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Characterization and modeling of 2-port wideband resistance standards

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Abstract

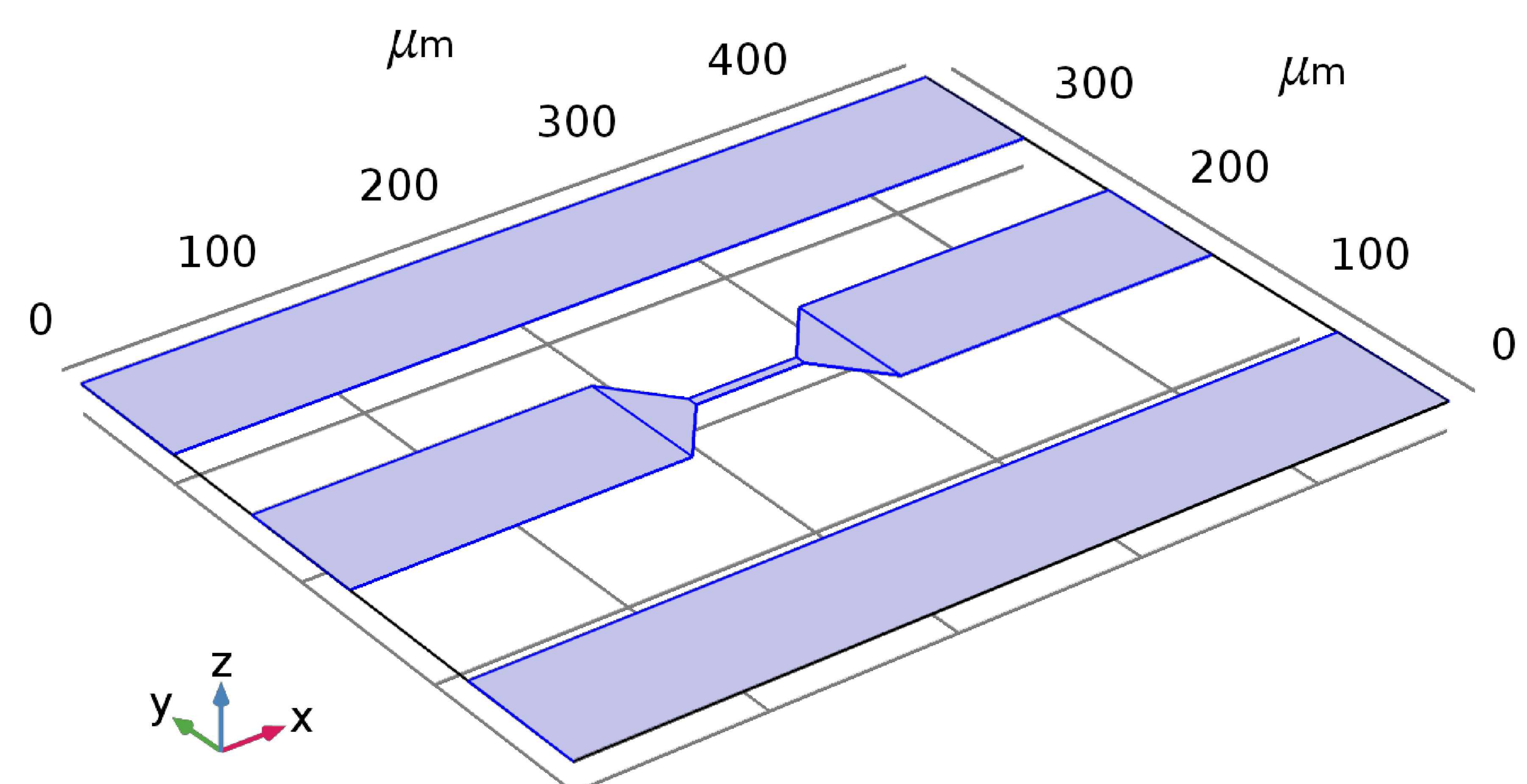
15 different potential wideband resistance standard designs were fabricated. Devices consisted of 10 nm thick Ti/Au resistors of varying lengths and widths. The resistors were fabricated alongside coplanar waveguides and on a polished alumina substrate. This study aimed to characterize the fabricated standards through experimental and simulation methods. Resistor geometries were measured with optical and atomic force microscopes. A 4-point probe measured resistivity. The resulting values were used to calculate the conductivity of the thin-film Ti/Au. The conductivity was found to be about 6.93 x 10^6 ohm/m, which deviates approximately 83% from the bulk value[1]. These experimentally determined device properties were implemented in COMSOL Multiphysics models of the resistors. COMSOL's Radio Frequency and Heat Transfer in Solids modules were used to calculate sample S-parameters and temperature distributions. Then, 2-port measurements were produced from 10 MHz to 30 GHz using a Vector Network Analyzer and probe station. The COMSOL simulation matched the experimental measurements within 0.03 ± 0.14 dB and 0.07 ± 0.14 dB for S11 and S21, respectively. The actual real-part resistances of the standards ranged from 120 to 543 ohms. COMSOL results showed that the resistance standards would not fail due to Ti/Au melting until reaching an applied voltage of about 100 V. The measurement and simulation techniques developed proved to reasonably characterize the response of the two-port resistance standard design and demonstrated that device failure due to heating is not of concern for 1 mW operations.

Introduction

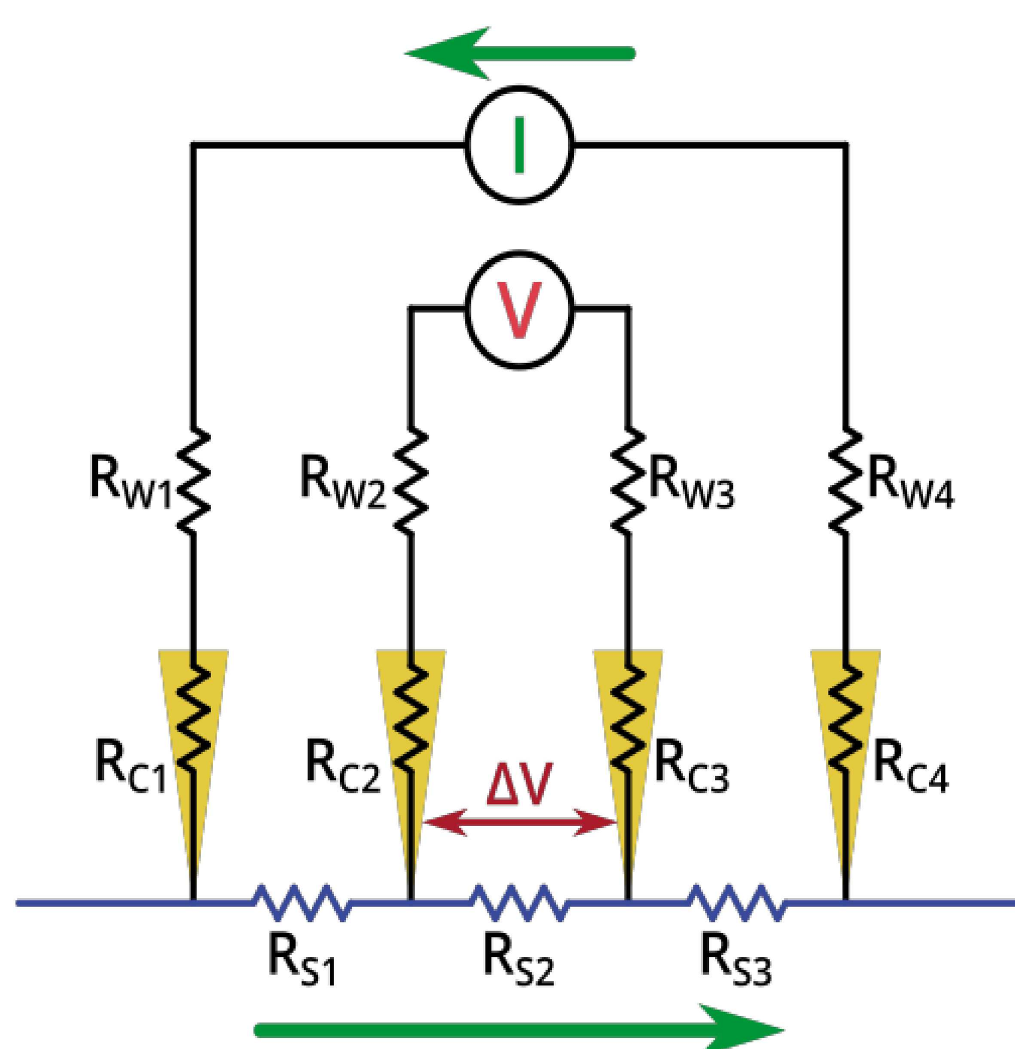
The qualification and reliability of every product in the nuclear weapon stockpile is based upon measurements traceable to the fundamental SI units through Sandia's Primary Standards Laboratory[2]. Some radio-frequency measurement devices are calibrated using resistance standards. Current calibration approaches use multiple resistance standards to cover a wide range of frequencies, yet leave a gap in coverage from 100 kHz to 100 MHz and add additional uncertainty where the ranges of each standard are stitched together. A single wideband resistance standard is desired to reduce time, cost, and sources of error. The wideband resistance standard should hold a 50 ohm real-part resistance at 1 mW power from 100 kHz to 50 GHz.

Methods

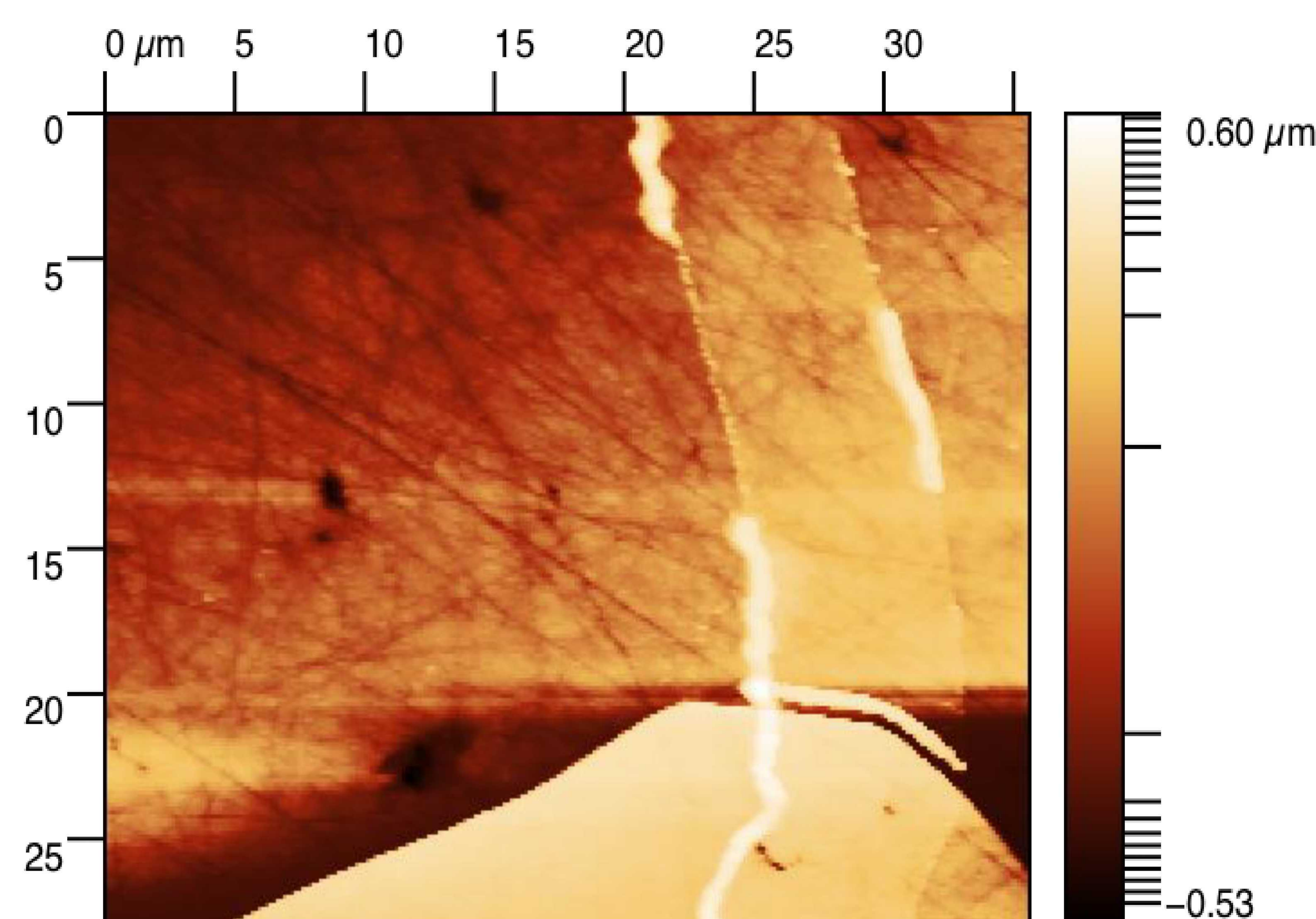
1. Fabricate 15 different 2-port resistor designs via a 2-mask photolithography and electron beam evaporation process
2. Experimentally verify device properties using optical and atomic force microscopy, and 4-point probe DC measurements
3. Input experimentally determined properties in COMSOL Multiphysics 3.4a model using Radio Frequency and Heat Transfer in Solids modules. Run study at 0.8899 V from 0.01 GHz to 30 GHz
4. Perform experimental measurements with a Vector Network Analyzer and probe station at 12 dBm (~0.8899 V) from 0.01 GHz to 30 GHz. Evaluate heat transfer approximations for problem geometry
5. Compare model results to experimental measurements and theoretical calculations



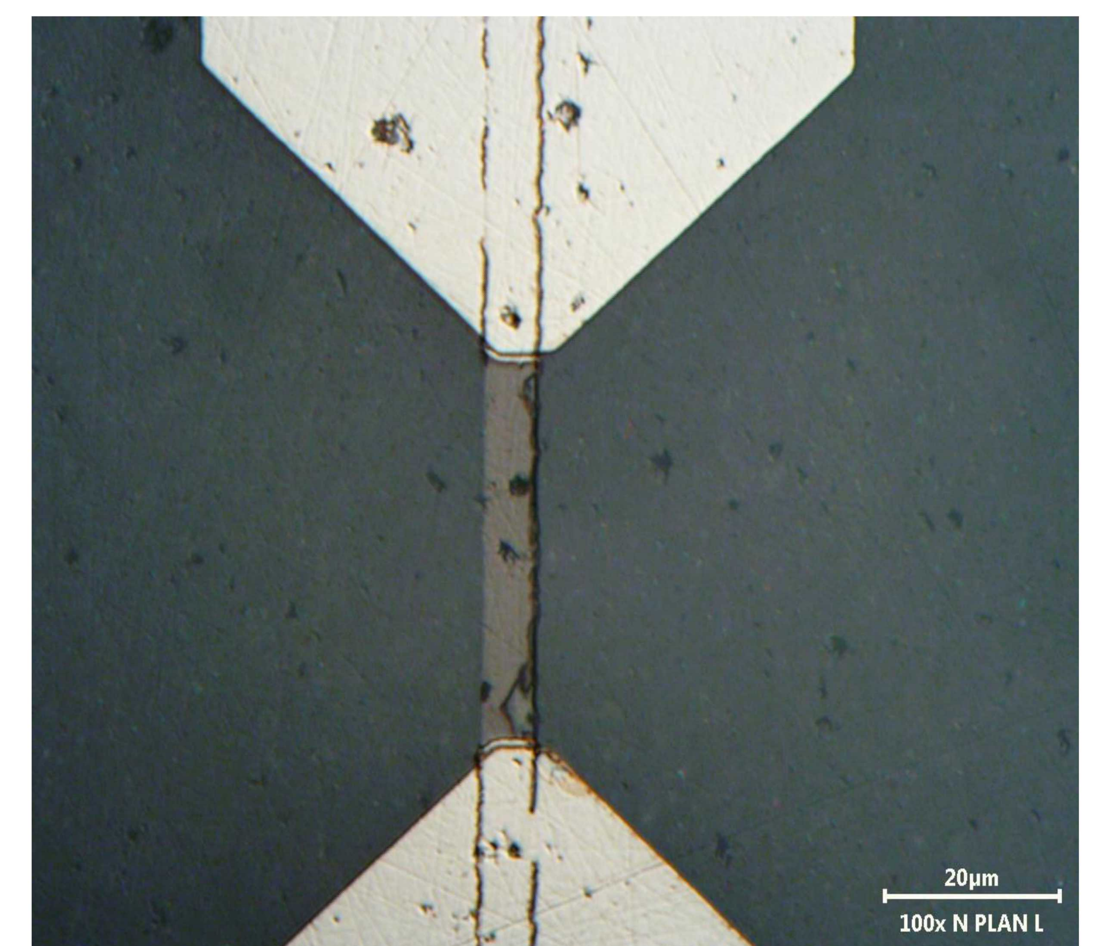
(Above) 2-port resistor design with 6 um by 60 um resistive filament. Resistive filament widths varied by 2 um, 4 um, and 6 um. Resistive filament lengths varied by 40 um, 60 um, 80 um, 100 um, and 120 um



(Above) Equivalent circuit diagram of a four-point probe for thin-film resistivity measurements, adapted from "ossila.com." The wire resistances (RW), contact resistances (RC), sample resistances (RS), and current flow (green arrows) are shown



(Above) Atomic Force Microscope capture showing the roughness profile of a Ti/Au resistive filament and step junction

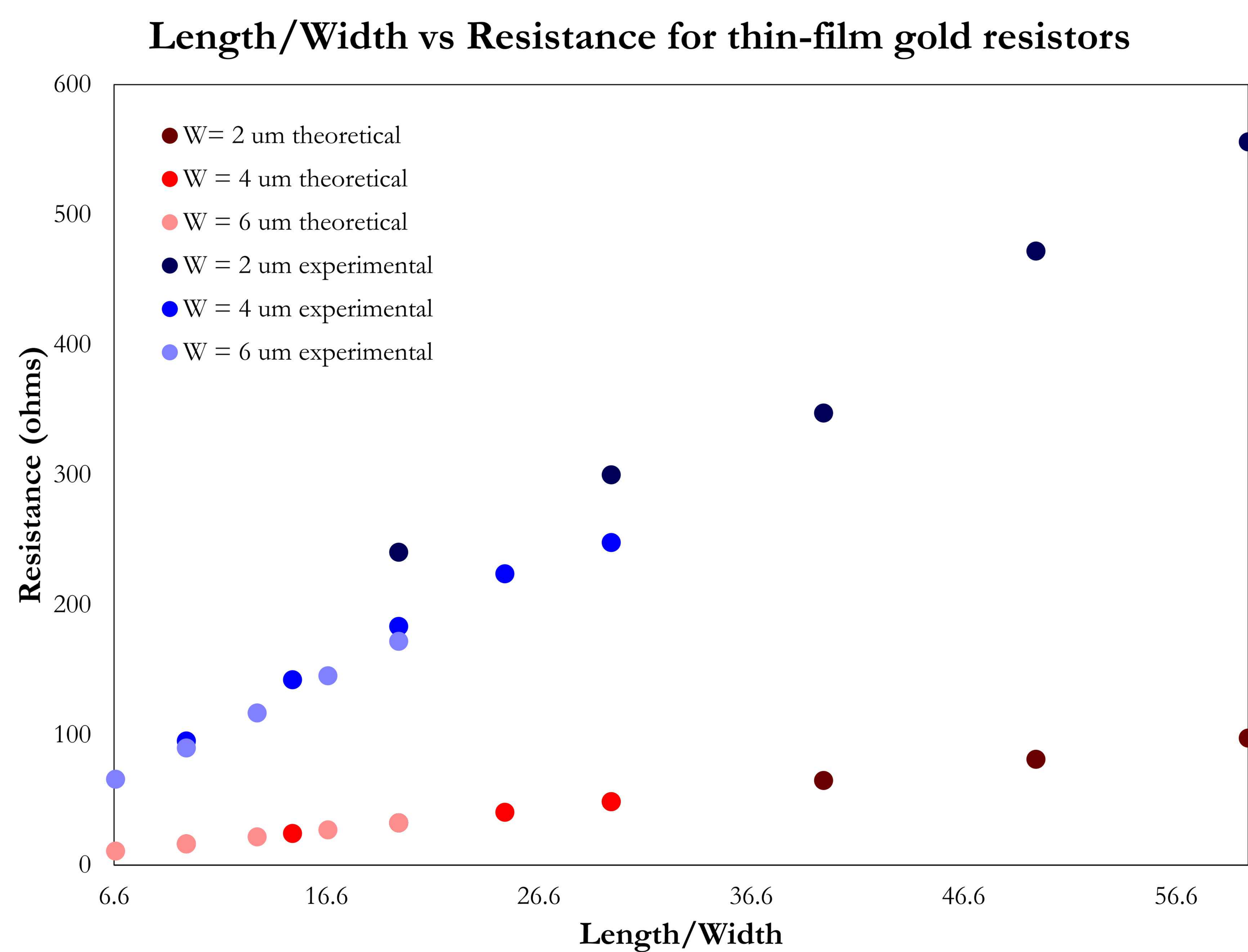


(Above) Optical microscope image of 6 um by 40 um Ti/Au resistive filament and Ti/Au step junctions on polished Al_2O_3

Results

Resistivity

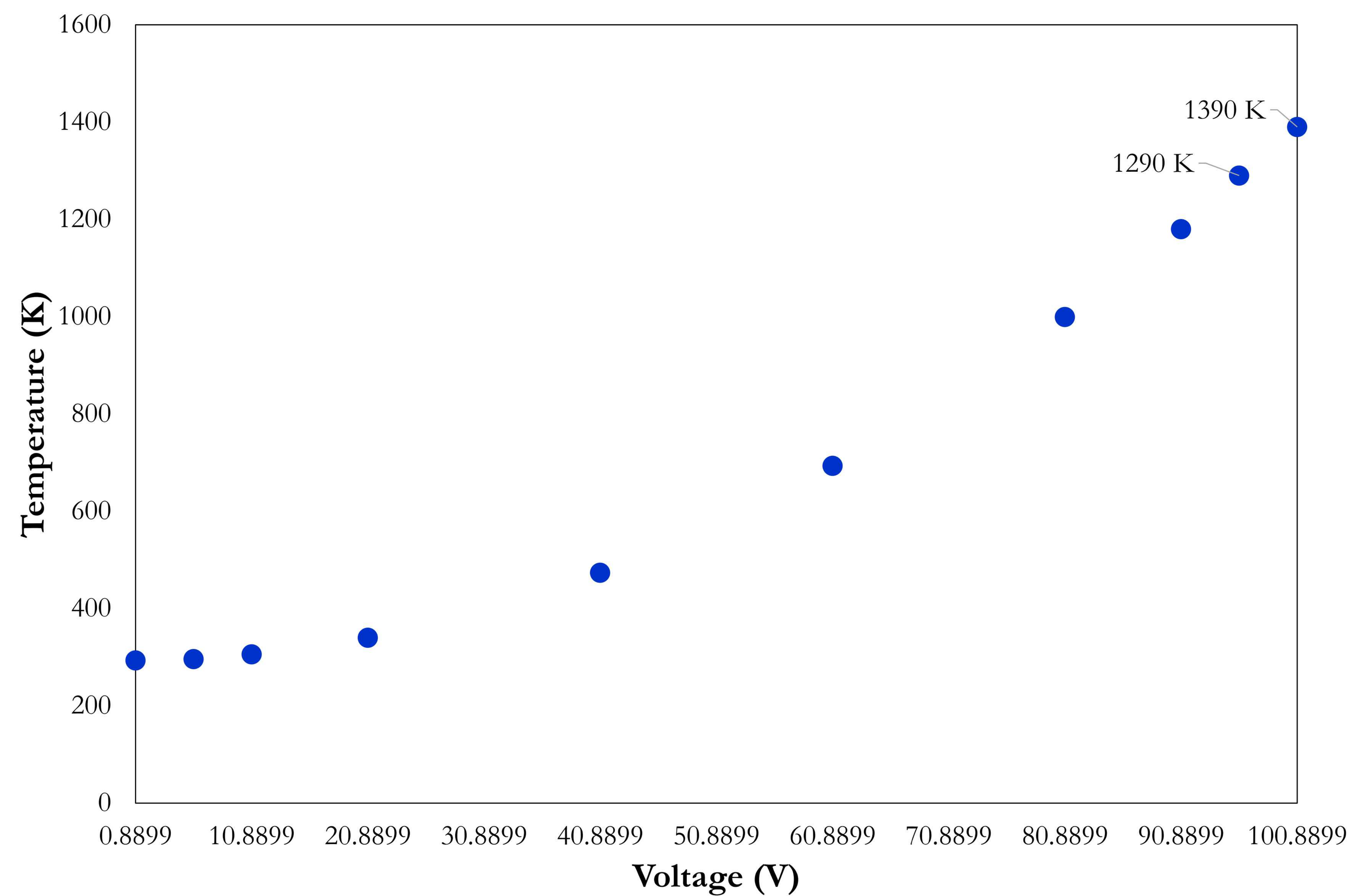
- Measured thin-film conductivity was found to be about 6.93×10^6 ohm/m, which is an about 83% deviation from bulk values[1]



(Above) Length-width ratio versus resistance for bulk Au resistivity values ("theoretical") and resistivity values measured with a 4-point probe ("experimental"). As expected, the resistance increased with respect to the length-width ratio

Heat Transfer

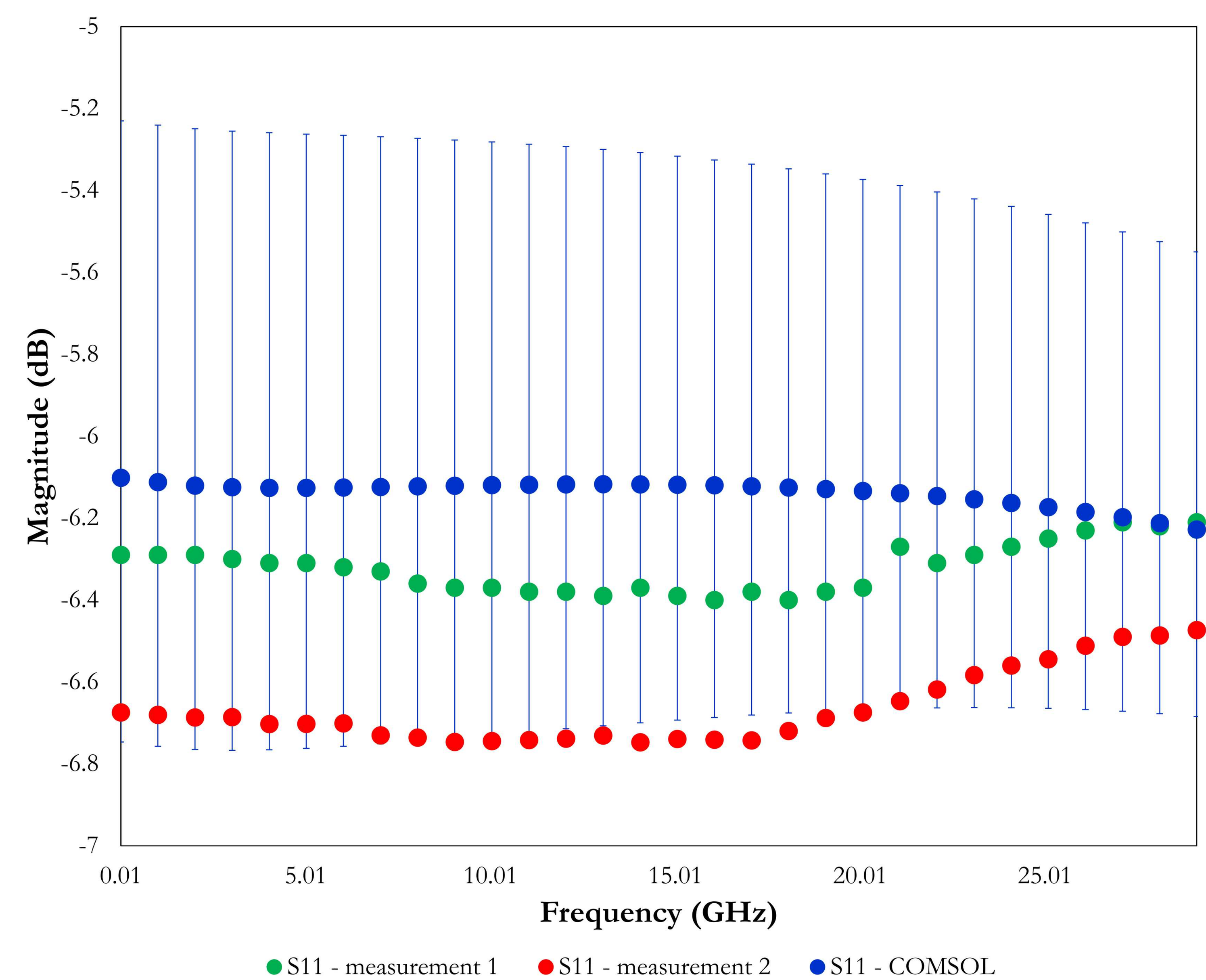
- Resistance standards would not meet the melting point of gold[3] until reaching an applied voltage of about 100 V
- The conservative heat transfer approximation showed a less-than 2 degK temperature change at 1 mW applied power in resistor



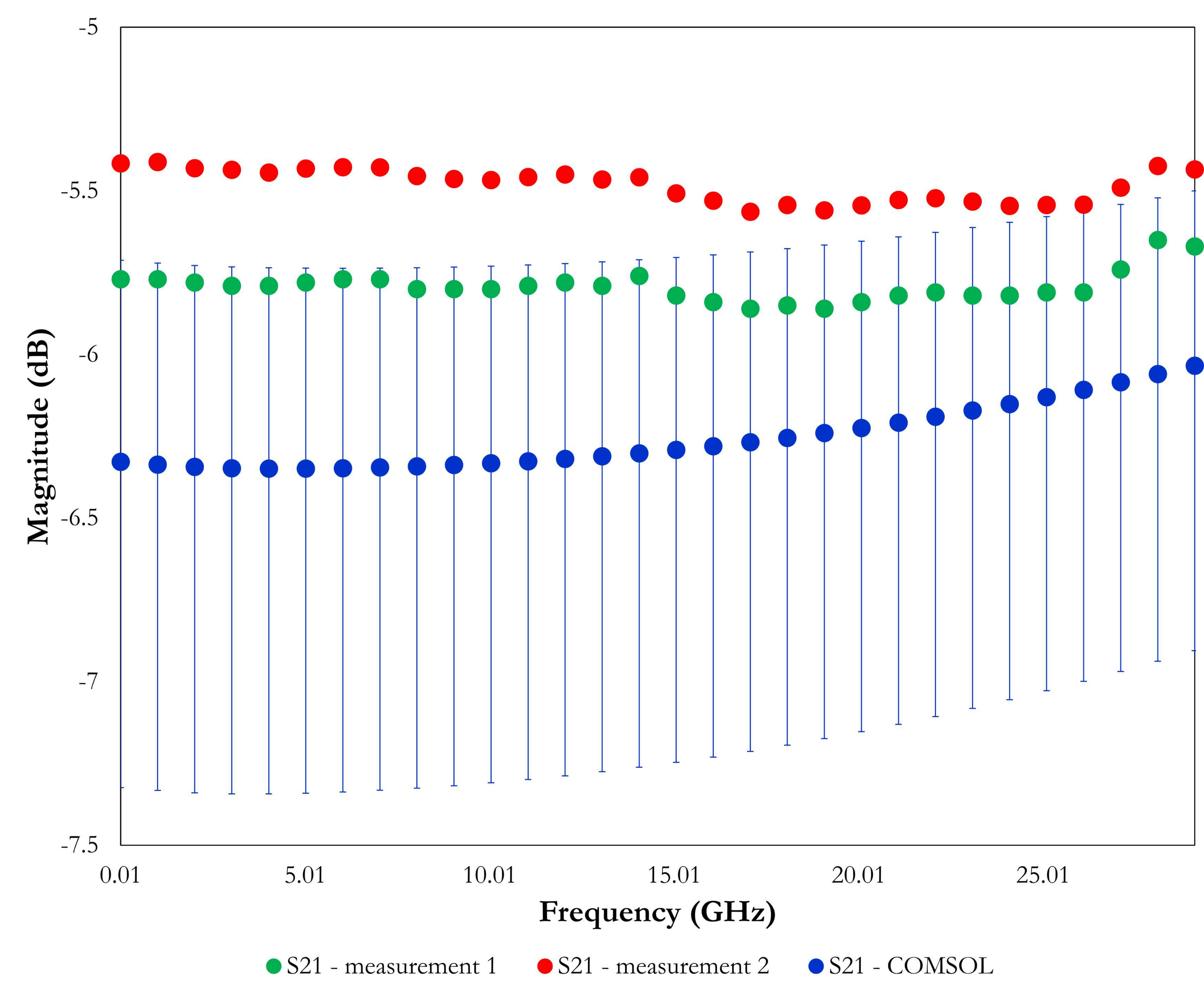
(Above) Maximum temperature values from joule-heating in 2-port resistor evaluated using COMSOL Multiphysics

S-Parameters

- COMSOL simulation matched the experimental measurements within 0.03 ± 0.14 dB and 0.07 ± 0.14 dB for S11 and S21, respectively



(Above) Comparison of experimental and theoretical 2-port resistor reflection coefficients. The COMSOL model error was determined by propagating the error from the measured Au resistivity values



(Above) Comparison of experimental and theoretical 2-port resistor transmission coefficients. The COMSOL model error was determined by propagating the error from the measured Au resistivity values

Discussion

- The COMSOL simulation reasonably traced device responses
- S11 and S21 experimental measurements could be improved by performing the Vector Network Analyzer and probe station calibration with calibration markings patterned on the substrate adjacent to the resistors
- Device failure due to heating is not of concern for 1 mW operations. Negligible thermal effects could be experimentally verified by holding an applied voltage for an and observing if the resistance changes over an extended period of time
- Devices should be fabricated again, with a thicker layer of Au to reduce the real-part resistance toward 50 ohm
- Electromigration effects on device lifetime should be investigated in the future

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NNSA National Nuclear Security Administration
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[2]9140, Primary Standards Laboratory (2018). Retrieved 16 July, 2018, from https://webprod.sandia.gov/SAPLE/search.jsp?query=org:9140&source=org_roster&showAll=true
[3]Periodic Table of the Elements. Retrieved 16 July 2018, from https://www.cs.colorado.edu/~kena/classes/7818/f01/assignments/pt.html

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