Characterization and modeling of thermal impedance for advanced SiGe HBT

Xiaodi Jin[1,2], Guangsheng Liang[1], and Michael Schröter[1]

[1] Chair for Electron Devices and Integrated Circuits, TU Dresden, 01062 Dresden, Germany

[2] SemiMod U.G., 01159 Dresden, Germany

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Outline

Introduction

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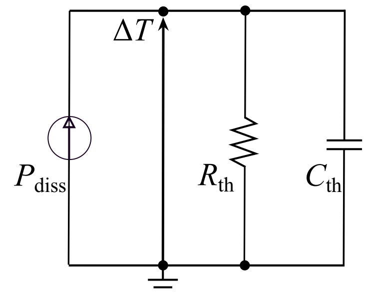
- Mainstream HBT/BJT compact models utilize single-pole thermal network
  - good accuracy at high frequency above 1 GHz;
  - computation efficient due to two elements.



single-pole network

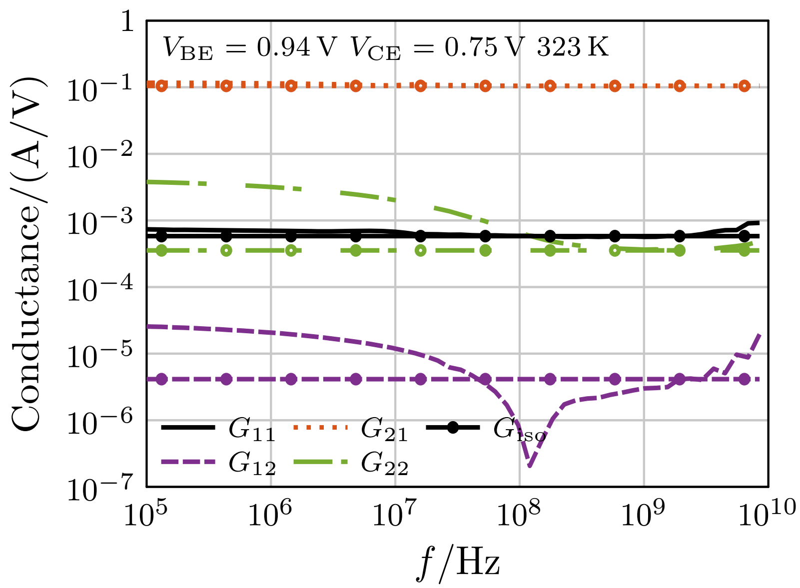
- Measurement, characterization, and multi-pole thermal network modeling have been done for many BiCMOS technologies (DTI/STI) but SG13G2

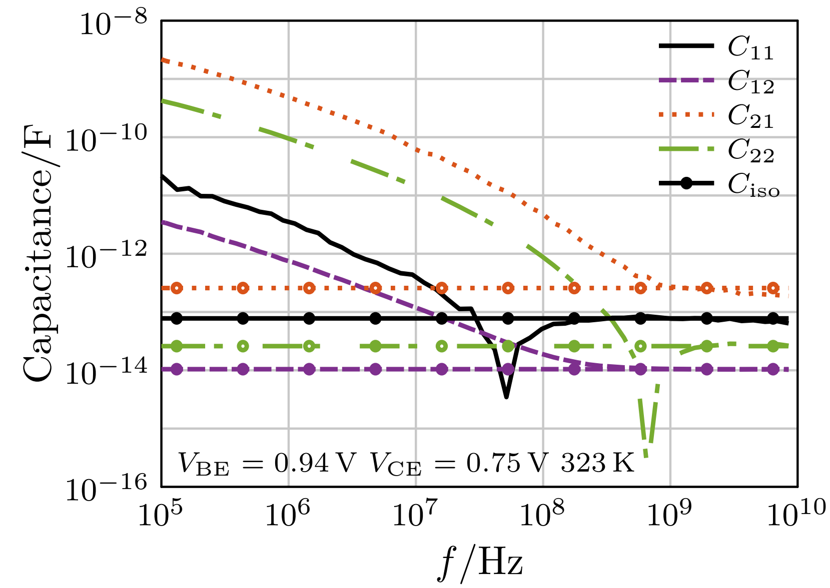
=>here focus on SG13G2 (only has STI)

- Modeling purpose:
  - intermediate frequency circuits below 1 GHz with large power consumption => AC SH is relevant.
- Investigation on the extraction method for SG13G2

Conductance and capacitance parameter

real(Y) imag(Y/(2*π*f))





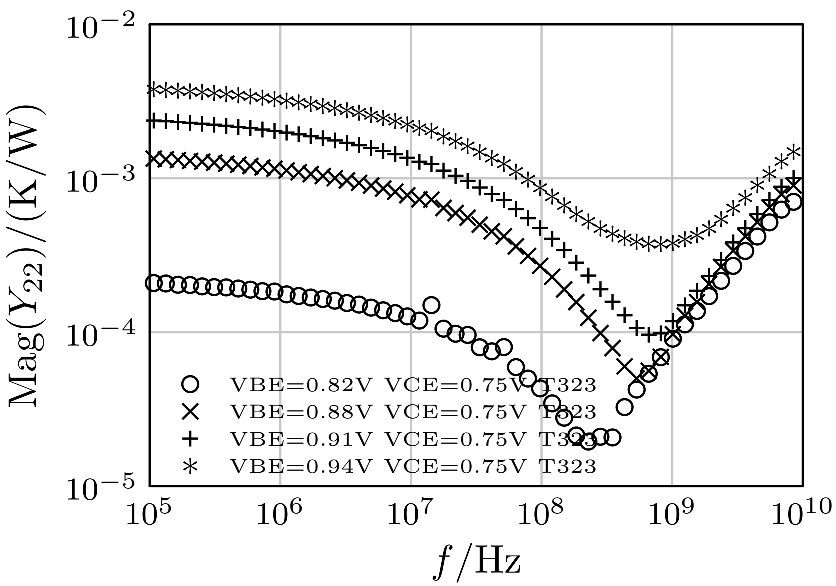
- *G*(G22 and G12) parameters (real(*Y*)) and *C* parameters (imag(*Y*/(2πfreq))) decreases with frequency;
- SH
  - Below 1 GHz: AC+DC SH readout circuit for quantum computing;
  - above 1 GHz: only DC SH -- most SiGe HBT based circuits;
- Y22 and Y12 are more sensitive to SH, and used as reference to characterize thermal impedance and verify thermal network
  - All *C* parameters change a lot with frequency;
  - G11 and G21 changes slightly with frequency, whereas G22 and G12 change a lot with frequency;

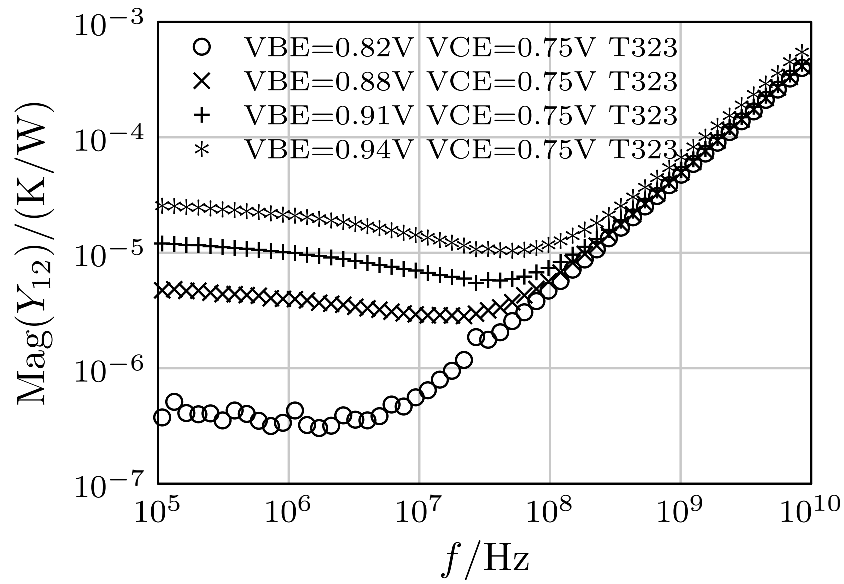
Measurement and Characterization

Measurement setup

- Technology: SG13G2
- Device: b_{E0} = 0.12 μm, l_{E0} = 0.95 μm in CEB configuration, Nx=4
- DC: HP 4142B Modular DC Source/Monitor
- S-Parameters: Rohde&Schwarz ZNB8 for 9 KHz-8.5 GHz
- Probe: FormFactor C1N |Z| probes from DC-67 GHz
- Probe station: Süss MicroTec PA 200
- Measurement script: pylab (Christoph Weimer)

Magnitude of Y22 and Y12





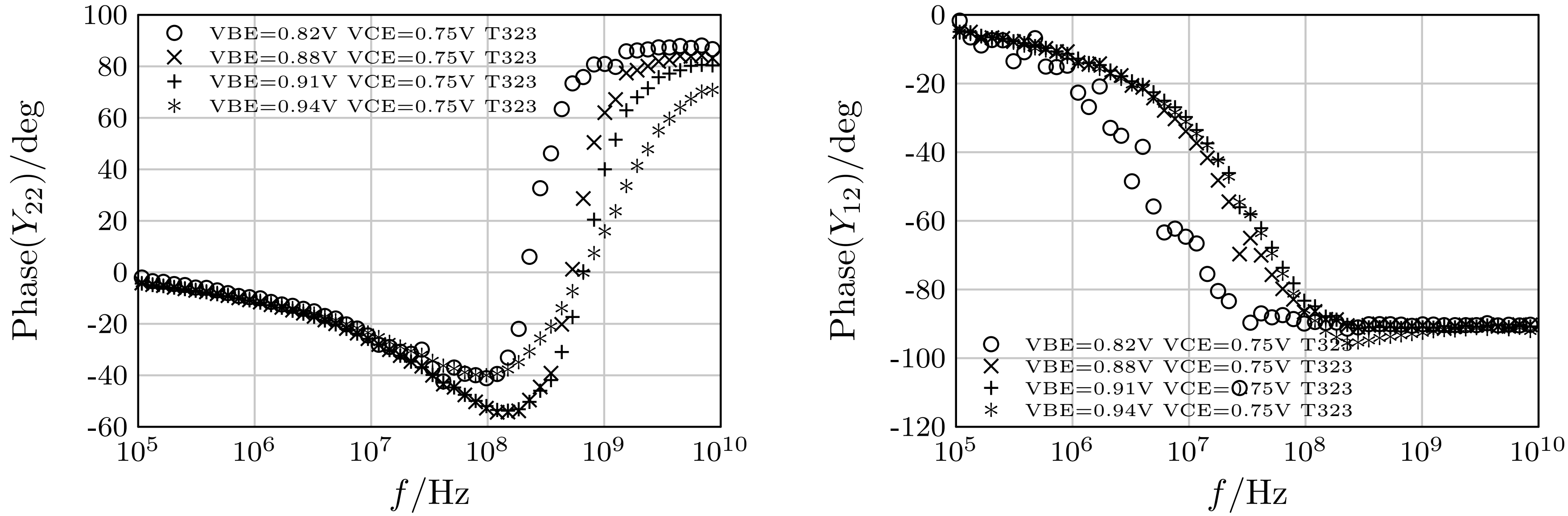
- Y22 and Y12 are more sensitive to SH;
- Increased mag(Y22) and mag(Y12) with V_{BE} due to bias dependence of diode and transfer current;
- Slight reduction of magnitude with frequency at lower frequency range;
- Magnitude decreases smooth with frequency

  => may indicate a relatively uniform distribution of thermal conductivity

  => the STI does not located in the heat path.

  - nonuniform => may have the kink in the curve.

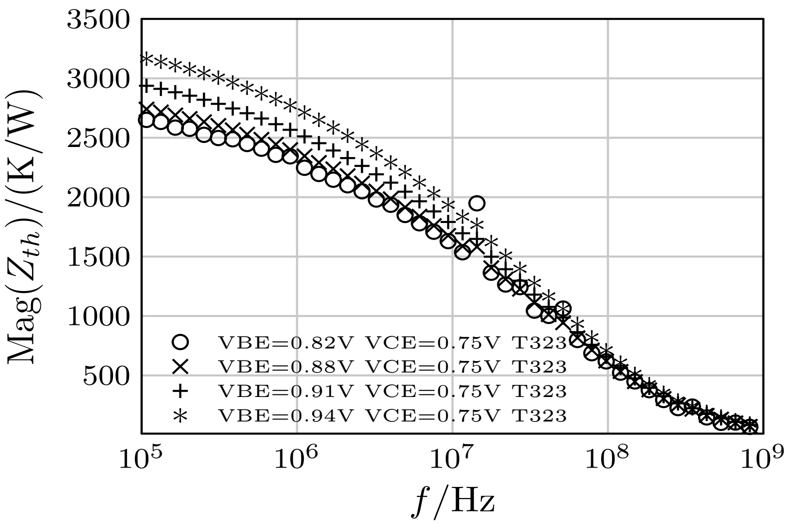
Phase of Y22 and Y12



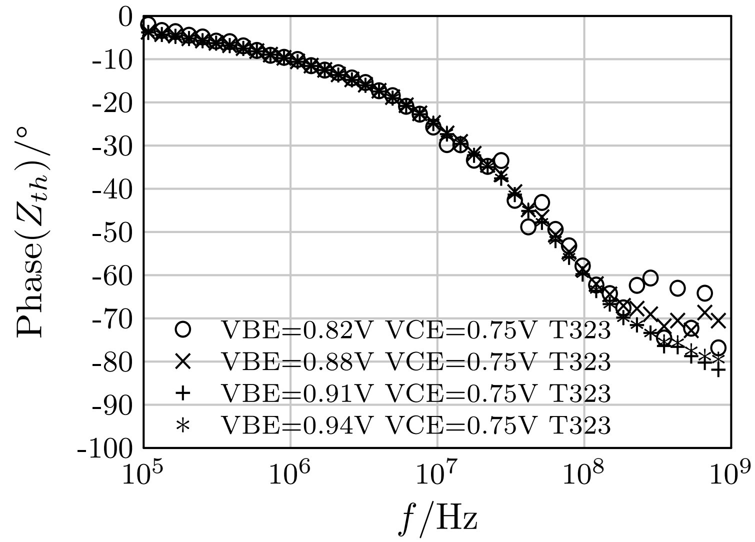
- Decrease of phase (from 0) starts slightly below 0.1 MHz => AC SH starts to disappear;
- Sign change of phase(Y22) between 100 MHz and 1 GHz due to the sign change of imag(Y22);
- Constant values of phase(Y22)(=90°) and phase(Y12)(=-90°) at high frequency indicate that imaginary part is much larger than real part with increased frequency for Y22 and Y12.

Thermal impedance

magnitude



phase



- Mag(Z_{th}) and Phase(Z_{th}) decrease with frequency from 0.1 MHz to around 1 GHz:
  - AC SH disappears with increased frequency;
  - Maximal phase reached is around 80°.
- Mag(Z_{th}) increases with V_{BE} for same V_{CE} due to the increase of I_C causing high $T_{junction}$.
- Monotonous reduction of Z_{th} without kink may demonstrate the uniform heat diffusion.

Extraction method

Z_{th} extraction method

- y parameter method:

$$Z_{th} = \frac{y_{22} - y_{22T}}{c_m(I_C + V_{CE}y_{22} + V_{BE}y_{12})(1+b)}$$

- y_{22T} is the isothermal y_{22}, i.e., where AC SH disappears;
- c_m is given by

$$c_m = \frac{\partial I_C}{\partial T},$$

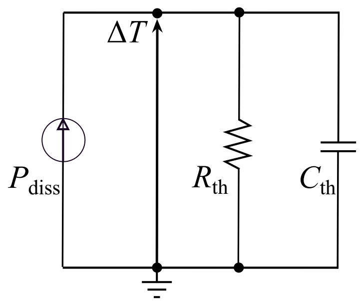
- b is given by

$$b = \left.\frac{P}{Z_{th}}\frac{\partial Z_{th}}{\partial P}\right|_T$$

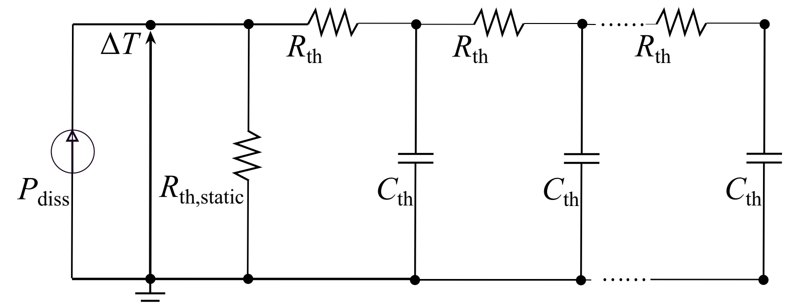
but for the simplification b is typically assumed to be zero in the literature.

Different thermal networks versus the measurements

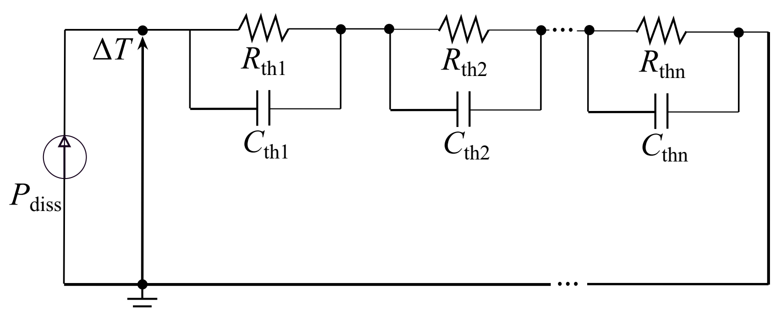
Thermal networks



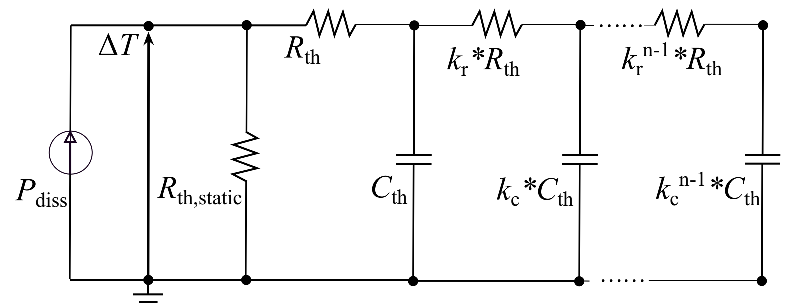
single-pole network



Nodal



Foster

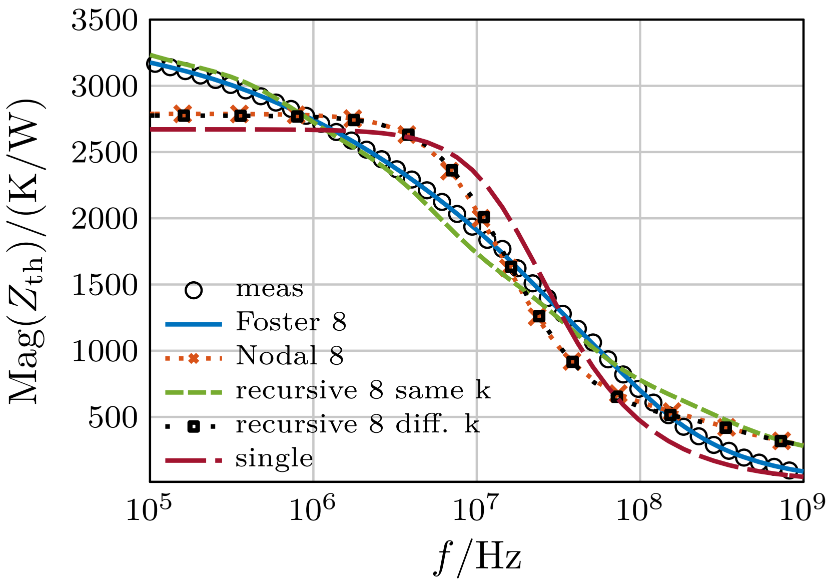


recursive

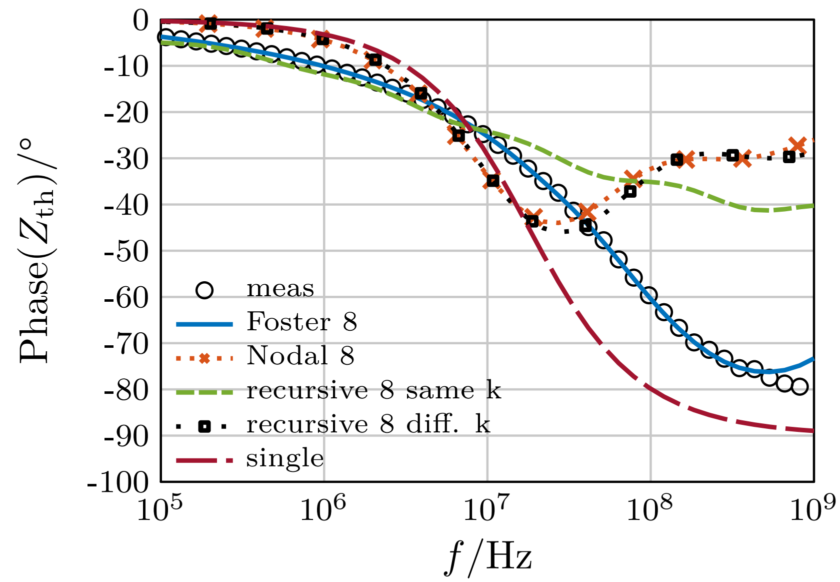
- single pole: 2 parameters;
- Foster: 2*n parameters;
- Nodal: 3 parameters -> simplified form of recursive model;
- recursive: 4 parameters for $k_r = k_c$, 5 parameters for $k_r < 1$, $k_c > 1$.

Model vs. measurement

magnitude



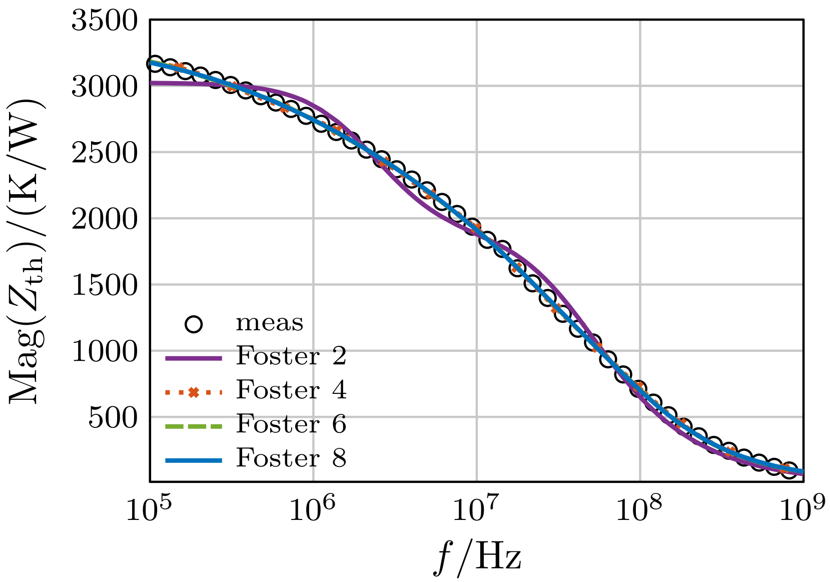
phase



- V_{BE}=0.94 V, V_{CE}=0.75 V, T=323 K;
- Magnitude: Foster and recursive model (same *k*) show a good agreement;
- Phase: Foster has the best agreement, single pole agrees reasonable, others cannot reach phase angle below -45°
  - EC form of nodal and recursive model do not allow a smaller degree than -45°;
- In previous publications, recursive model was preferable as it had the most accuracy with only 4 or 5 parameters, much less than foster model;
- Foster agrees best with measurements.

Foster model with different poles

magnitude



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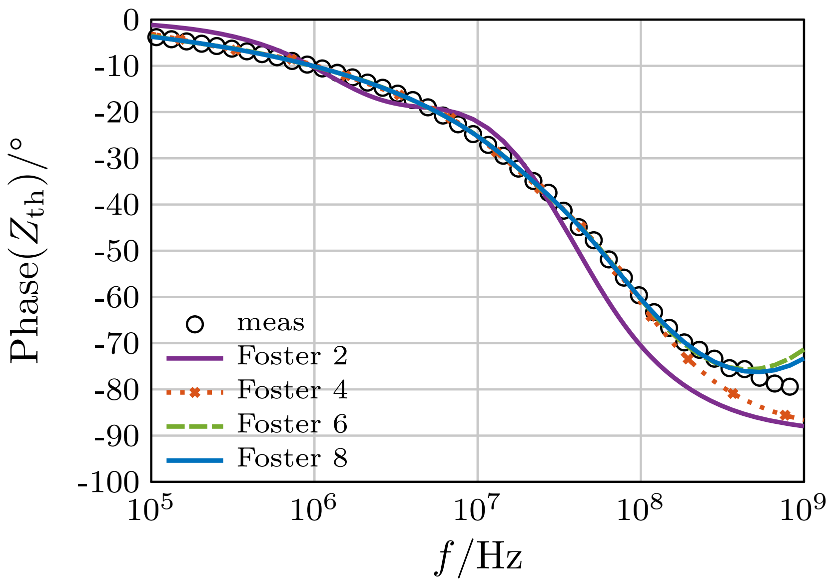
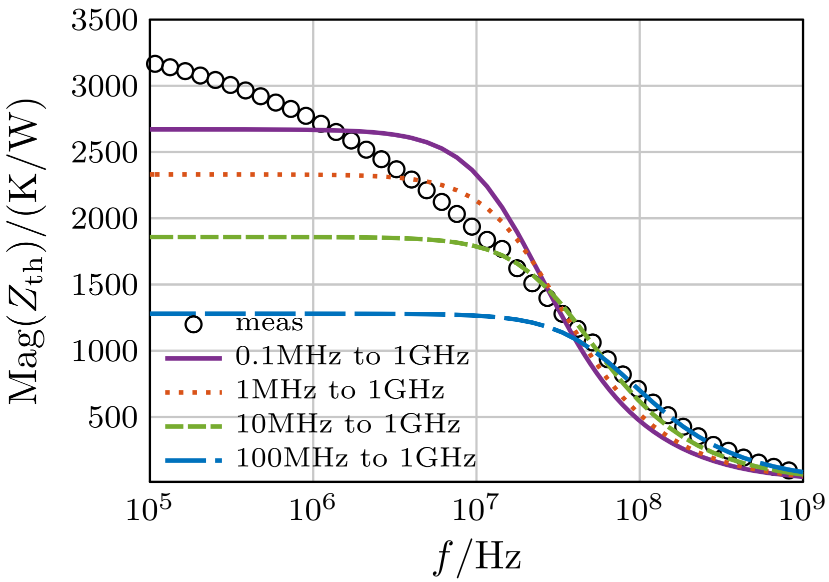


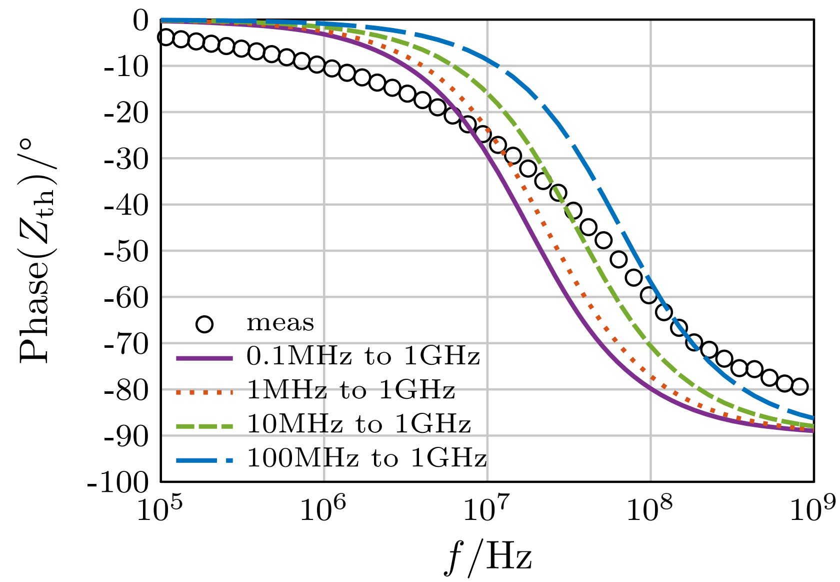
- V_{BE}=0.94 V, V_{CE}=0.75 V, T=323 K
- Foster model with different poles all show reasonable agreement with measured results;
- Model with least number of poles (2-pole Foster network) has wiggles, but is still reasonable;
- Model with 4 poles already shows very good agreement.

Single-pole model

magnitude



phase

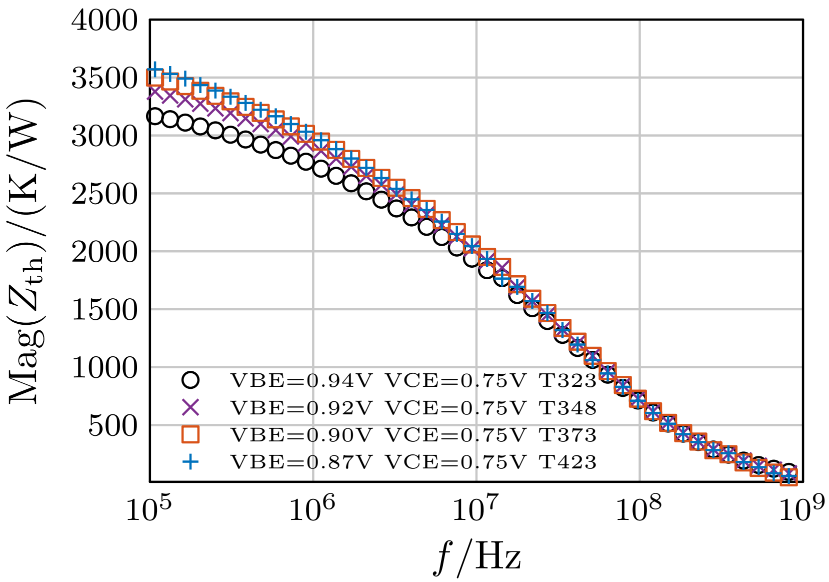


- Optimize single-pole model over different frequency ranges
  - 0.1 MHz to 1 GHz
  - 1 MHz to 1 GHz
  - 10 MHz to 1 GHz
  - 100 MHz to 1 GHz
- Magnitude can be optimized down to 10 MHz, phase can only be optimized down to 100 MHz.
- For frequency lower than 100 MHz, single-pole network is not accurate anymore.

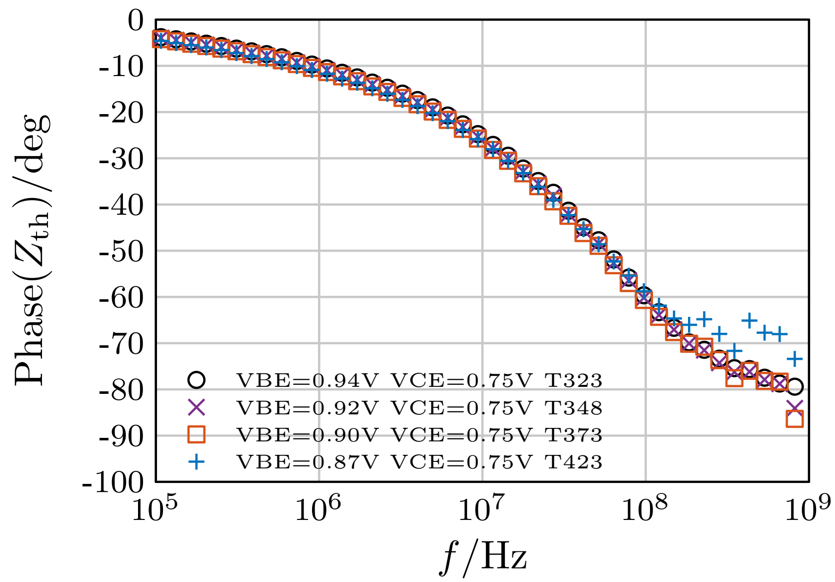
Characterization of *T* dependence of thermal impedance

T dependence of Z_{th}

magnitude



phase



- The I_C is around 12 mA for all *T*;
- Mag(Z_{th}) increases with *T*;
- Phase(Z_{th}) does not change with *T*.

$$R_{thi} = \int_{z_{lower}}^{z_{upper}} \frac{1}{\kappa_i A_i(z)} dz \quad \text{and} \quad C_{thi} = \int_{z_{lower}}^{z_{upper}} \frac{\kappa_i}{\alpha} A_i(z) dz$$

- ratio of imaginary and real part are *T* independent;
- inaccurate modeling using Nodal and recursive network;
- consistent T trend for single-pole and Foster network.

Summary

Conclusion

- The accurate thermal impedance modeling is required for circuits at low frequency range requiring large power;
- Uniform frequency dependence of thermal impedance and Y parameters may indicate the uniform distribution of thermal conductivity for SG13G2;
- The Y-parameter method is used to extract the Z_{th};
- Four thermal networks are compared with the measurement, and the favorably used recursive network in the previous work cannot model the thermal impedance for SG13G2 due to its minimal phase of -45°;
- The Foster network shows the best agreement, the 2-pole Foster agrees with measured value reasonably over 0.1 MHz to 1GHz with 4 parameters;
- Single-pole network can be used above 100 MHz with great accuracy;
- The magnitude of Z_{th} shows a T dependence, and phase of Z_{th} is T independent, which confirms the Foster rather than recursive network as an preferable thermal network G2.

Outlook

- T dependence of C_{th} needs to be determined in single-pole thermal network;
- Determination of T dependence of the elements in multiple-pole thermal network;
- The comparison of Y-parameters between model simulation using va code and measurements needs to be done;
- CPU time between single-pole and multi-pole network need to be compared;
- Measurement, characterization and modeling of thermal impedance at cryogenic T.

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Thanks for your attention!

Any further question and discuss are welcome:
xiaodi.jin@tu-dresden.de