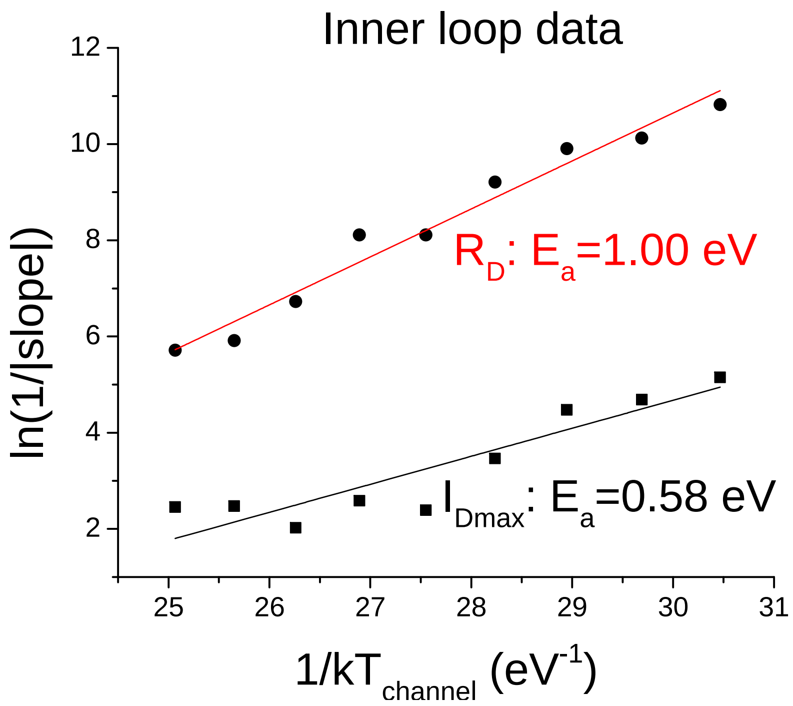
- Inner loop data :

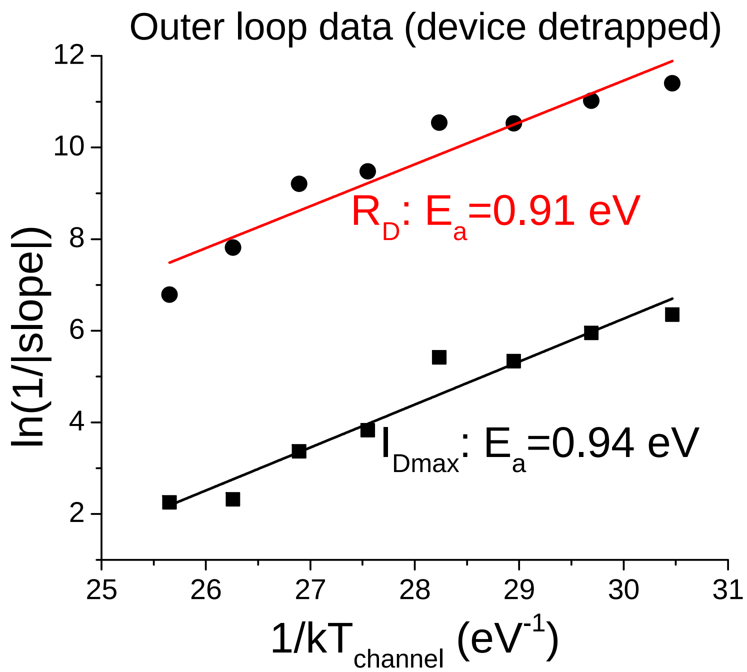
  Large difference between E_a for I_{Dmax} and R_D

- Outer loop data :

  Thermally activated behavior

Activation Energies of Degradation Rates





$T_{channel}$ obtained from thermal model of MMICs

- Inner loop data :

  Large difference between E_a for I_{Dmax} and R_D

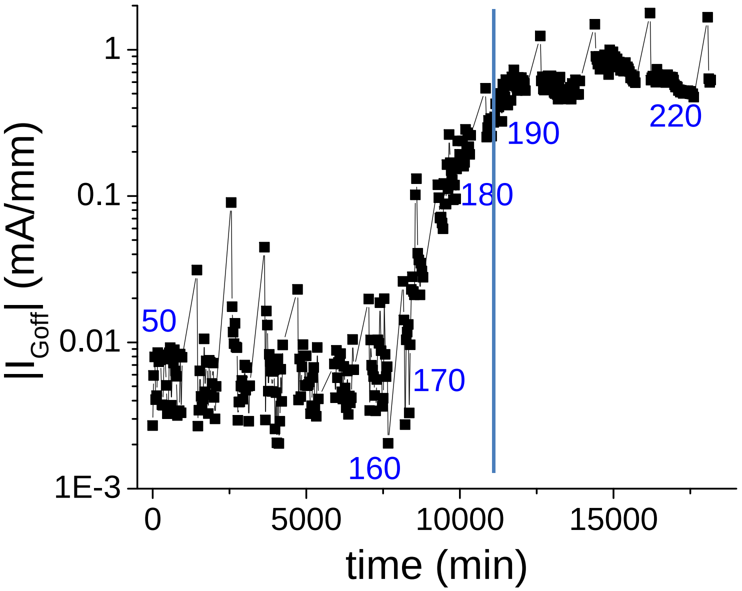
- Outer loop data :

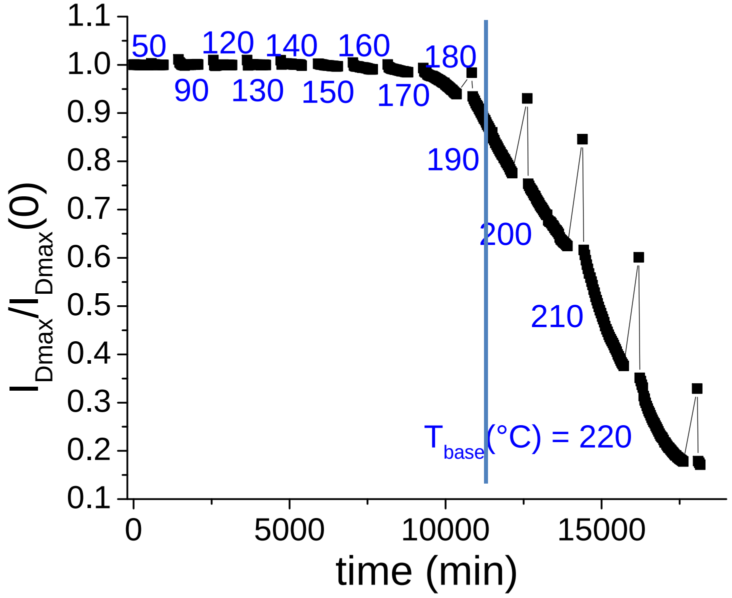
  Close E_a values for I_{Dmax} and R_D →common physical origin

Conclusions Drawn from the Experiment

- I_G degradation:
  - Increases fast at first
  - Eventually saturates

- I_D degradation:
  - Significant degradation only *after* I_G degradation is saturated
  - Thermally activated





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- I_G degradation:
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  - Significant degradation only *after* I_G degradation is saturated
  - Thermally activated

- Desirable: separate I_G and I_D degradation
- Key idea: short stress to degrade I_G without I_D degradation, then long stress to degrade I_D

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DC Experiment : Improved Approach

- **Phase 1**: degrade I_G without significant I_D degradation
- Short stress period
  - T_{base} = 50-220 °C, in 20 °C steps
  - Stress time: 6 minutes

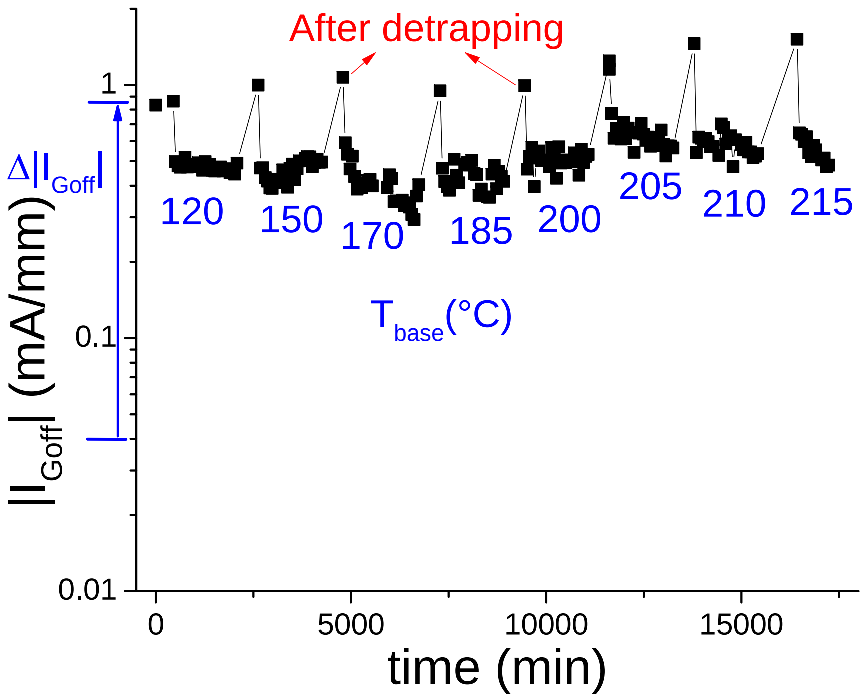
DC Experiment : Improved Approach

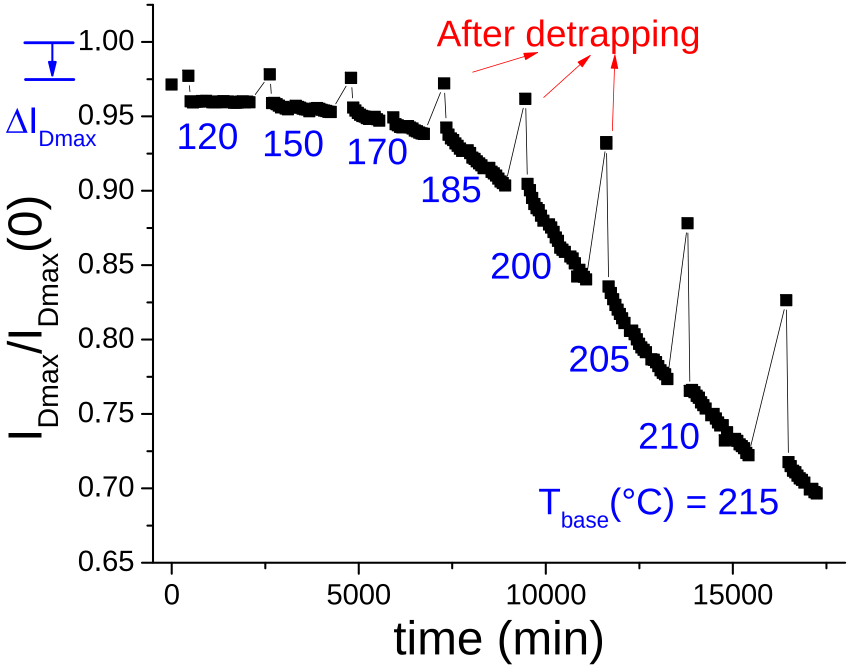
- **Phase 1**: degrade I_G without significant I_D degradation
- Short stress period
  - T_{base} = 50-220 °C, in 20 °C steps
  - Stress time: 6 minutes

- **Phase 2**: degrade I_D without further I_G degradation
- Longer stress period
  - T_{base}: from 120 °C, increase in steps
  - Stress time: 24 hours

A Typical Experiment (Phase 2)

High-power stress: V_{DS} = 40 V, I_D = 100 mA/mm, T_{base} = 120 °C – 215 °C, 24 hours/step





During phase 1:

$|I_{Goff}|$ increases by 2 orders of magnitude; I_{Dmax} decreases by 3%

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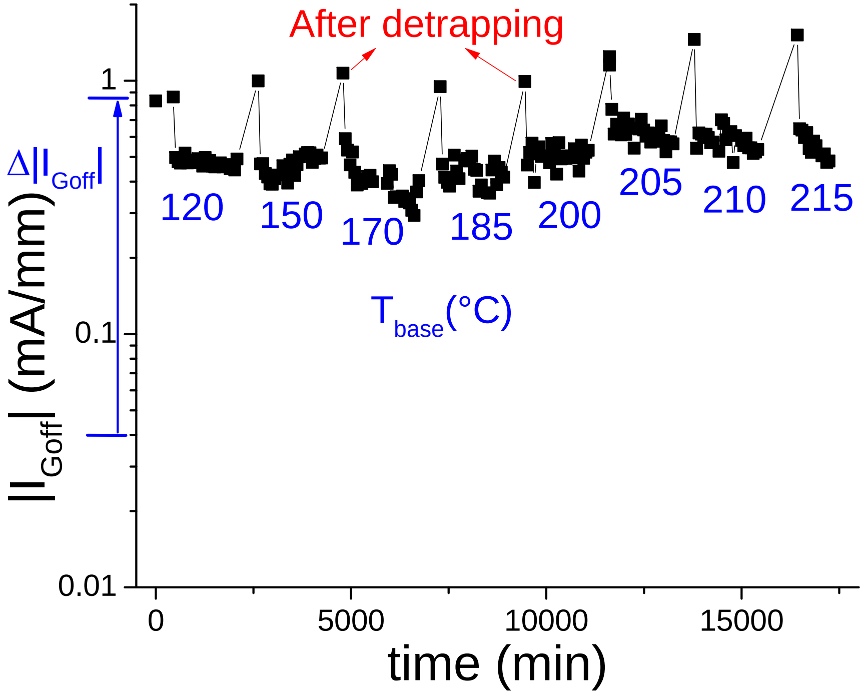
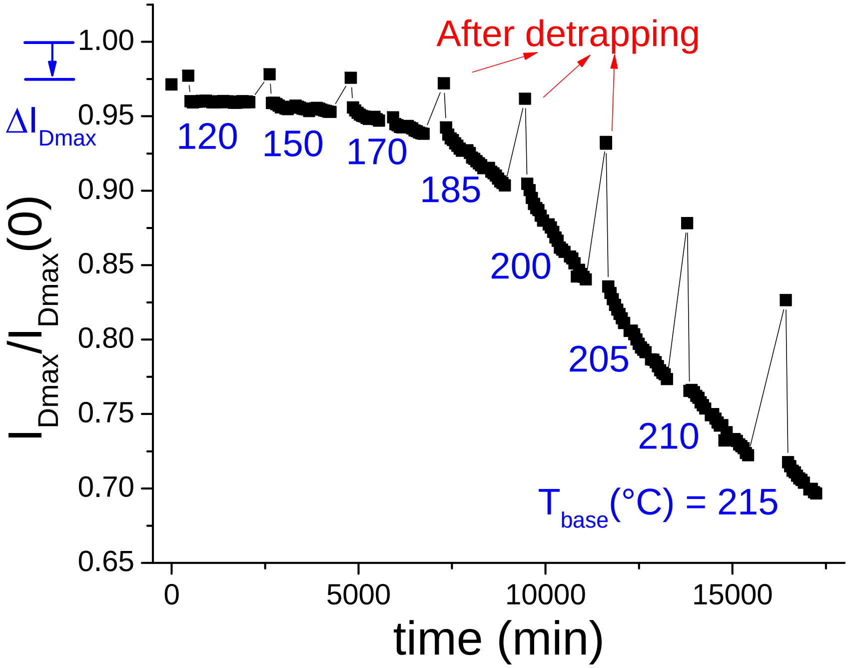




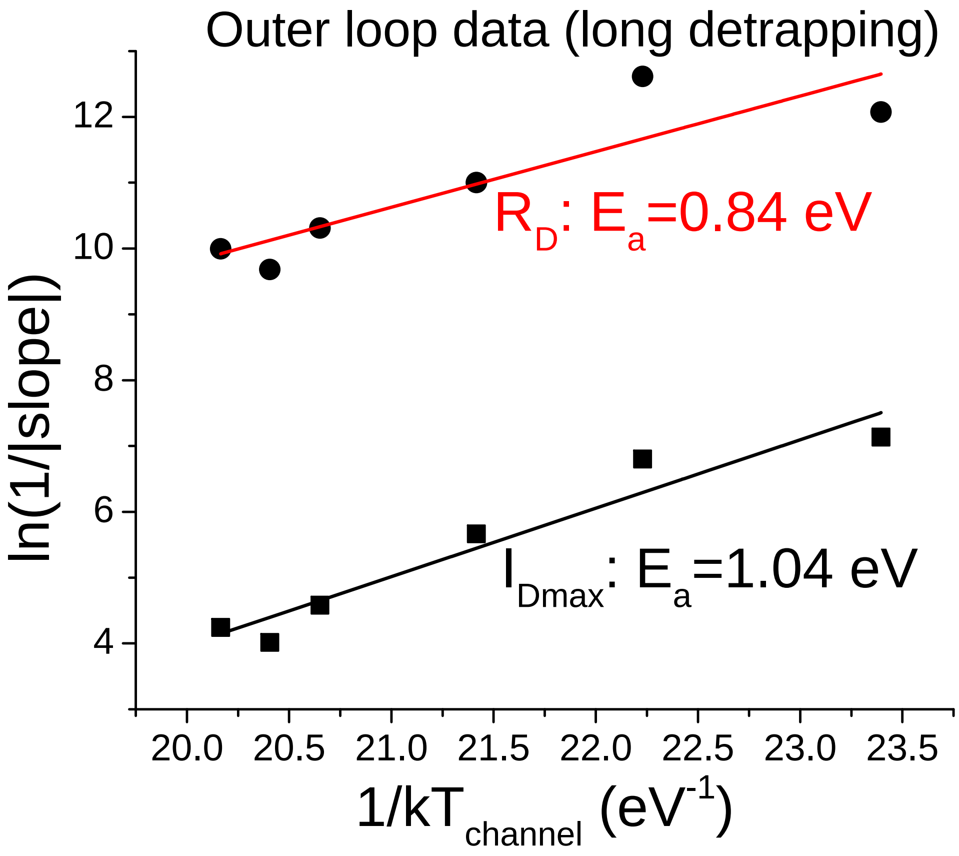
During phase 1:

|I_{Goff}| increases by 2 orders of magnitude; I_{Dmax} decreases by 3%

During phase 2:

- |I_{Goff}| stays at saturated level (~0.5 mA/mm)
- I_{Dmax} degradation shows thermally activated characteristics

Activation Energies of Degradation Rates



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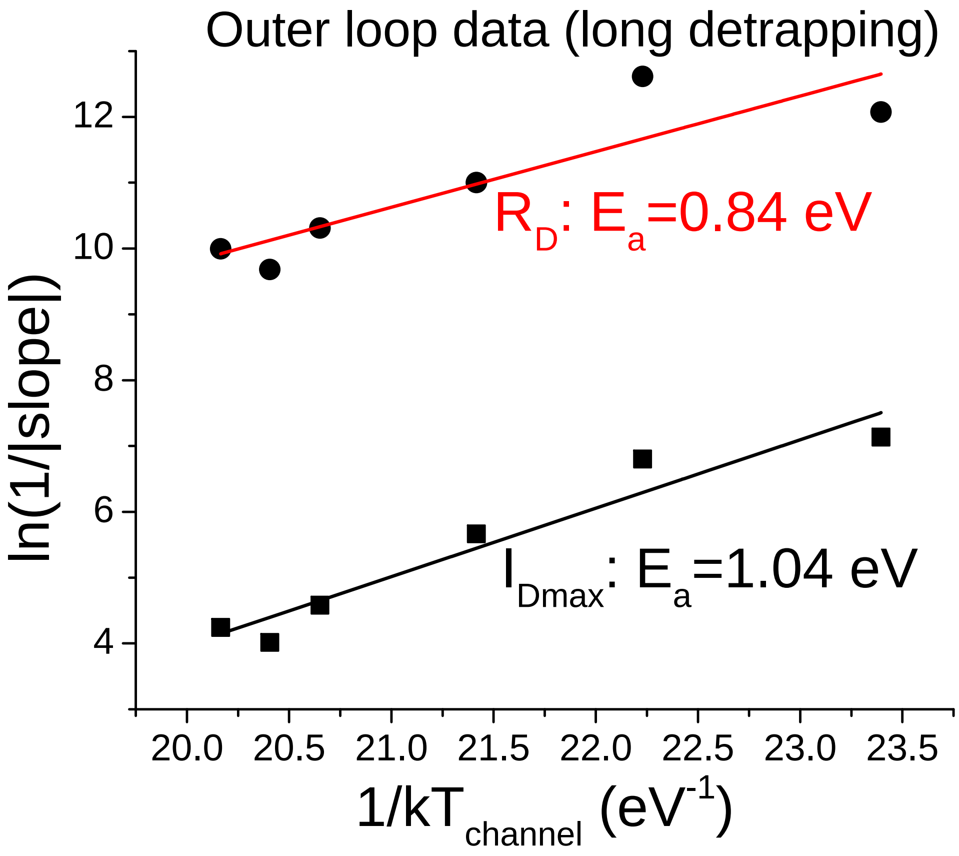

E_a for I_{Dmax} close to values reported on similar technologies in conventional long term experiments

Activation Energy for Drain Current Degradation from Literature

Reference	**Bias conditions**	**Temperature range**	**Activation energy E_a**
S. Singhal, et al. IRPS 2006	V_{DS}=28 V I_{DS}=64 mA/mm	T_j=260, 285, 310 °C	1.7 eV
P. Saunier, et al. DRC 2007	V_{DS}=40 V I_{DS}=250 mA/mm	T_j=260, 290, 320 °C	1.05 eV
E. Zanoni, et al. Microwave Integrated Circuits Conference 2009	V_{DS}=40 V I_{DS}=167 mA/mm	T_j=200, 245, 293 °C	0.68 eV - 1.58 eV
N. Malbert, et al. IRPS 2010	V_{DS}=25 V I_{DS}=417 mA/mm	T_j=150, 175, 275, 320 °C	0.8 eV – 1.2 eV
J. Joh, et al. IRPS 2011	V_{DS}=40 V V_{GS}=-7 V	T_j=75, 100, 125, 150 °C	1.12 eV
This work	V_{DS}=40 V I_{DS}=100 mA/mm	T_j=223, 249, 269, 289, 296, 302 °C	1.04 eV

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Conclusions

- Two-phase experiment: separates I_G and I_D degradation in GaN HEMTs under high-power and high-temperature stress
- Two mechanisms exist:
  - I_G degrades first and eventually saturates
  - I_D degrades after I_G degradation is saturated
- Demonstrated new technique to extract E_a from measurements on a single device
- E_a for permanent I_{Dmax} degradation rate : 0.95-1.05 eV