SAND2018-8401PE

# Characterization and modeling of 2-port wideband resistance standards

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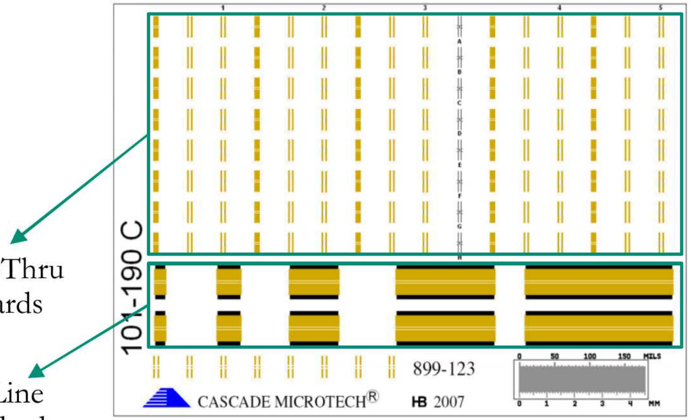
Presented by: Sarah Stevenson

# Motivation

Current method involves multiple standards

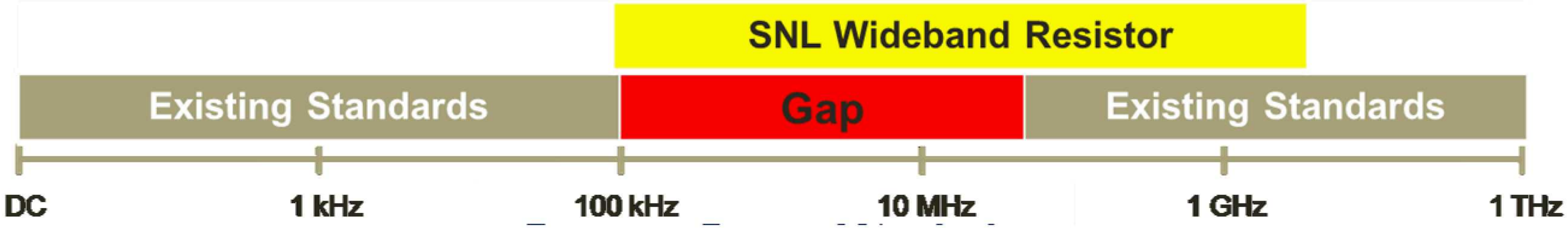
Proposed single resistance standard



Short-Open-Load-Thru calibration standards

Thru-Reflect-Line calibration standards

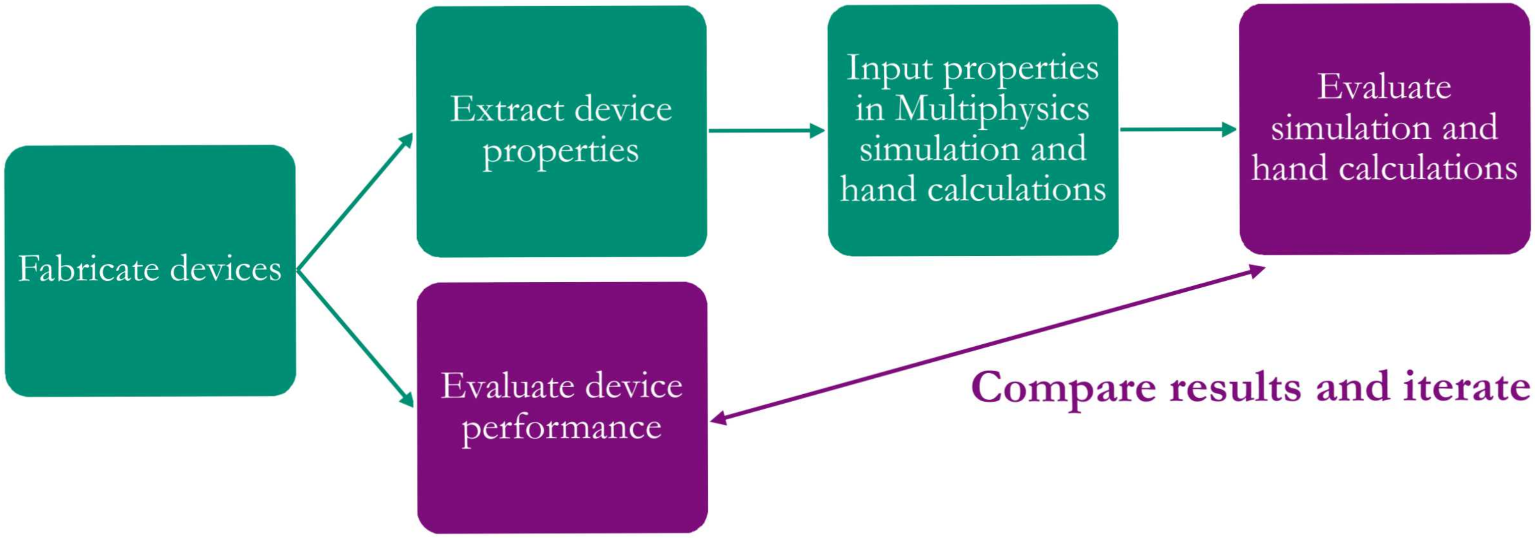
**Example of a current impedance standard chip**



**Frequency range of standards**

http://anlage.umd.edu/Microwave%20Measurements%20for%20Personal%20Web%20Site/a_guide_to_successful_on_wafer_rf_characterisation.pdf

# Research objective and methods



Fabricate devices

Extract device properties

Input properties in Multiphysics simulation and hand calculations

Evaluate simulation and hand calculations

Evaluate device performance

**Compare results and iterate**

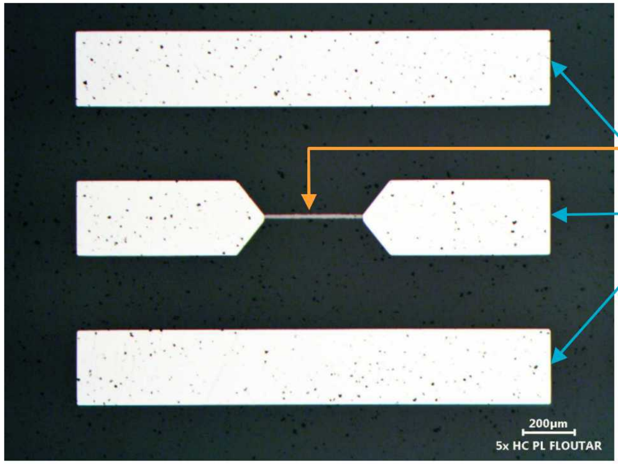
**Research methods model**

# Device fabrication

- 2-mask photolithography performed at the Center for Integrated Nanotechnologies
- 20 different resistor geometries considered

**(Below) Description of sample geometries**

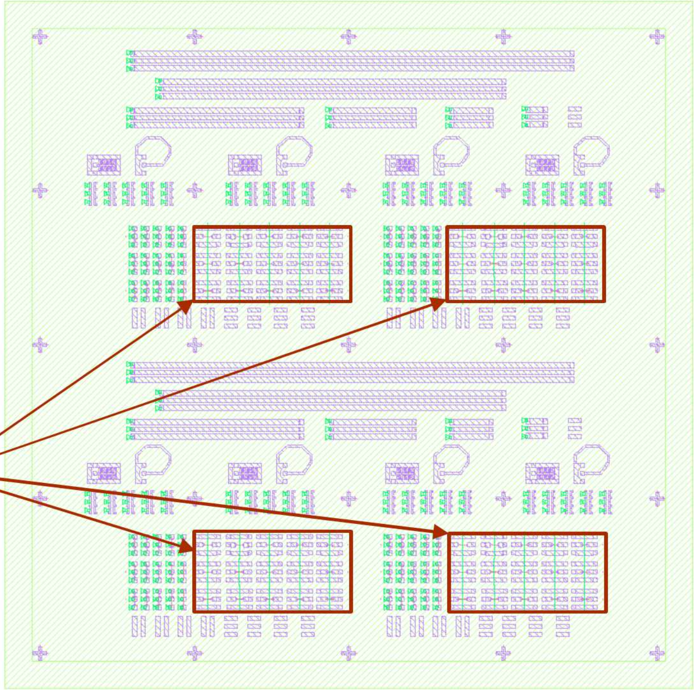
| Sample iteration | Layer 1 – resistive element | Layer 2 – contact pads/lines | Resistor L x W (μm$^2$) | | |
|---|---|---|---|---|---|
| 1st | 1 nm Ti + 9 nm Au | 10 nm Ti + 190 nm Au | 2 x 40 | 4 x 40 | 6 x 40 |
| | | | 2 x 60 | 4 x 60 | 6 x 60 |
| | | | 2 x 80 | 4 x 80 | 6 x 80 |
| | | | 2 x 100 | 4 x 100 | 6 x 100 |
| | | | 2 x 120 | 4 x 120 | 6 x 120 |
| 2nd | 2 nm Ti + 20 nm Au | 15 nm Ti + 200 nm Au | | | 6 x 40 |
| | | | | | 6 x 60 |
| | | | | | 6 x 80 |
| | | | | | 6 x 100 |
| | | | | | 6 x 120 |



Resistive element

Contact pads/lines

**(Above) Optical image of 2-port resistor sample**



4 sets of 15 2-port resistors

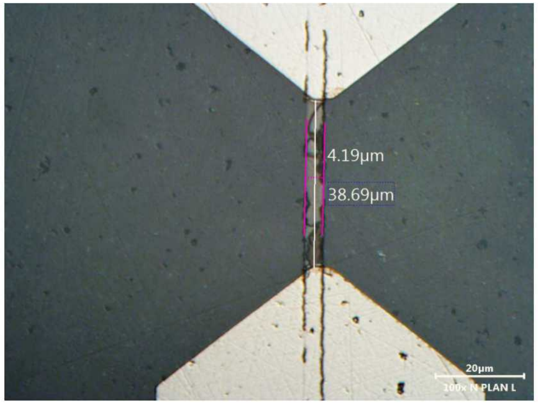
**(Above) Layout of photolithography mask**

# Device property evaluation

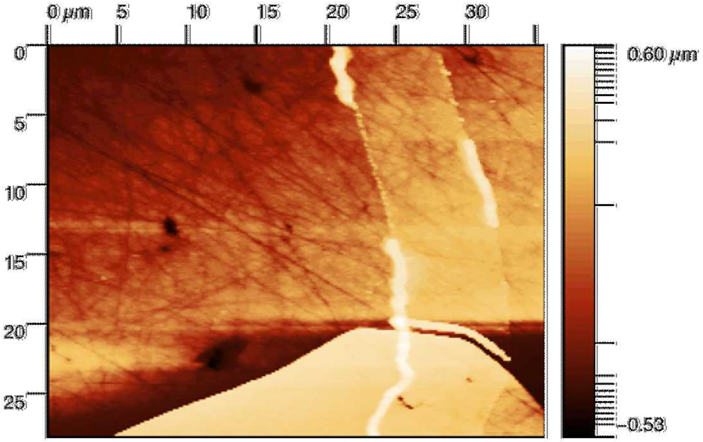
- The size of an object is well-known to have an effect on its resistivity*
- Measurements were produced to calculate the thin-film resistivity ($\rho$)
  1. Optical microscopy – resistor length (L) and width (W)
  2. Atomic force microscopy – resistor thickness (t)
  3. 4-point probe DC measurements – resistance (R)

$$\rho = \frac{W * t * R}{L}$$

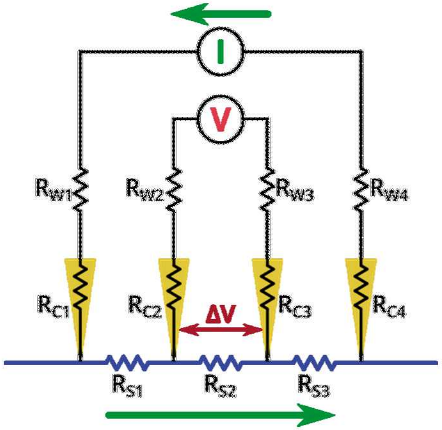
**Thin-film resistivity equation**



**Optical microscope image of resistive element**



**Atomic Force Microscope capture of resistive element**



**Equivalent circuit of a four-point probe measurement**

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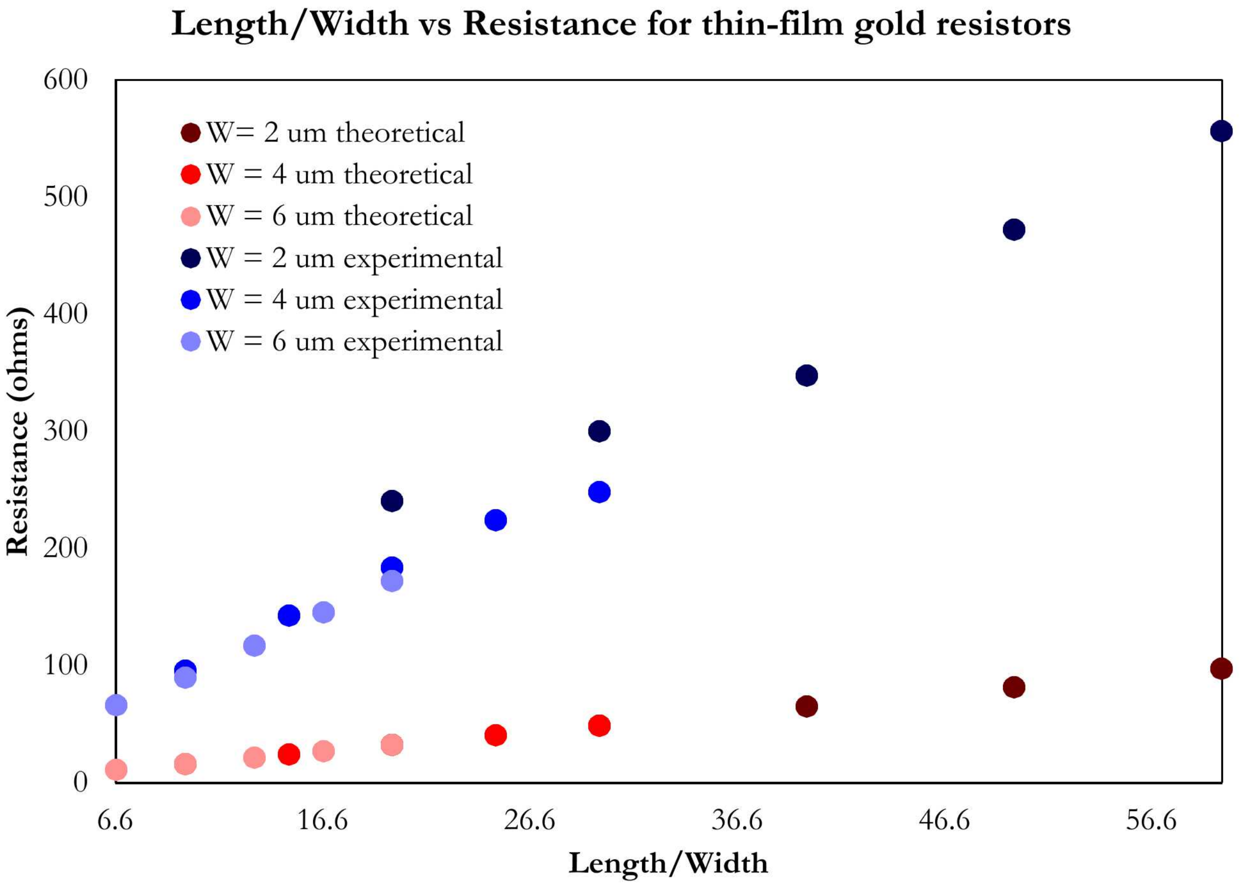
*Lacy, F. (2011). Developing a theoretical relationship between electrical resistivity, temperature, and film thickness for conductors. Nanoscale Research Letters, 6(1)

# Device property evaluation: thin-film resistivity results

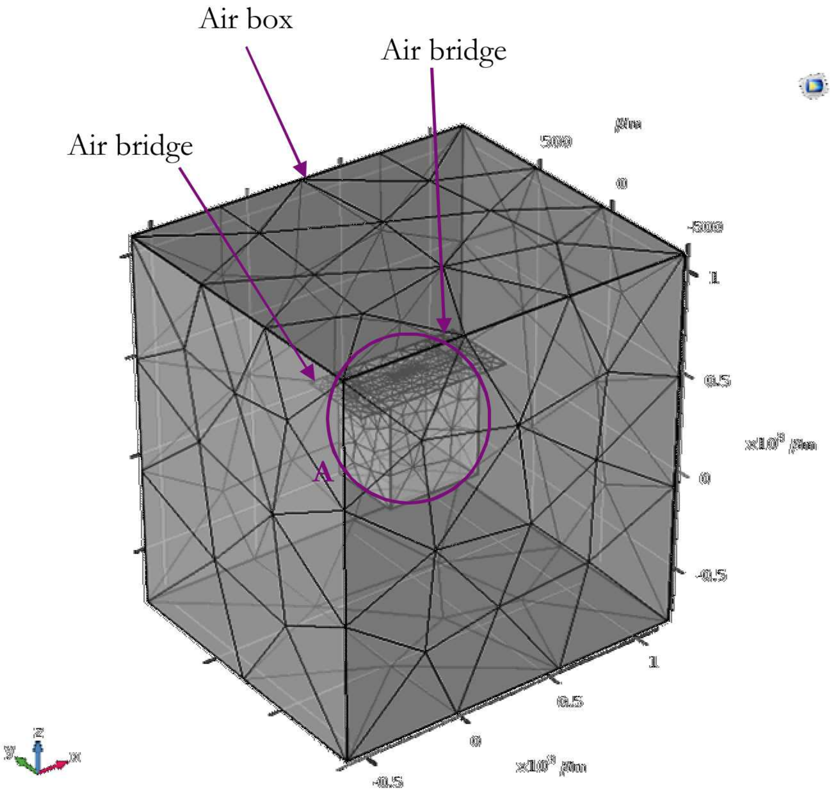
- Measured (experimental) thin-film resistivity: $1.4 \times 10^{-7}\ \Omega\cdot\text{m}$
- Bulk (theoretical) gold resistivity: $2.4 \times 10^{-8}\ \Omega\cdot\text{m}$*



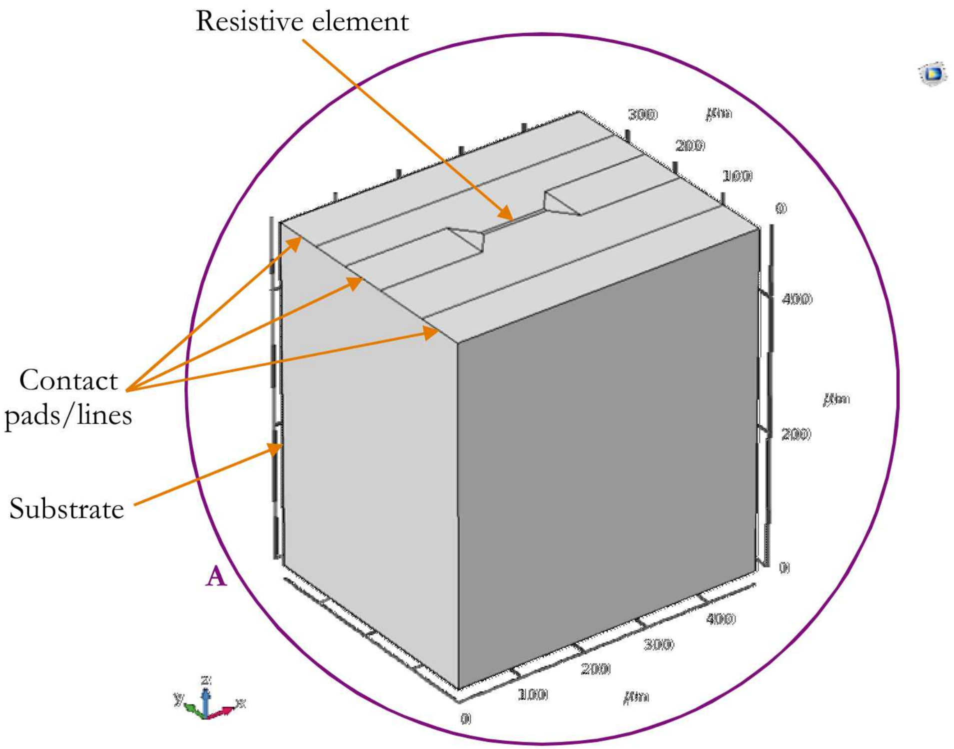
*Cutnell, John D & Kenneth W Johnson. Physics. 4th Edition. New York: Wiley, 1998: 591.

# COMSOL Multiphysics simulation

- Radio Frequency and Heat Transfer in Solids Modules
  - Joule heating Multiphysics
- Lumped Port and Transition/Thin Layer boundary conditions

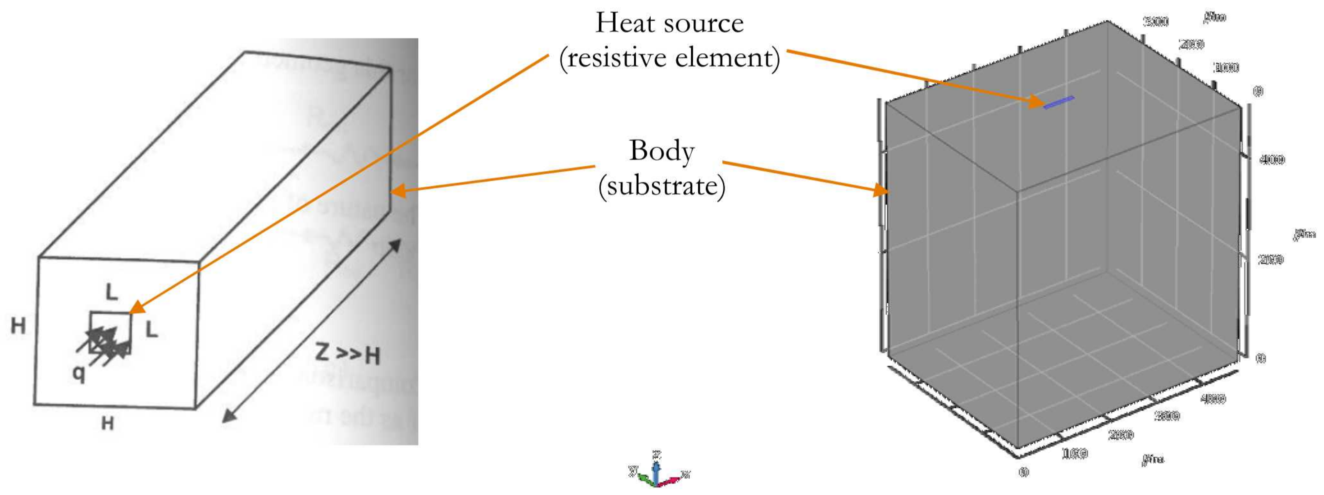


**Full rendering of 1300 mesh vertices**



**General substrate-pattern geometry**

# Heat transfer approximation



**Textbook geometry**

**COMSOL geometry**

Heat source (resistive element)

Body (substrate)

$$Q_{in} = \frac{\Delta T}{R_{spr} + R_{cond}}$$

$$R_{spr} = \frac{0.55}{Lk}\left[1 - \frac{L}{H}\right]^{3/2}$$

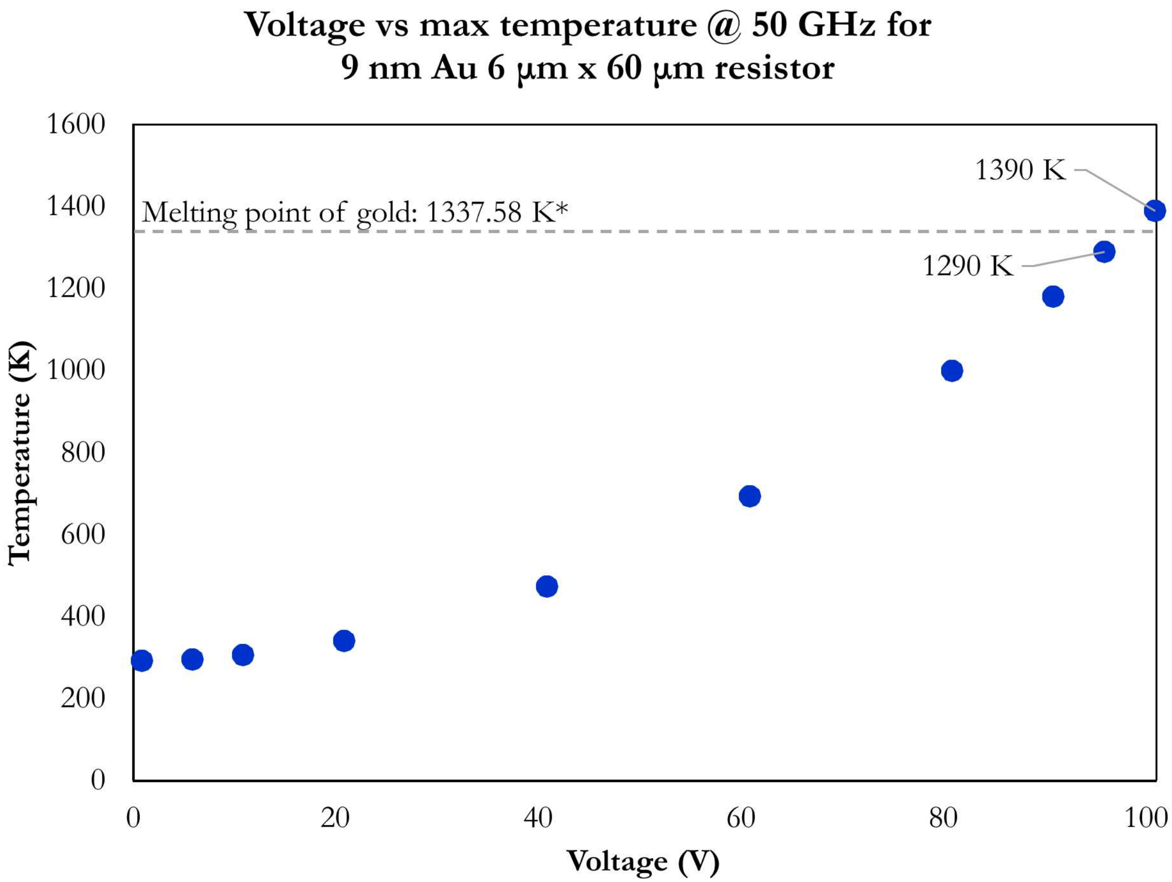
$$R_{cond} = \frac{Z}{kH^2}$$

| Variable | Description |
|---|---|
| q, $Q_{in}$ | Power applied to the resistor |
| $\Delta T$ | Temperature difference between the heat source and the boundary temperature of the body |
| $R_{spr}$ | Spreading resistance |
| $R_{cond}$ | Conduction resistance of the body on which the source is mounted |
| L x L | Heat source area |
| H x H | Body cross sectional area |
| Z | Body depth |
| k | Thermal conductivity of the body |

- Found less than 2 degK temperature change at $Q_{in}$ = 1mW for resistive element

Ulrich, Richard K & William, D Brown. Advanced Electronic Packaging. 2nd Edition. New York: Wiley-IEEE, 2006: 263 & 264.

# Heat transfer results

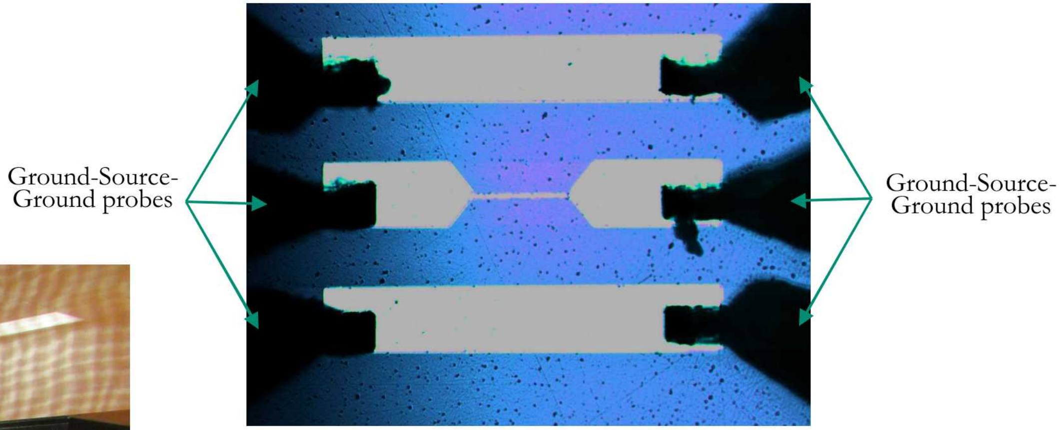


- Assumed fixed 50 Ω resistance and constant properties
- Negligible temperature effects at device operating voltage (~0.8899 V)

*Periodic Table of the Elements. Retrieved 16 July 2018, from https://www.cs.colorado.edu/~kena/classes/7818/f01/assignments/pt.html.

# Vector network analyzer and probe station measurements

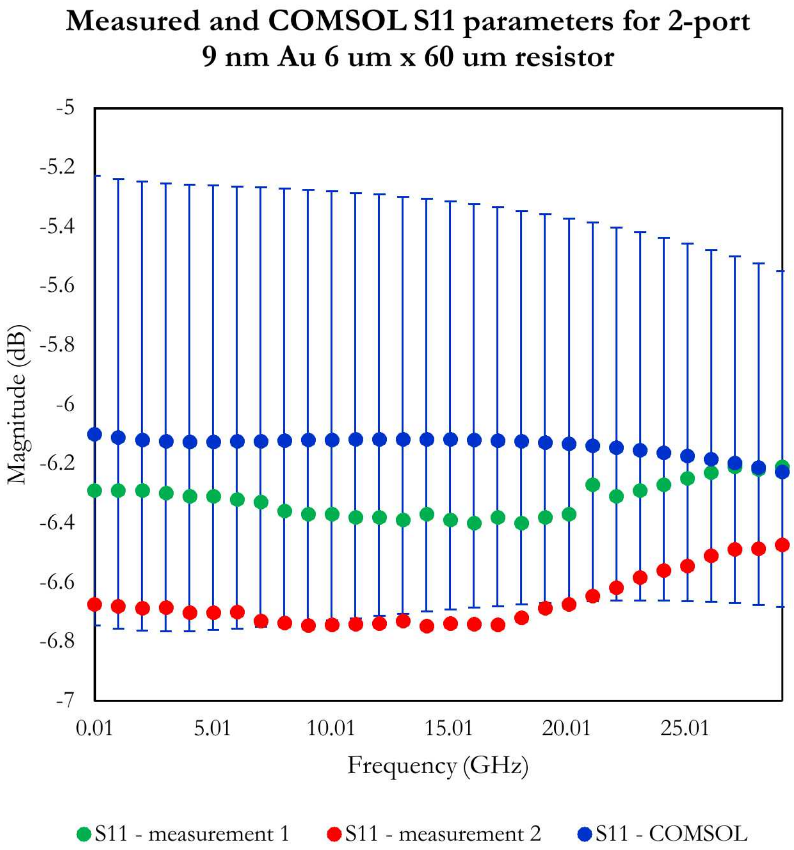
- Short-Open-Load-Thru and Thru-Reflect-Line calibrations used
- 12 dBm (~0.8899 V) from 0.01 GHz to 30 GHz



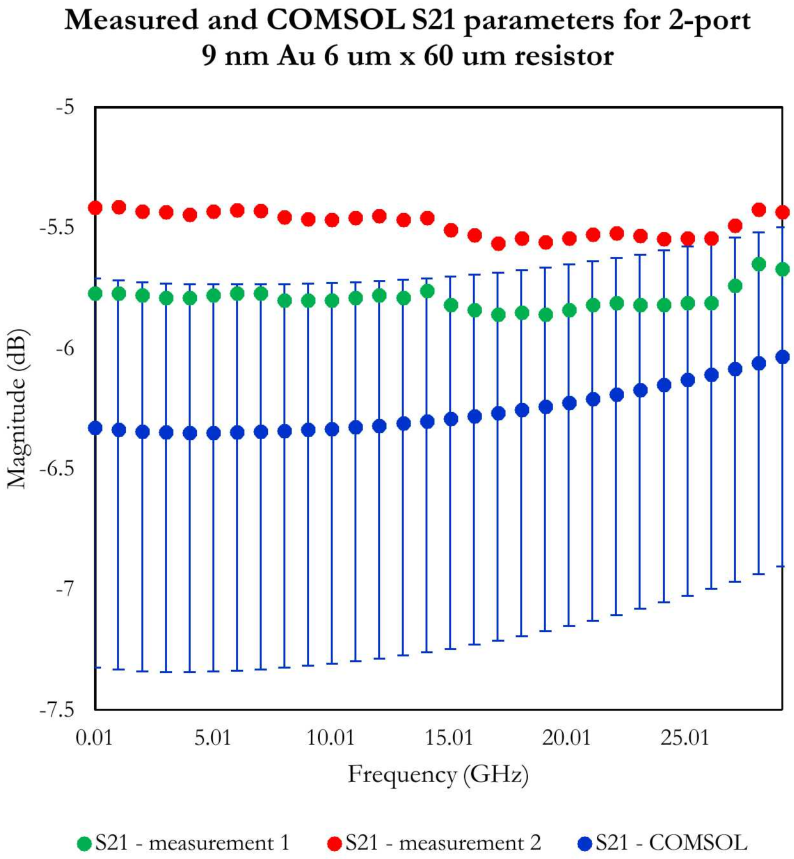
**(Above) Measurement probes landed on a device**

**(Above) Experimental setup**

# S-Parameter Results



Measured and COMSOL S11 parameters for 2-port 9 nm Au 6 um x 60 um resistor



Measured and COMSOL S21 parameters for 2-port 9 nm Au 6 um x 60 um resistor

- “Error” calculated from range in measured resistivity values
- All geometries showed results matching within 1 dB for S11 and S21

# Conclusions and future work

- Conclusions
  - Device failure due to heating is not of concern for 1 mW operations
  - The COMSOL simulation reasonably traced device responses
- Future work
  - Investigate electromigration effects on device lifetime
  - Improve simulation accuracy
  - Simulation studies could inform an optimized design

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