The Impact of Electro-Thermal Coupling on RF Power Amplifiers

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Review of Heating in Active Devices:

Self Heating
Mutual Heating
Transient Heating

(+ different approaches to modeling these)

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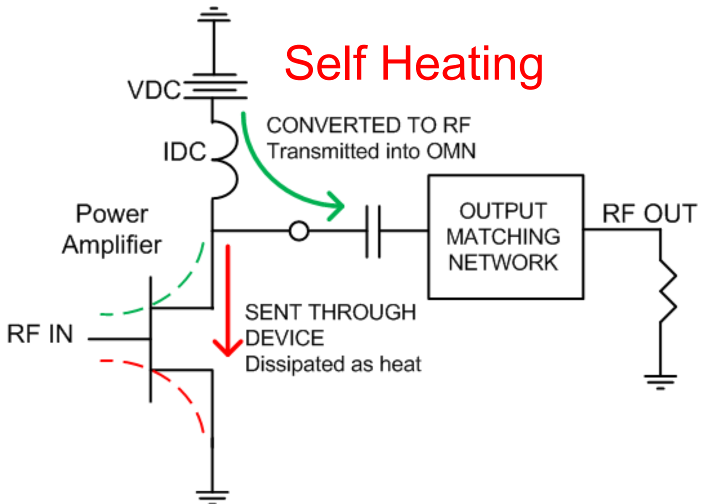
Device Heating Basics:

Self Heating



$$T_{device} = T_{ambient} + R_{th} * Pdiss$$

$$Rth = \frac{1}{2\kappa(L-W)} \ln\left(\frac{L(W+2t_{sub})}{W(L+2t_{sub})}\right)$$

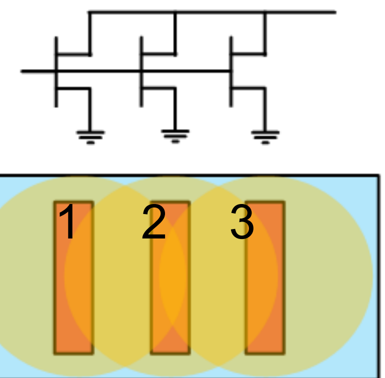
Thermal Conductivity

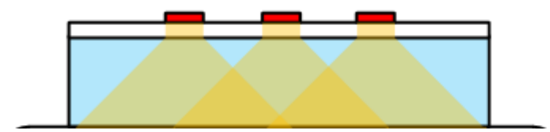
Mutual Heating

Self Heating Terms

$$R_{ij} = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix}$$

$$R_{ij} = \frac{\Delta T_i}{\Delta P_j}$$

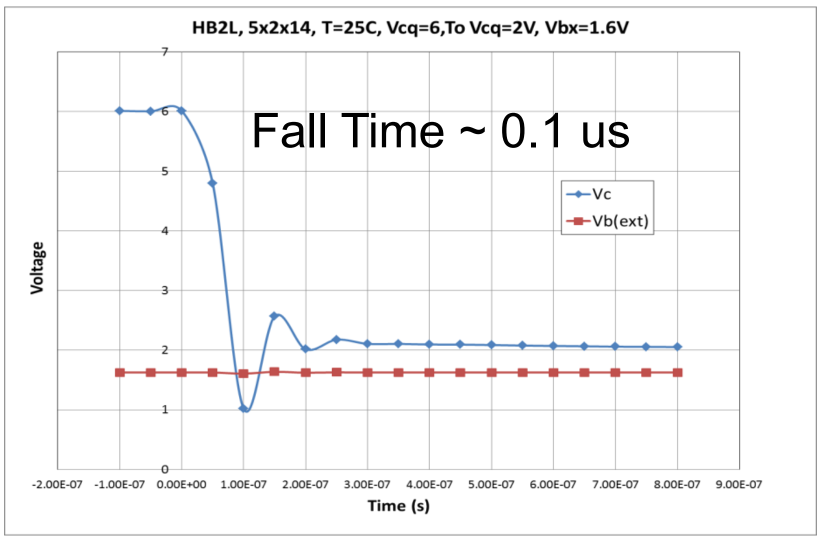




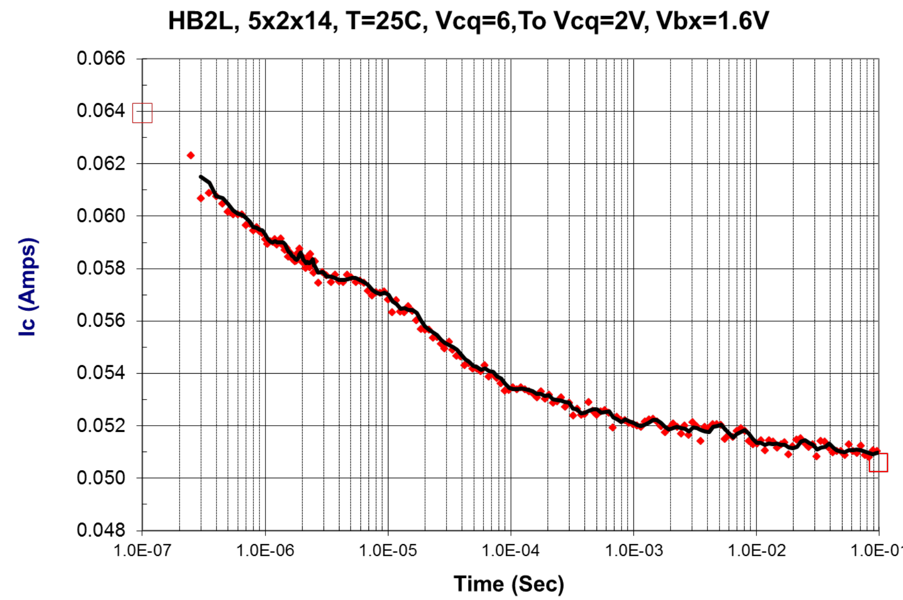
Substrate Spreading Term
(for rectangular geometries L>W)

Transient Thermal Response

Keysight GaAs HBT Test Device (Probe)
Transient pulse applied to Vcollector



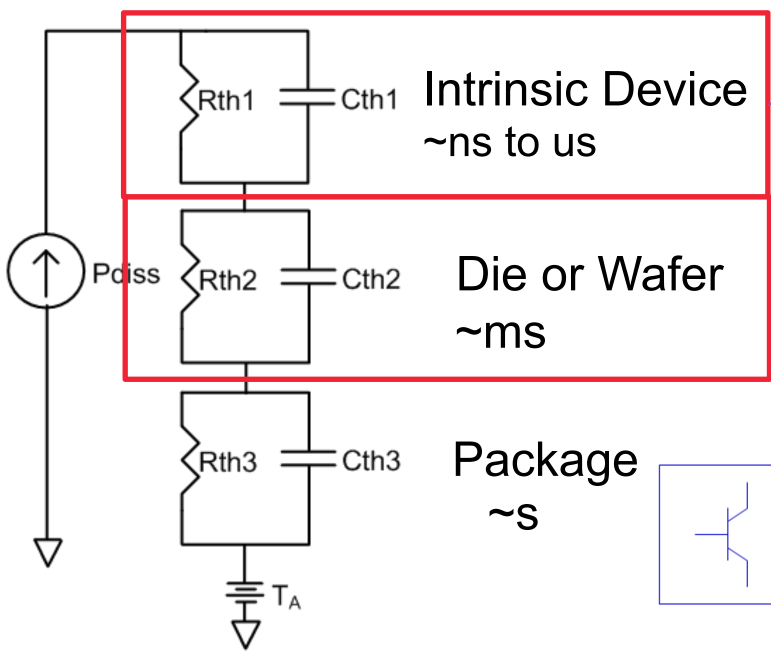
Resulting Thermal Response in Ic
(Current drop shown here is due to dev. cooling)

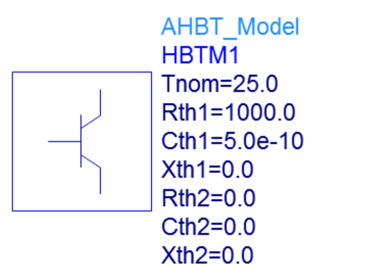


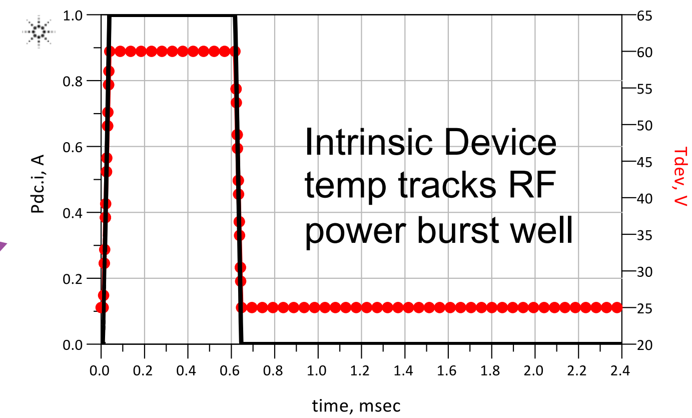
(Log Scale for time)

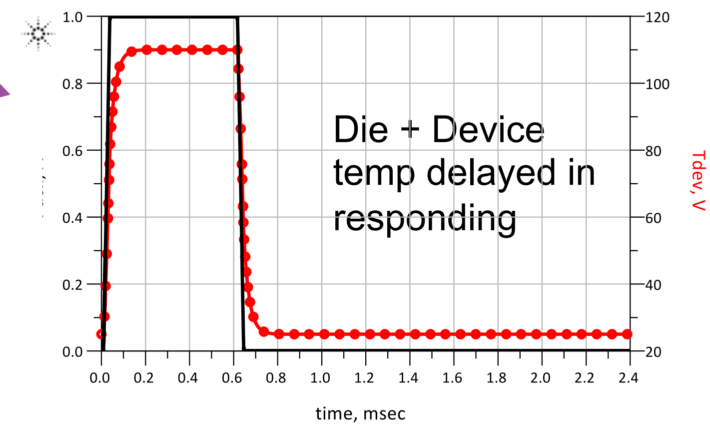
Lumped Modeling Approach

Thermal Network is modeled as a RC Network(s) for fast pulses $\tau_{th} = R_{th} C_{th}$

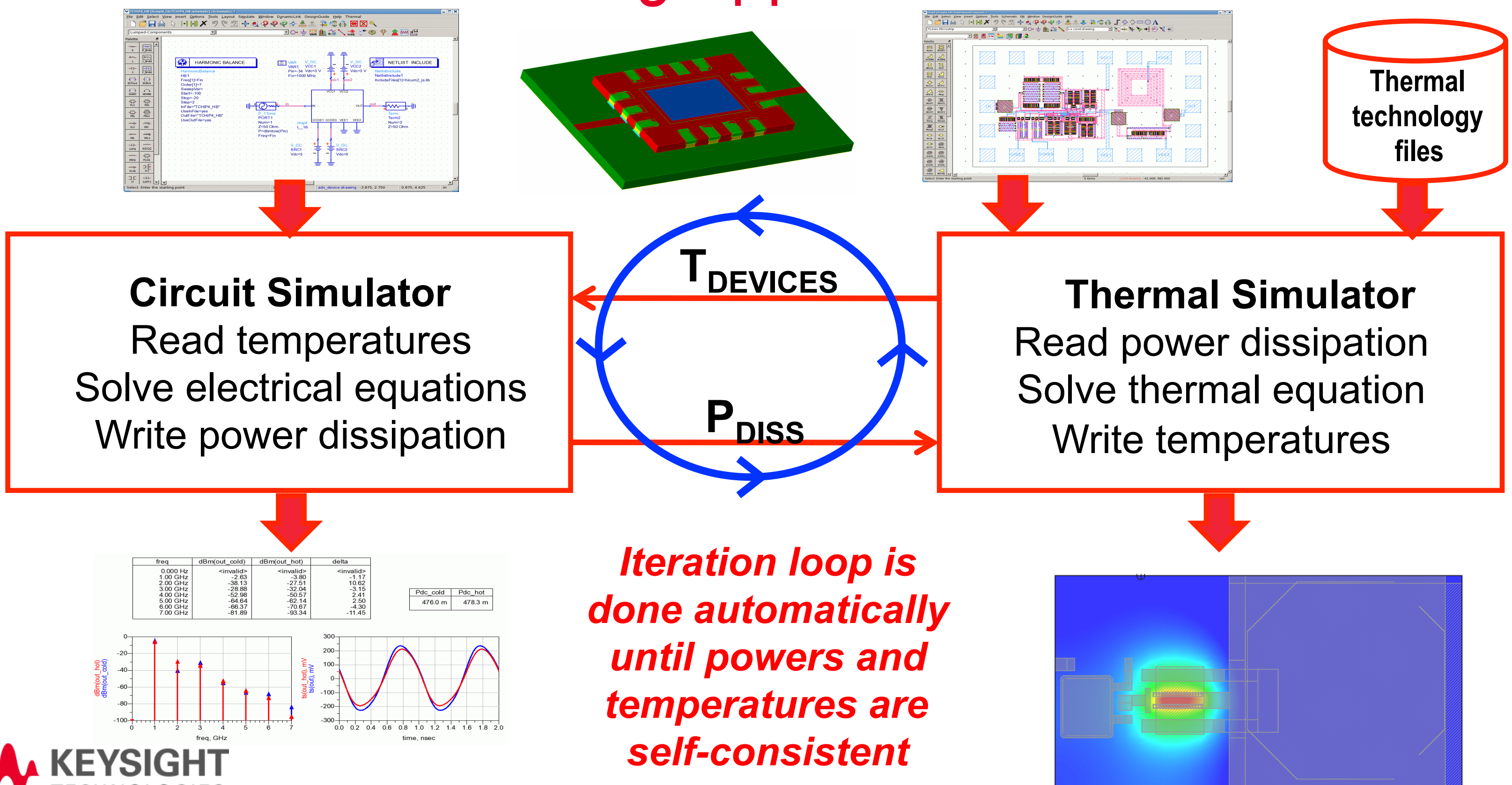








Electro-thermal Modeling Approach



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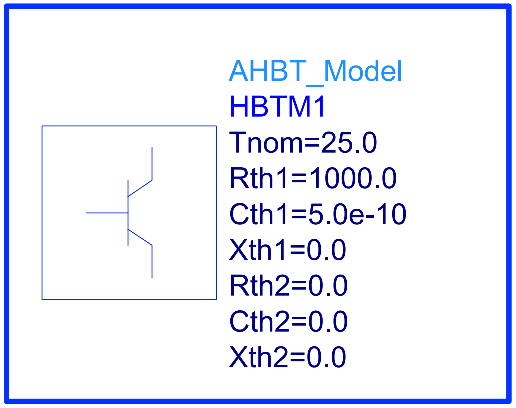
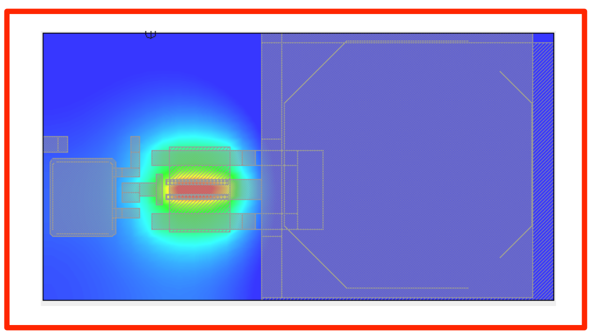
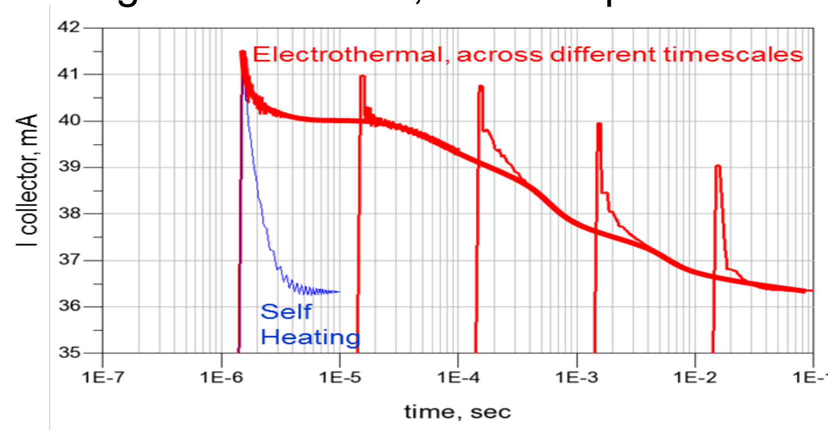
Lumped Thermal RC vs. Full 3D Electro-thermal

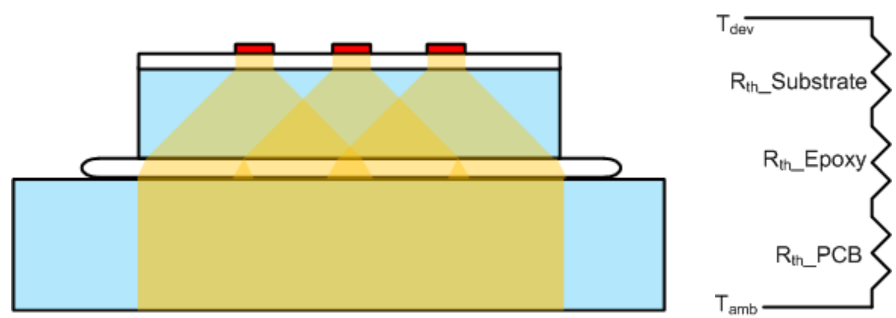


vs



Single HBT Device, Beta Drop due to heating





Review of Heating in Active Devices: ✔

Self Heating
Mutual Heating
Transient Heating

Areas where heating is impactful to PA Design:

- Long Term Failure
- Thermal Stability / Balance
- Device and Circuit Performance
- Memory Effects

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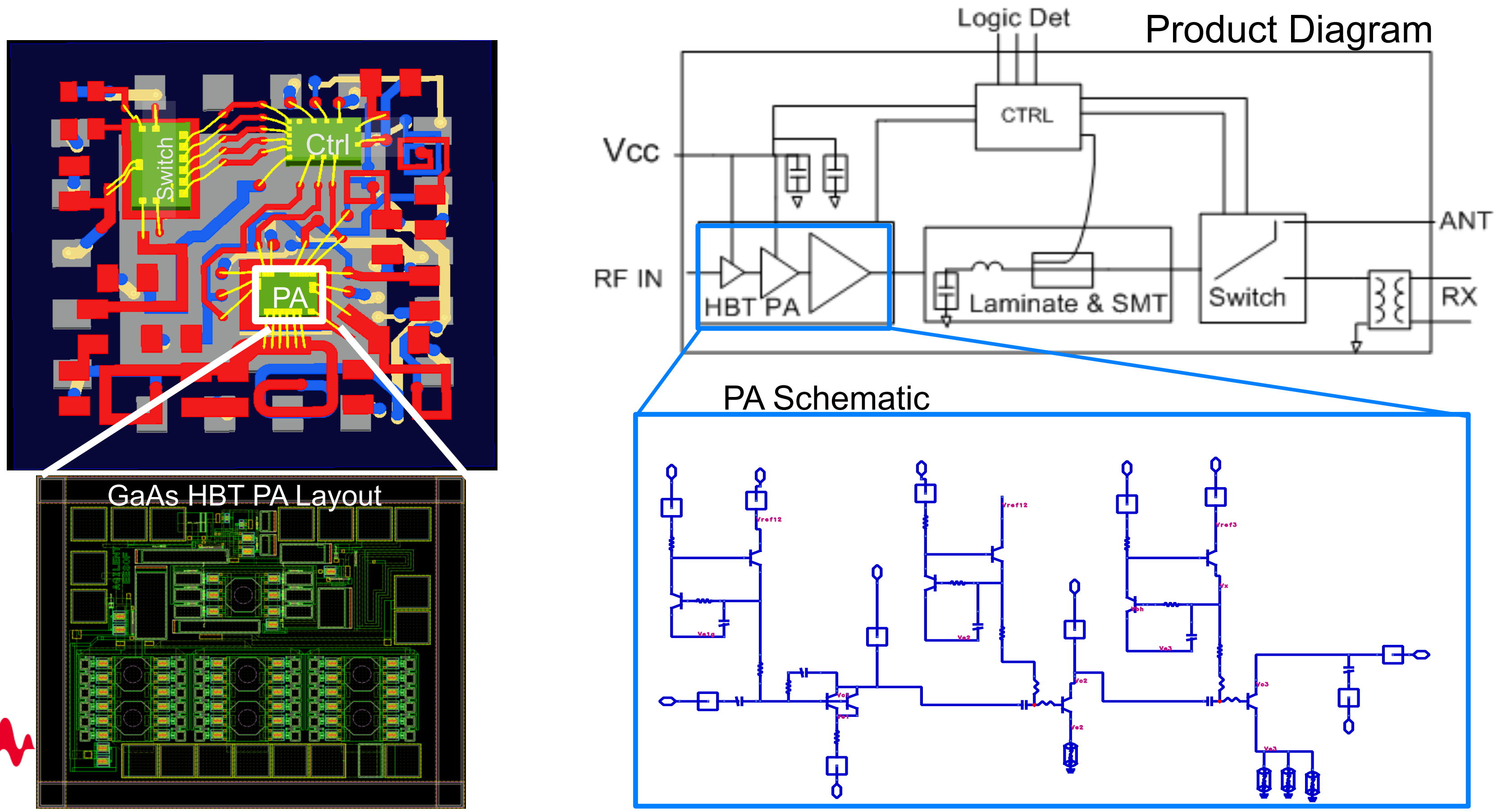
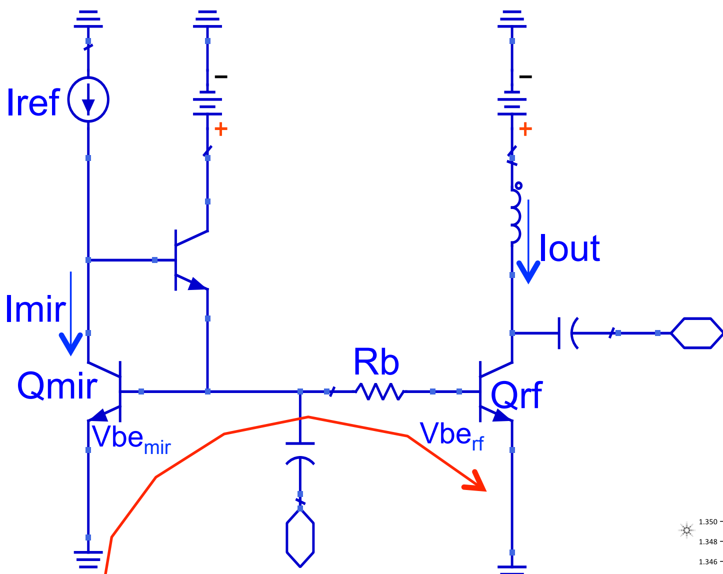
Context: Commercial WLAN PA (HBT)



PA Bias Topology



$$Vbe_{mir} = V_{Rb} + Vbe_{rf}$$

Hold RF Device Temp Constant, vary Tmirror:

$$\frac{dI_{OUT}}{dT_{MIR}} = \frac{dVbe_{MIR}}{dT_{MIR}} * \frac{dI_{OUT}}{dVbe_{MIR}}$$

$$\frac{dI_{OUT}}{dVbe_{MIR}} = \frac{Is}{V_{T(rf)}} e^{\frac{Vbe_{mir}}{V_{T(rf)}} - \frac{Rb}{r_{\pi(rf)}}}$$

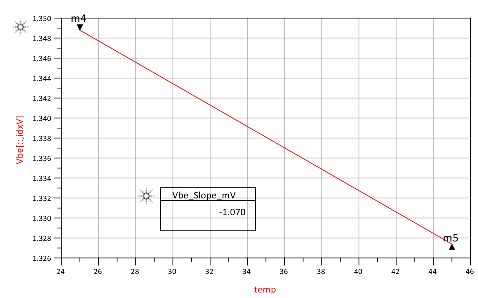
$$\frac{dVbe_{MIR}}{dT_{MIR}} \approx -1.1mV/^{\circ}C$$

If T_{MIR} ↑, Vbe_{MIR} ↓

If Vbe_{MIR} ↓, I_{OUT} ↓

If Qmir is cooler than Qrf, the bias current Iout will increase, which can increase the RF gain

Vbe vs. Temperature

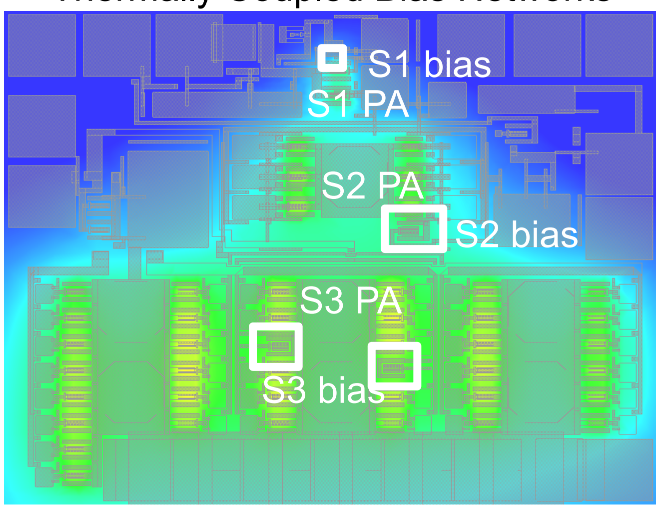


Well known characteristic of PN junction diodes: Diode voltage is CTAT

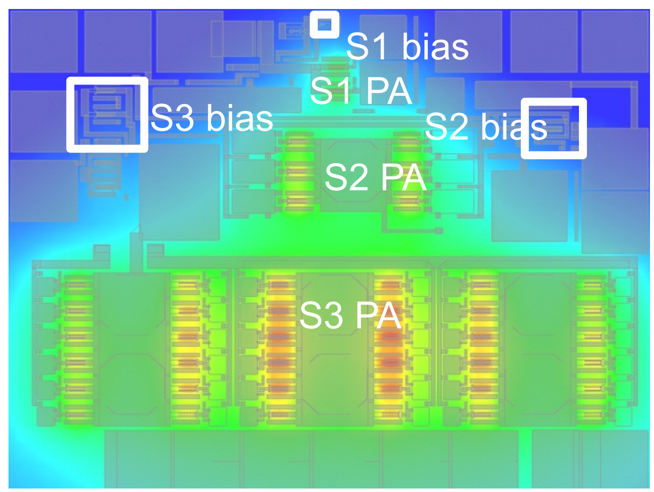
Test Case: Two Different IC Layouts, Identical Schematic

- Here we have two schematically identical WLAN PA layouts to demonstrate the differences between modeling approaches. The three conditions are:
  - Isolated Self Heating Simulation (Static Thermal Network, Internal to AHBT Model)
  - Full Electro-thermal Simulation with moderately thermal-coupled bias networks
  - Full Electro-thermal Simulation with a poorly thermal-coupled bias network

Thermally Coupled Bias Networks

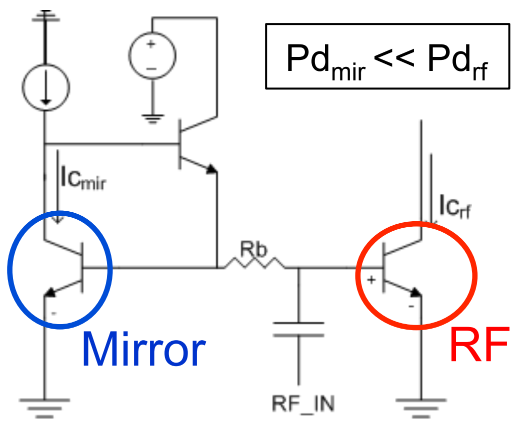


Thermally Decoupled Bias Networks



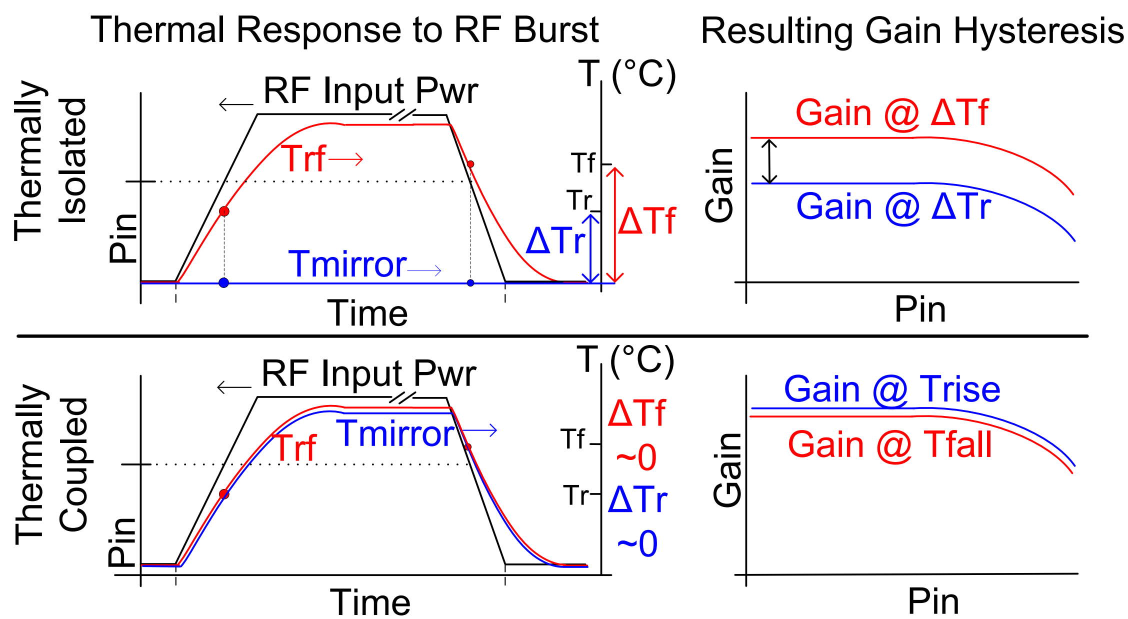
Temperature Coupling and Memory Effects

Bias Configuration



Tmir < Trf, Ibias ↑, Gain ↑

…Apply a low frequency RF power pulse

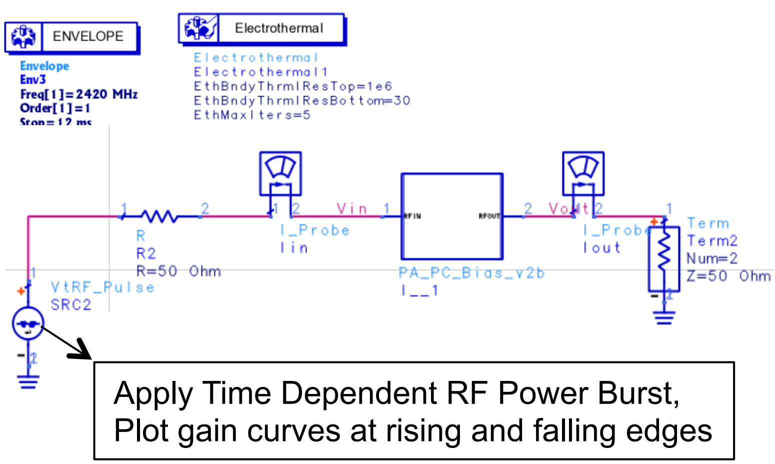


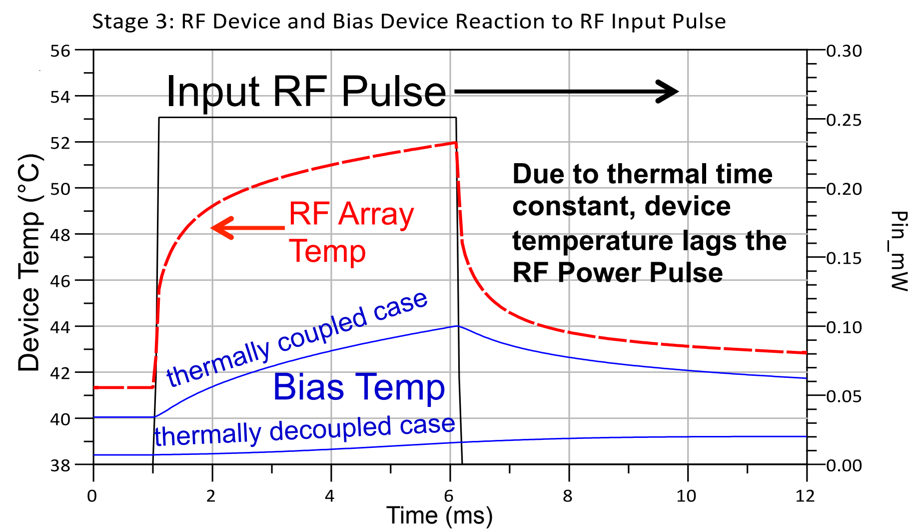
Simulation Results

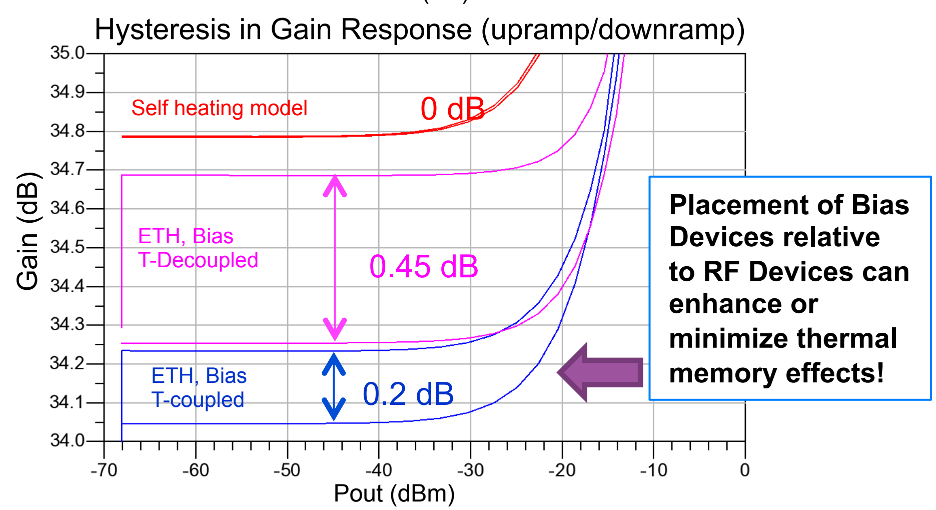
Transient Simulation with mutual heating between RF and bias device for different layout configurations

These plots compare:

- Isolated Self Heating Model
- Mutual Heating Model, thermally decoupled
- Mutual Heating Model, thermally coupled







Closing

– Modeling distributed heating is critical in RF Power Amplifier Design, especially for low frequency phenomena such as memory effects or device-to-device interaction

– Memory effects at low frequencies might be due to:

  • Cross-circuit, layout-dependent mutual heating

  • Distributed heating on longer time scales

– This is a case where full Electro-thermal analysis is useful in the design process because it predicts problems that the intrinsic thermal RC network inside the device model does not

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Thanks!

Feel free to contact me with any additional questions:

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