THERMAL RUNAWAY AND ITS IMPLICATIONS ON HBT CIRCUIT RELIABILITY

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Outline

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- Determining ballast resistance
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Don’t mess with Microwave man, it is GHz!!
Why ballasting is good for thermal stability?

Ballasting helps:
1. Mitigate current collapse at high $V_{ce}$
2. Lowers the drop in $V_{be}$ and consequent decrease in current density.
3. Reduces self heating.

Ref. William Liu, The use of base ballasting to prevent the collapse of current gain in AlGaAs/GaAs HBT, IEEE EDL, 43, 2, 1996.
Determining ballast resistance

\[ I_{critical} = \frac{n k T}{q} \frac{1}{(\phi \cdot R_{th} \cdot V_{ce} - R_e)} \]

Emitter ballast resistance

\[ R^{opt}_e = R_{th} \cdot \phi \cdot B V_{ceo} (1 - L) \]

Base ballast resistance

\[ R^{opt}_b = \beta \cdot R_{th} \cdot \phi \cdot B V_{ceo} (1 - L) \]

The required amount of base ballasting depends on DC current gain, current gain vs. temperature, emitter resistance and base resistance.
RF Biased Life Test

The test device was a power amplifier circuit which contained specific attributes to assess the impact of resistor ballasting.

Stress conditions:

- Frequency (MHz) 787.5
- Output Power (dBm) 26
- Duty Cycle (%) 100
- Temperature (C) 125

Sample Size: 3 randomly selected lots each with 77 samples

Readout points: 500 hrs and 1000 hrs.

Block diagram of RFHTOL station set-up
RF Biased Life Test

- Mean value RF output power shifted by 0.23 dB after first 500 hrs. and 0.33 dB at the end of 1000 hrs.
- The DUTs with lower Pout also appears to have lower Icc. Some DUTs deviated from linearity.
- The std. deviation of the population increased from 0.17 to 0.71 at the end of 1000 hrs.
RF Biased Life Test

Median leakage current over the Vcc pin increases as much as 88 mA (500 hrs) and 98 mA (1000 hrs) due to stress.

CDF plot showing distribution of collector currents in drawn by the amplifier.
Failure analysis

1. DUTs with lower Pout during the test exhibited low $\beta$ ($\sim 2$) in the first stage.
2. Some DUTs also had 10-15% degradation of $\beta$ in the final stage.
3. Thermal scans showed non-uniform heating in HBT array for low $\beta$ DUTs.
Simulation (dual ballast)

Schematic of first stage.

DC simulation: Sweeping $V_{cc}$

At 85°C, the thermal instability occurs at 7.4 V, junction temperature increase by 4x (100 to 400°C). For 144°C, instability point moves to 3 V.

Power dissipation vs. Current density.

As the power dissipation increased above 0.1 W, the current density in Q2 and Q3 cells increased to 30 kA/cm² while in Q1 and Q4 dropped by 0.004 kA/cm².

Thermal resistance values $a_{12}$, $a_{13}$ and $a_{14}$ were found to be 90 Ω, 45 Ω and 22.5 Ω.
Simulation (individual ballast)

Schematic of first stage.

DC simulation: Sweeping $V_{cc}$

Junction temperature

Individually ballasted transistor cells are thermally stable. More uniform increase in $T_j$ among HBT cells.

Base resistor of 300 ohms insufficient for $V_{cc} > 3V$
Electro-thermal results

To understand the thermal interactions between the two stages at instability bias point electro thermal simulation was performed.

Thermal runaway occurs in Q3 HBT cell in first stage and its temperature rises to 180°C.

Temperature over the second stage is 15°C above the ambient.

Strong thermal coupling between the first stage and second stage is observed.
Experimental validation.

DC ramp of $I_{cc}$ vs. $V_{ce}$ revealed thermal run-away phenomena occurring at 7.4 V and shared ballast showed gradual increase in current in several parts.
Conclusion

1. Individual ballast is thermally more stable in than shared ballast biasing configuration.
2. RHTOL test on shared ballast HBT array showed degradation in Pout and current over Vcc pin under RF conditions. The DUTs with lower Pout also had lower Icc. Data also showed drop in Icq and leakage currents due to stress (no RF).
3. Failure analysis revealed beta degradation in both first and second stages having shared ballast. Thermal scans attributed non-uniform heating in HBT array for low $\beta$ DUTs.
4. Electro-thermal simulation showed thermal coupling between the first stage and second stage under thermal instability conditions.
5. Type of HBT ballasting and its level are both important for reliability and circuit performance.
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