Development of a High Frequency Class-A Amplifier for High Temperature Wireless Microsystems based on a Silicon Carbide Static Induction Transistor

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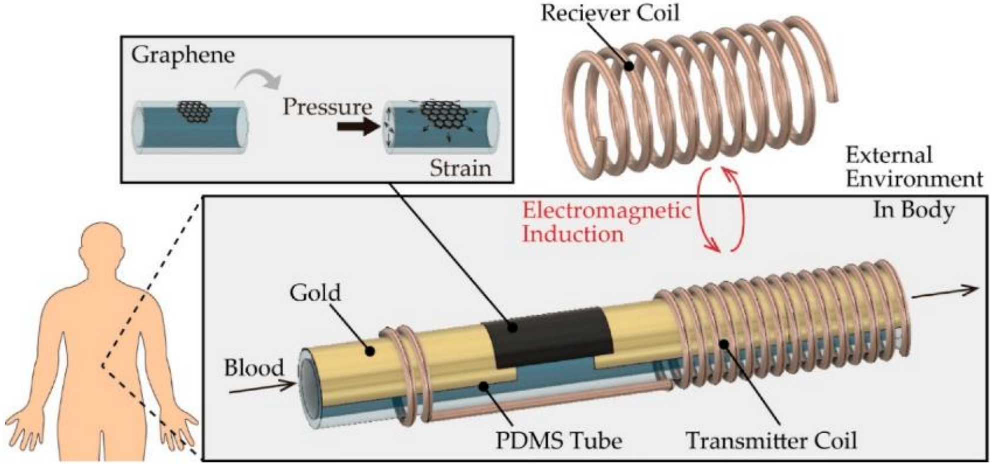
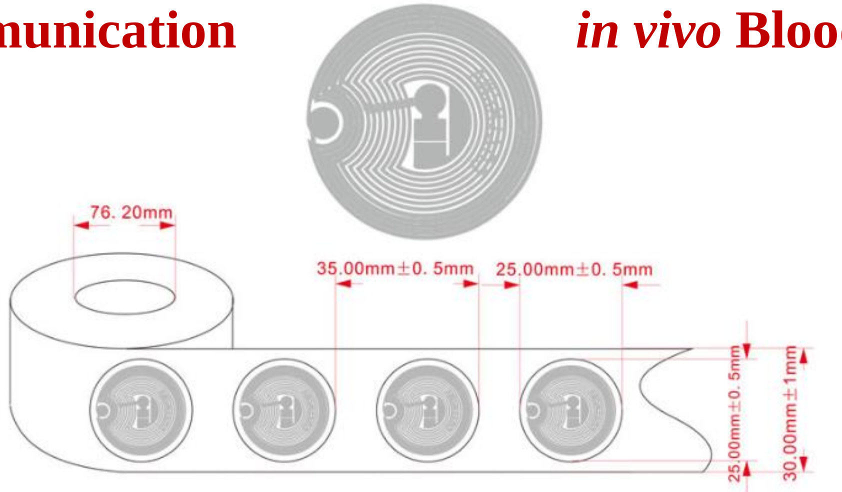
Wireless Sensing Systems Applications

Wireless Sensor Systems draw out multiple disciples requiring an array of solutions

Bluetooth Communication



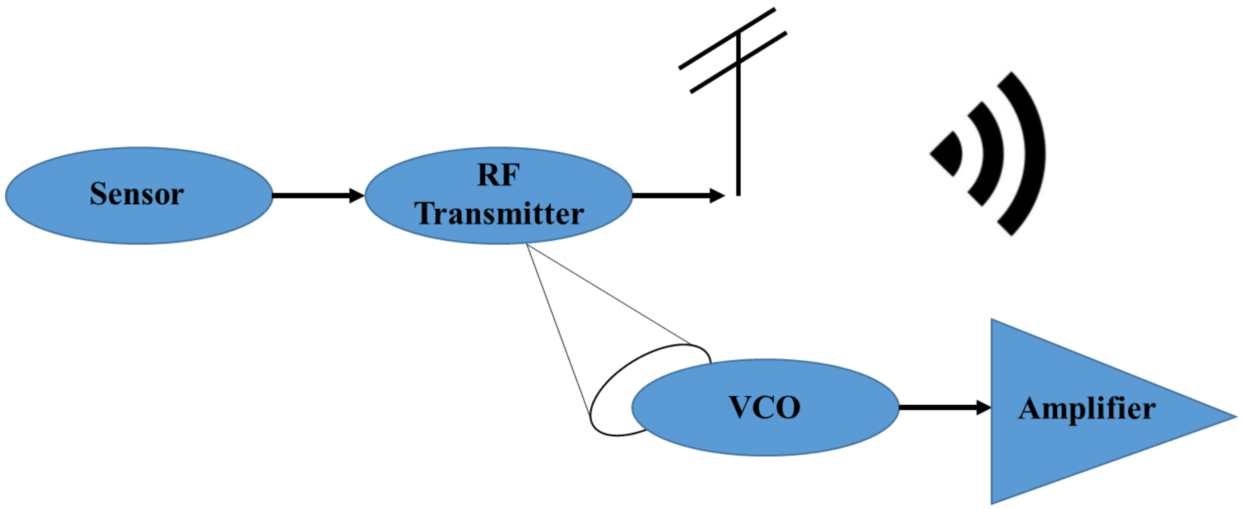
***in vivo* Blood Pressure Monitoring**



Radio Frequency ID Technology

Wireless Sensor System Overview

Wireless Sensor Systems are applicable to handle input signals for information transfer



Wireless Sensor System Applications

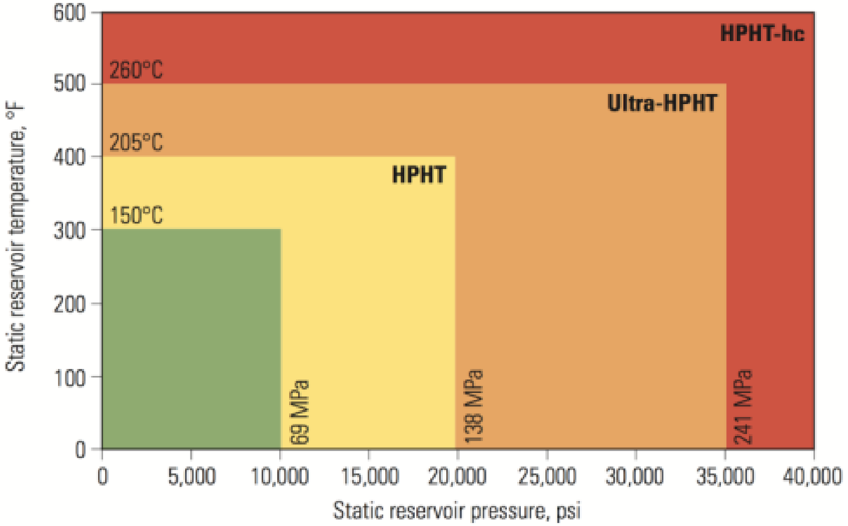
- MIM Capacitor Pressure Sensors
- Piezoresistive Pressure Sensors
- Thermocouple Temperature Sensing
- Gas sensor systems for Air Composition

Harsh Environment Operational Monitoring

Harsh Environment Sensing Systems Vary Depending on Application

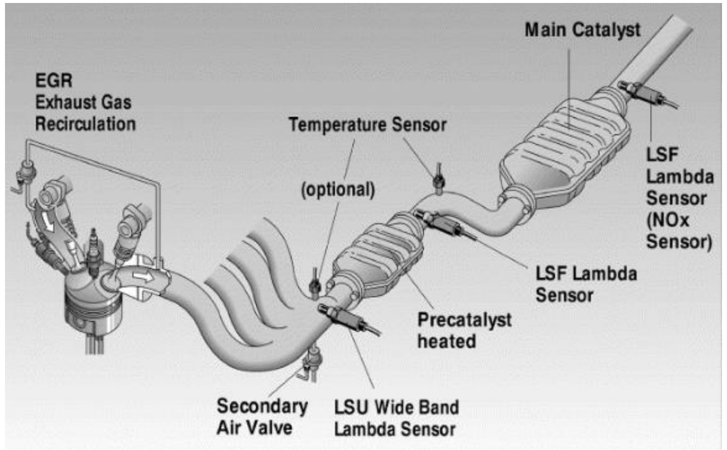
Sensing Temperature Ranges

- Downhole Drilling (150 to ~300^{o}C)
- Automotive Sensing (150 to ~850^{o}C)
- Aerospace (150 to ~550^{o}C)



Downhole Drilling Applications

Aerospace and Foreign Planet Exploration

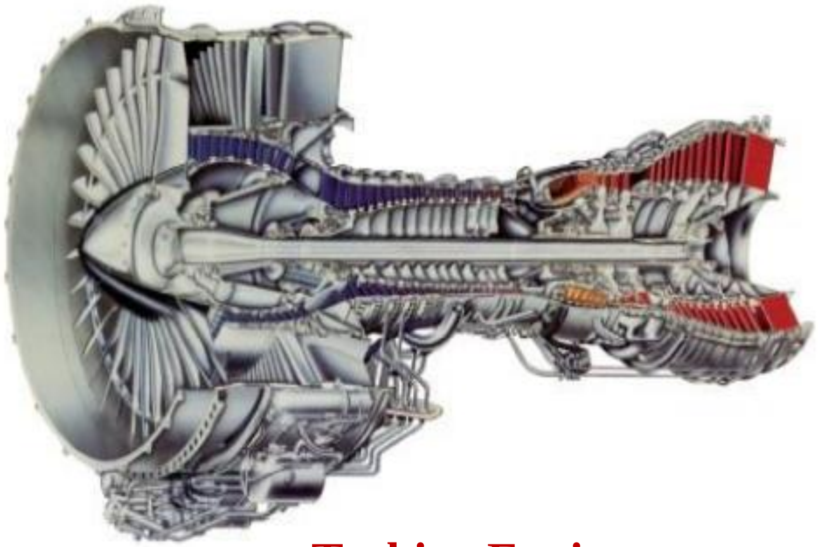


Automotive Exhaust Monitoring

Gas Turbine Engine Health Monitoring

Operating Conditions

- Temperature: 400^{o} C
- Pressure: 0 to 300 psi
- Vibration: up to 5.3 G_{rms}



Turbine Engine

Engine Health Concerns

- Temperature sensing and flow probing are critical for fuel consumption efficiency and total gas velocity.

- Wireless systems would limit the interference with structural integrity for housing the configuration.

- Small signal amplification is needed in the transmitter for the wireless system

Wireless Sensor System Needs

Need for High Temperature-High Frequency Transistors

Sensors may need signal amplification in wireless transmission

High Temperature Amplifier Needs

- **Temperature: Operation up to 400^{o}C**
- **Frequency: 50 MHz design for antenna form factor**
- **Demonstration of a transistor with stable operation**

Objectives:

- **Characterization of the SiC SIT at temperatures up to 400^{o}C and frequencies of up to 300 MHz**
- **Development of a small signal model for the SiC SIT for high temperatures**
- **Development of suitable high temperature passive components**
- **Modeling based design of a Class-A amplifier for harsh environment applications**
- **Fabrication and bench testing of the device to test for prototype viability**

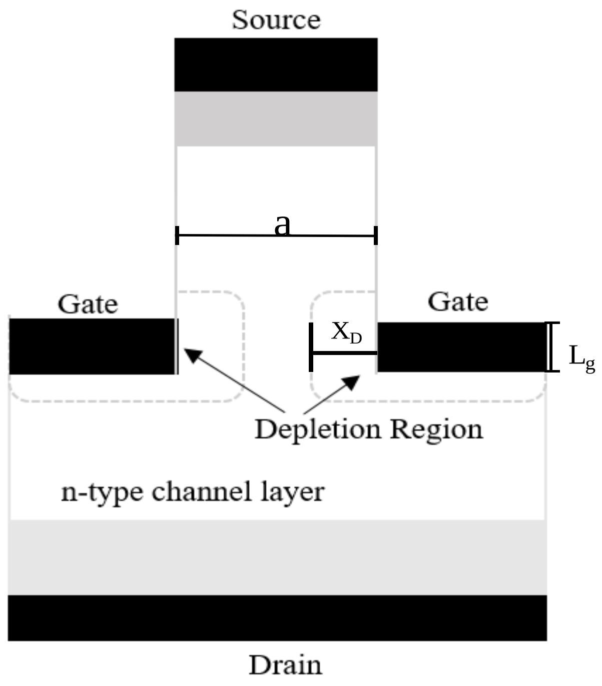
Objectives:

The Class-A amplifier will attempt to meet the following design criteria:

- **An operating temperature of 400^{o}C without passive cooling**
- **Gain > 10 dB at 400^{o}C**
- **Unconditional stability at the operating frequency of 50 MHz**
- **Input (S_{11}) and output (S_{22}) reflections coefficients of < -15 dB at the center frequency**

Static Induction Transistors

SITs are vertically normally-on devices that require negative gate biasing for operation

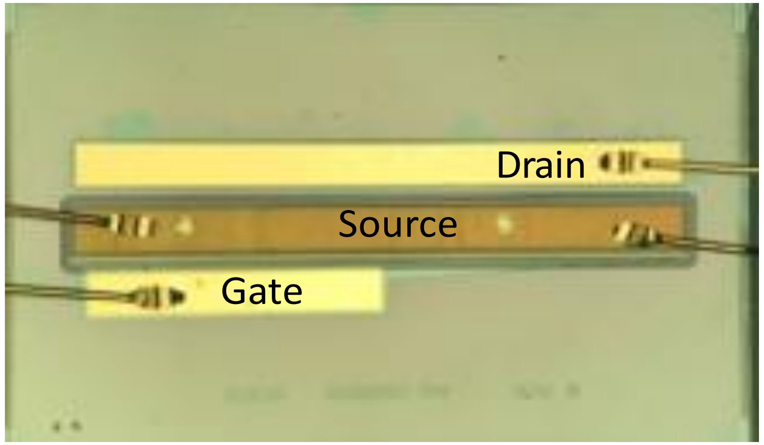


Cross-sectional Schematic of a SIT

- **Developed originally in Silicon**
- **Schottky Contacts on Gate**
- **High Power Device Applications included:**
  - **Induction heating**
  - **Power supplies**
  - **Ultrasonic generation**

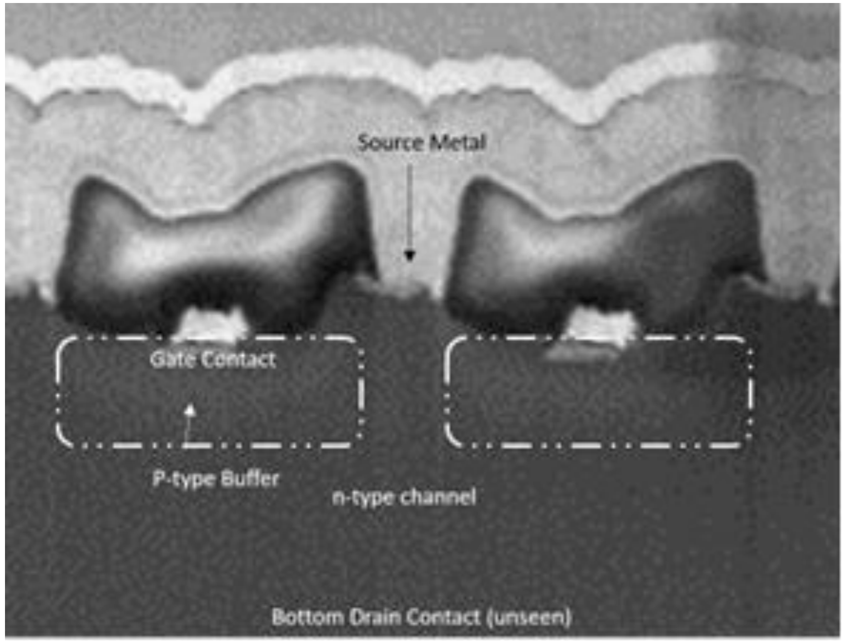
SiC Static Induction Transistors

The SiC SIT used in this dissertation were manufactured by MicroSemi



Photograph of the SiC SIT

- **Marketed for high-power applications**
- **4H-SiC device**
- **Wire-bonds used to connect SIT to a HT package**
- **Bottom contact not visible**
- **SiC SIT theorized up to 600°C Operation**

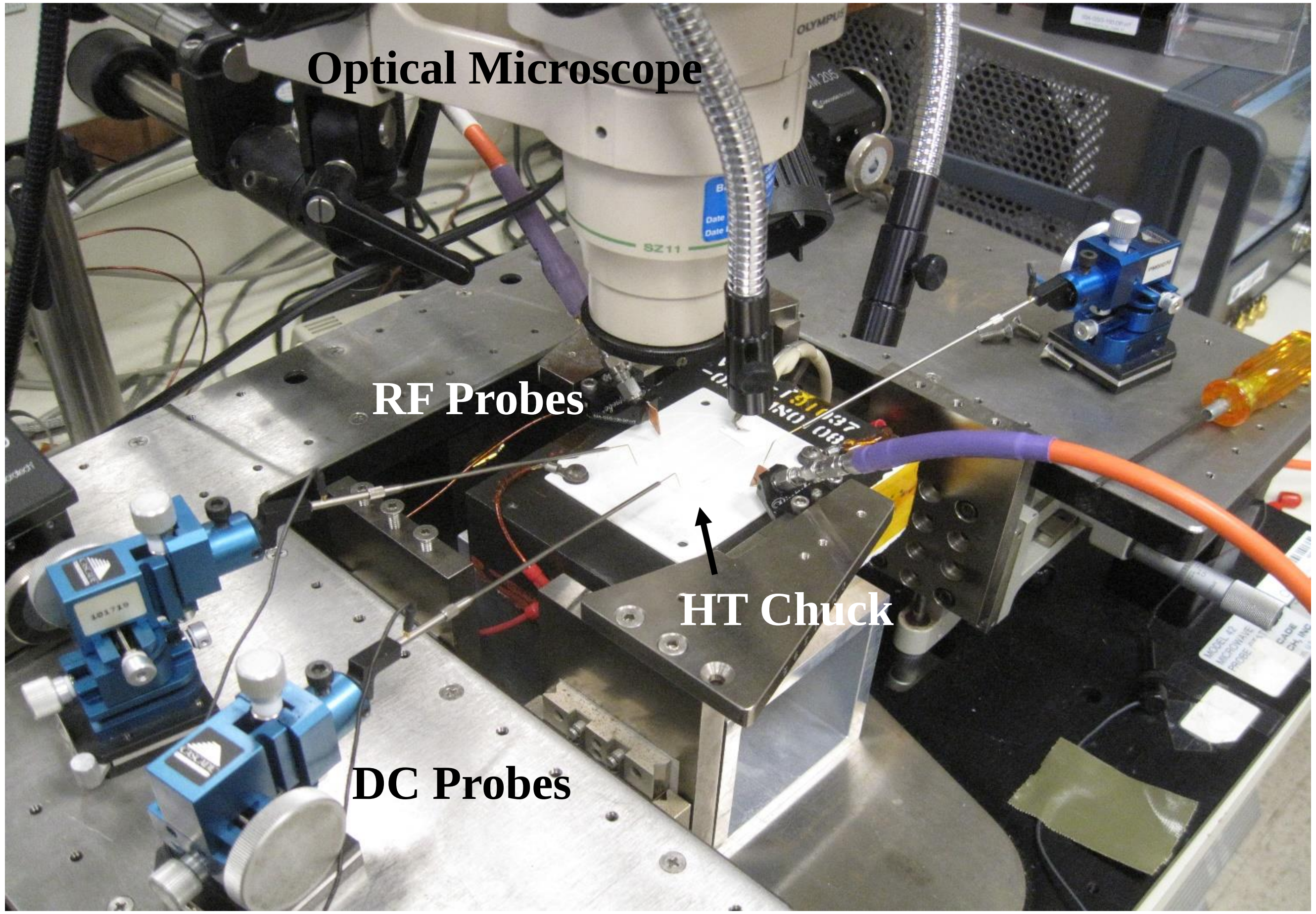


Cross-sectional SEM of the MicroSemi SIT

- **P-type buffer allows for manufacturing ease overcoming poor breakdown and reverse leakage associated with Schottky gates**

DC and RF Characterization

The High Temperature Probe Station at NASA Glenn Research Center was used in all Characterization Measurements



High Temperature Probe Station

Device Characterization

The High Temperature Probe Station at NASA Glenn Research Center was used in all Characterization Measurements

DC Characterization

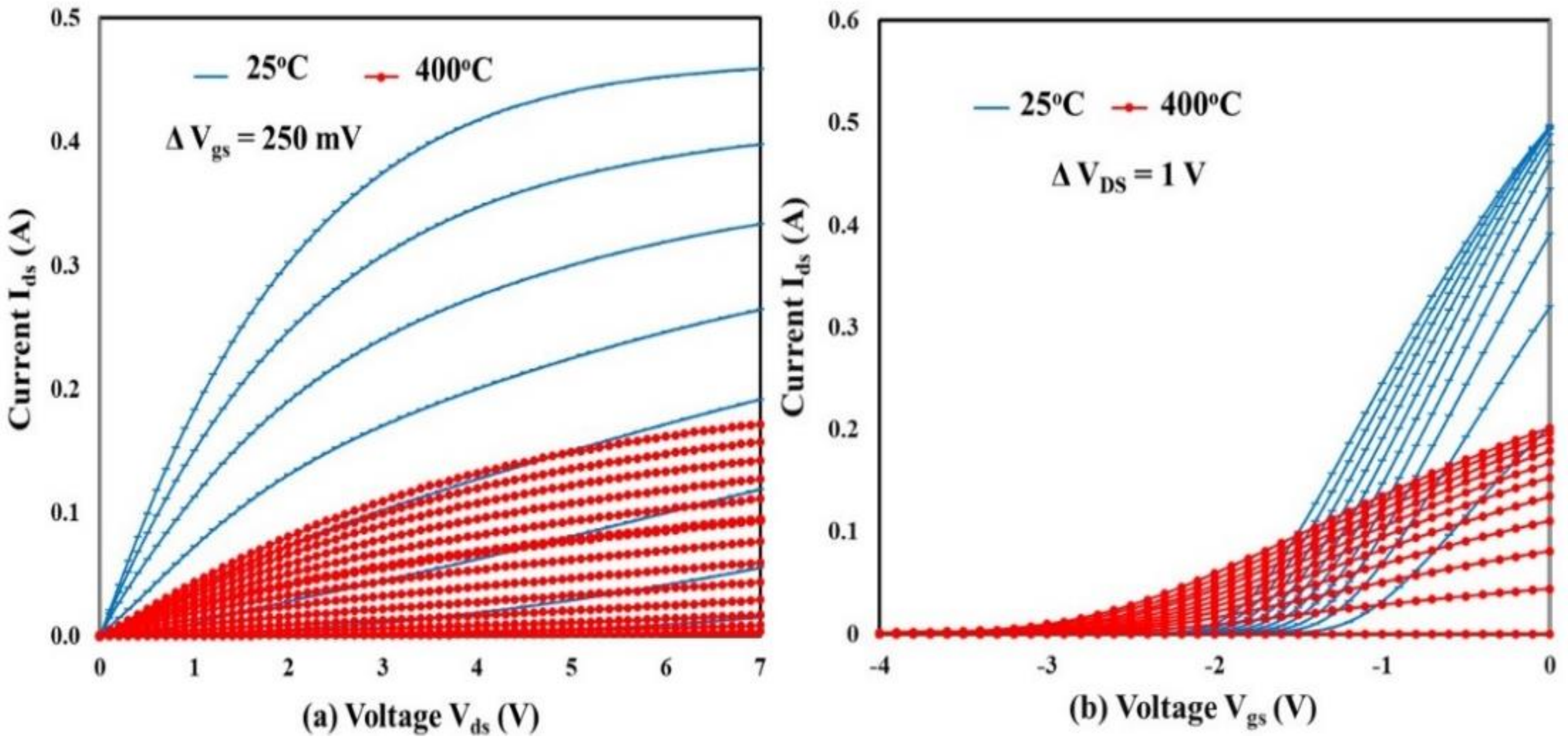
- **B1505A Power Analyzer for C-V and I-V Measurements at Temperature.**
- **High Temperature Au/W Probes for all DC connections**
- **Alumina Substrate for the high temperature chuck from 25-600^{o}C is positioned on NASA Space Shuttle Tile**

RF Characterization

- **S-Parameter Measurements with N5224B Network Analyzer**
- **High Temperature Ground-Signal-Ground (GSG) Probes with 150µm pitch.**
- **Calibration at 25^{o}C with Measurements Done from 25-600^{o}C**

I-V Characterization

Representative I-V Curves of the SiC SIT at 25°C and 400°C

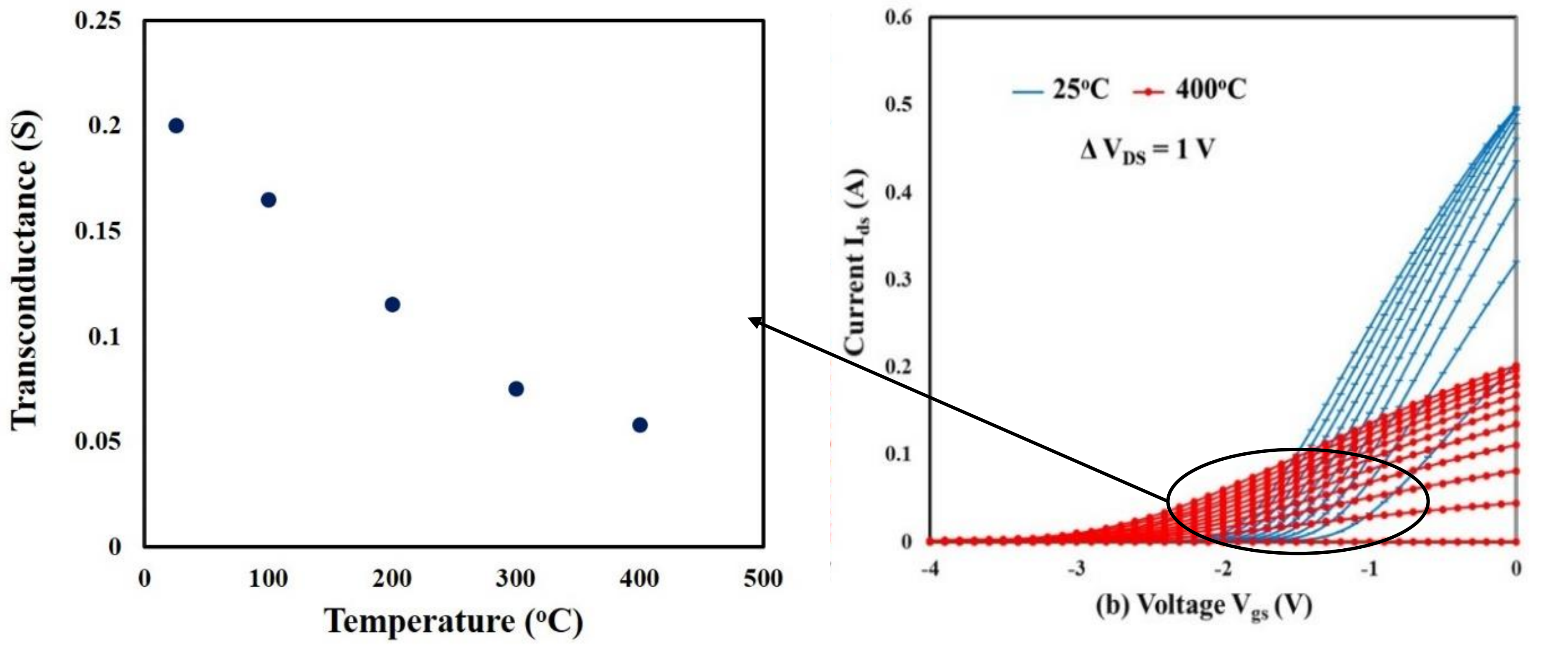


I-V Characterization Details

- I-V Measurements from 25-400ºC on 5 devices
- The observed decrease in drain current due to mobility: 62.7 % decrease in I_{ds}
- I_{ds}-V_{ds}: Steps of 250 mV
- I_{ds}-V_{gs}: Steps of 1 V

Transconductance

Transconductance between 25°C and 400°C



$$\frac{\Delta Ids}{\Delta Vgs} = g_m\Big|_{Vds=constant}$$

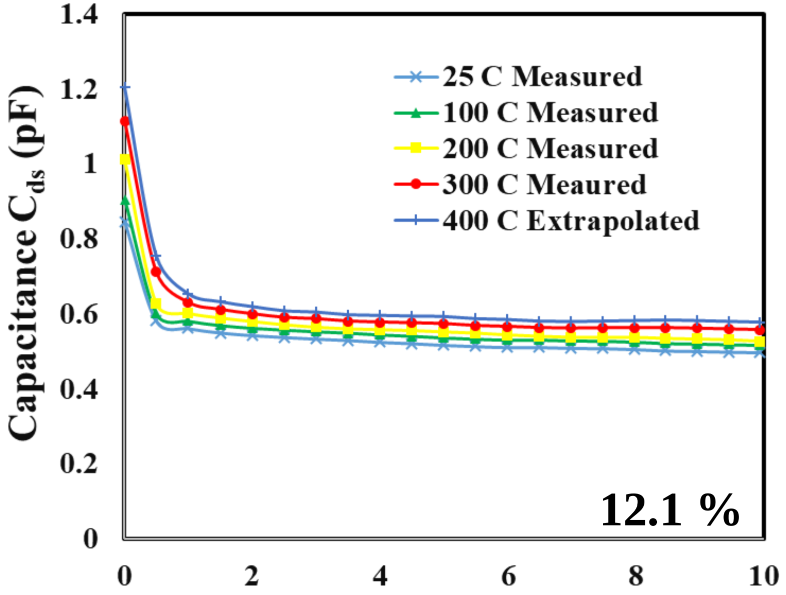
SiC SIT transconductance

- Temperature dependences of g_m
- Small signal current to voltage ratio
- Operation at high temperature (I-V)
- Greater g_m, the greater gain capability

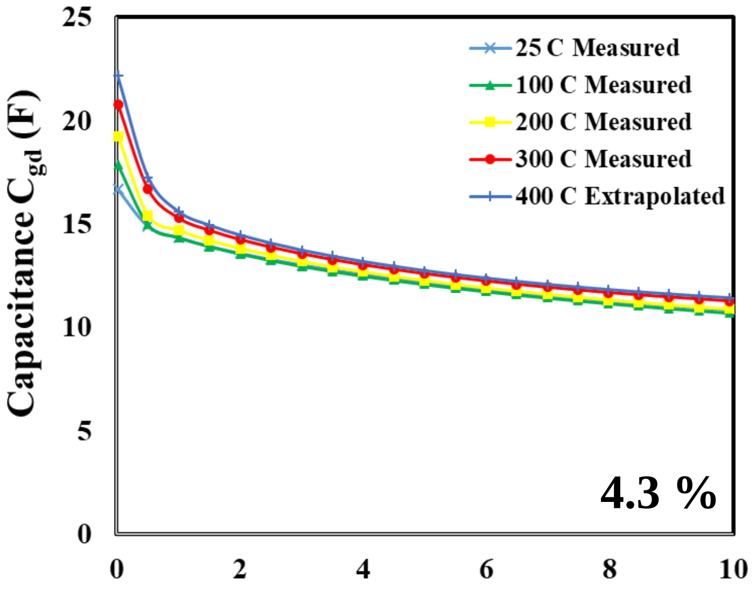
C-V Measurements

Representative SiC SIT C-V Measurements

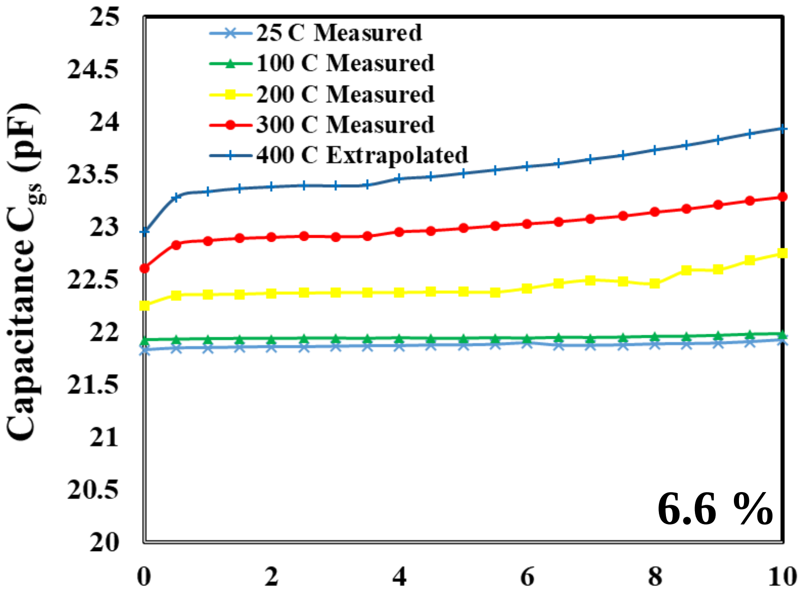
- C_{gs}, C_{ds}, C_{gd} Terminal Measurements
- Sweeping from 0-10 V_{ds}, -3 V on V_{gs}
- Measurements made when the device was operating in a non-conducting mode
- Calibrations to ensure accuracy (open, short, phase)



(a) Voltage V_{ds} (V)



(b) Voltage V_{ds} (V)

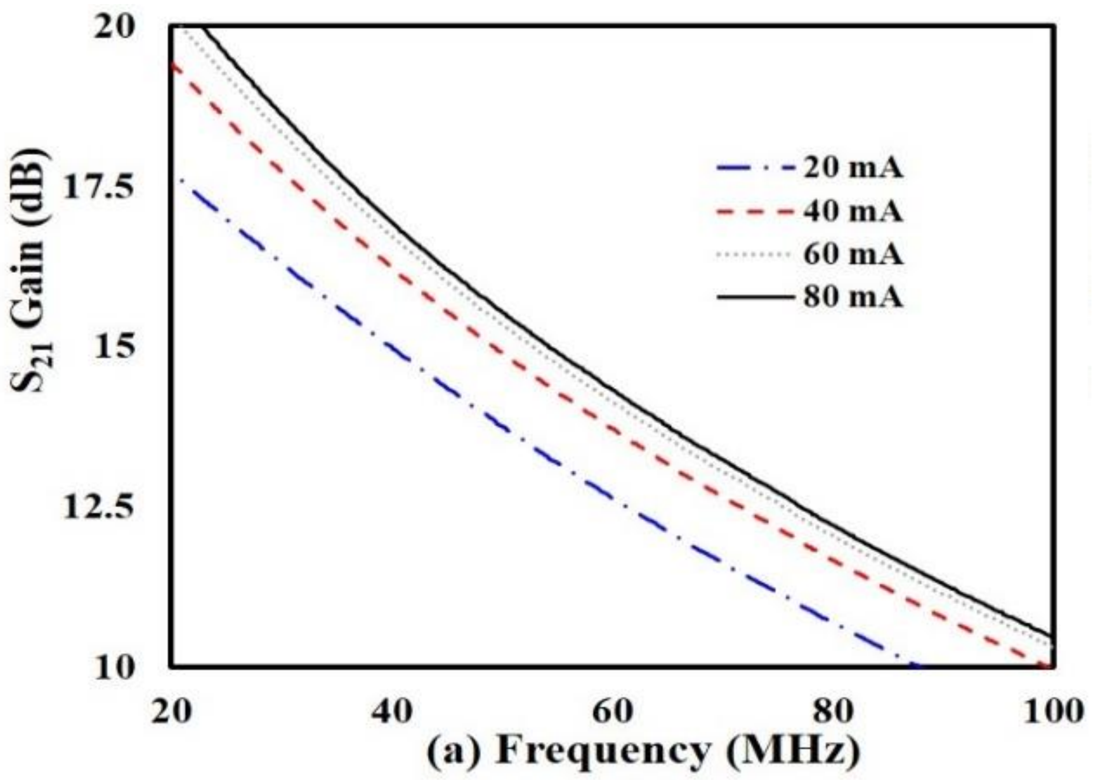


(c) Voltage V_{ds} (V)

RF Measurements

S-parameter, S_{21}, as a Function of Device Bias

S_{21} as a Function of Drain Current (I_{ds})

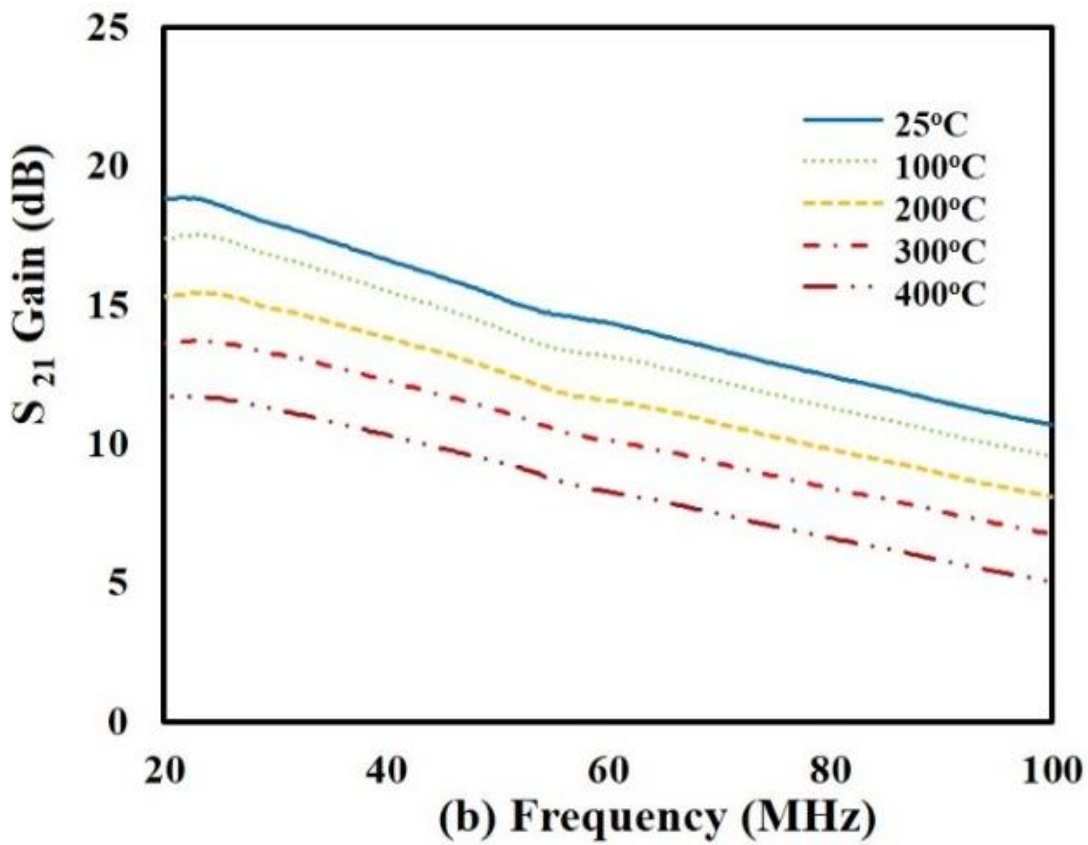


Biasing Goals

- Keep overall power of device as low a possible
- Optimize a drain current, I_{ds}
    - (20 to 40 mA increase 8.75% where 40 to 60 mA increases 2.61% @ 50 MHz)

RF Measurements

S-parameter, S_{21}, from 25°C to 400°C

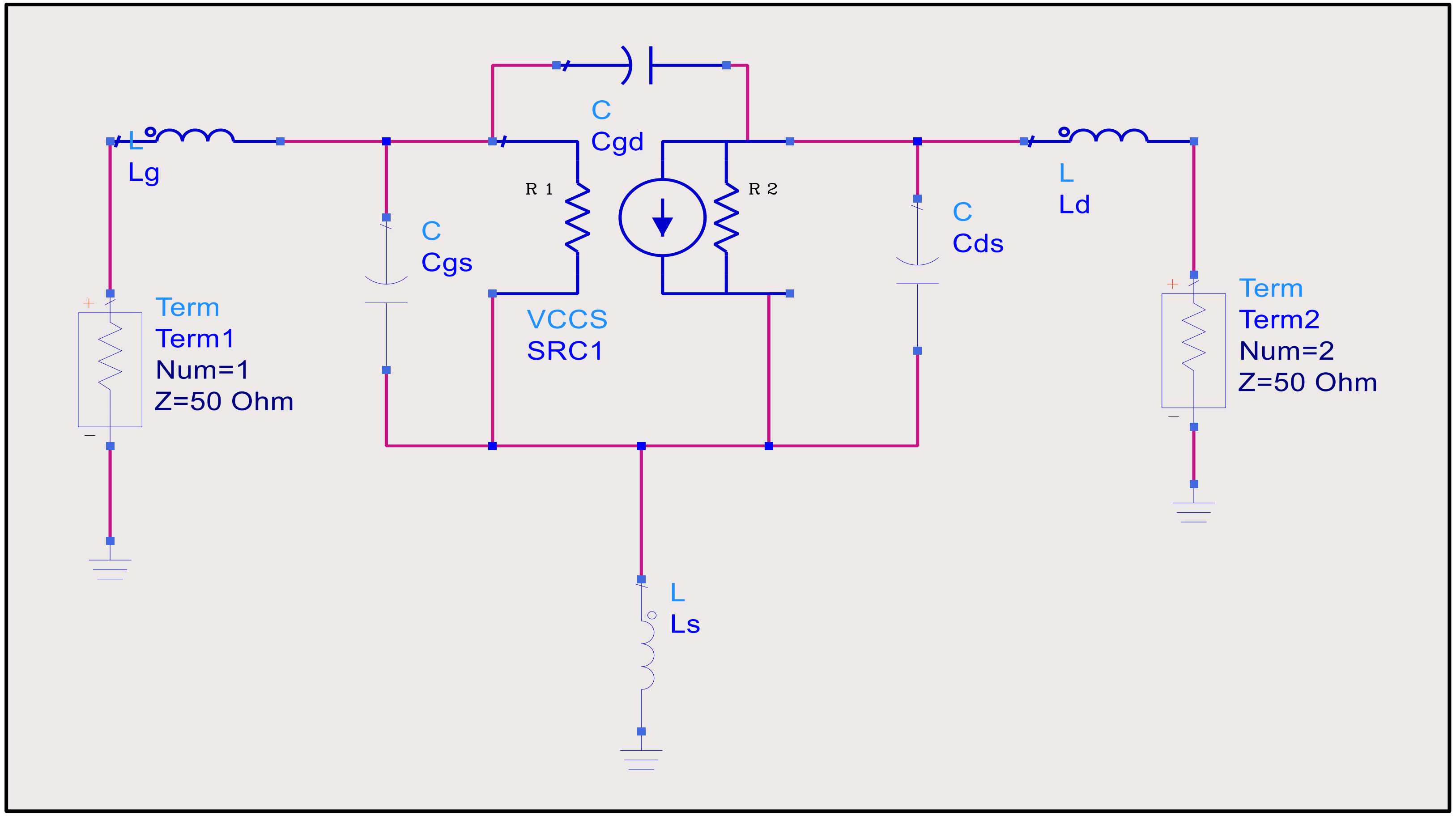


Constant Drain Current, I_{ds}

- Data recorded from 25-400°C:
  - 9.35 dB at 50 MHz which is sufficient for the envisioned wireless sensor applications
- Varied gate voltage, V_{gs}, for constant current at I_{ds} = 40 mA

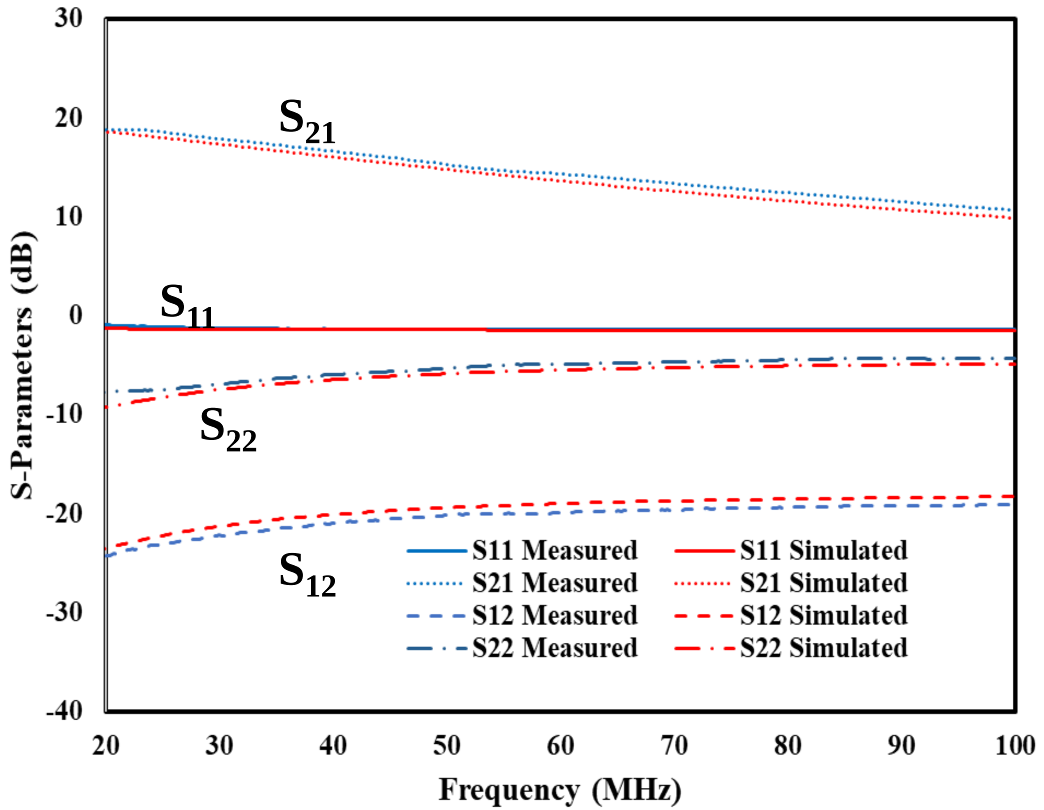
Small Signal Modeling

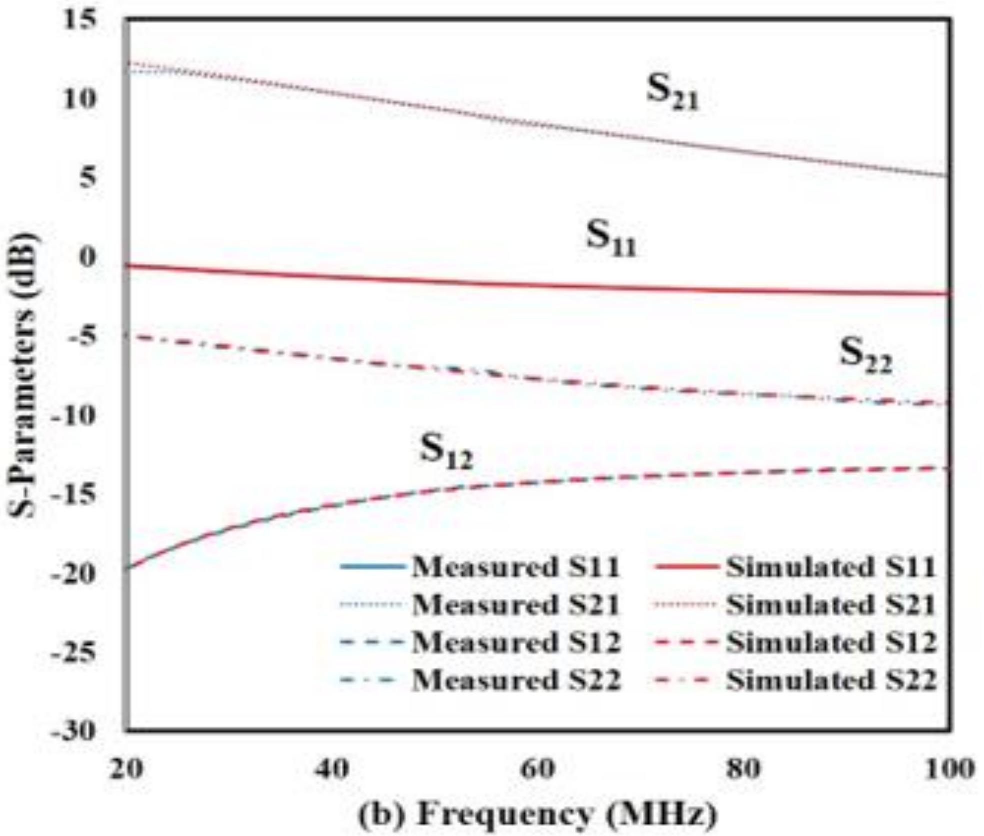
Small Signal Model of SiC Static Induction Transistor



Small Signal Modeling of the SiC SIT

Measured and Modeled S-parameters at 25^{O}C





Measured and Simulated from 20-100 MHz

- S_{21}: 15.28 dB, 14.95 dB (% change of 1.40% at 50 MHz)
- S_{12}: -20.18 dB, -19.41 dB (3.88%)
- S_{11}: -1.422 dB, -1.434 dB (0.84%)
- S_{22}: -5.346 dB, -5.869 dB (9.32%)

Measured and Simulated from 20-100 MHz

- S_{21}: 9.351 dB, 9.354 dB (% change of 0.03 % at 50 MHz)
- S_{12}: -14.74 dB, -14.79 dB (0.33%)
- S_{11}: -1.577 dB, -1.619 dB (2.62%)
- S_{22}: -7.024 dB, -7.128 dB (1.46%)

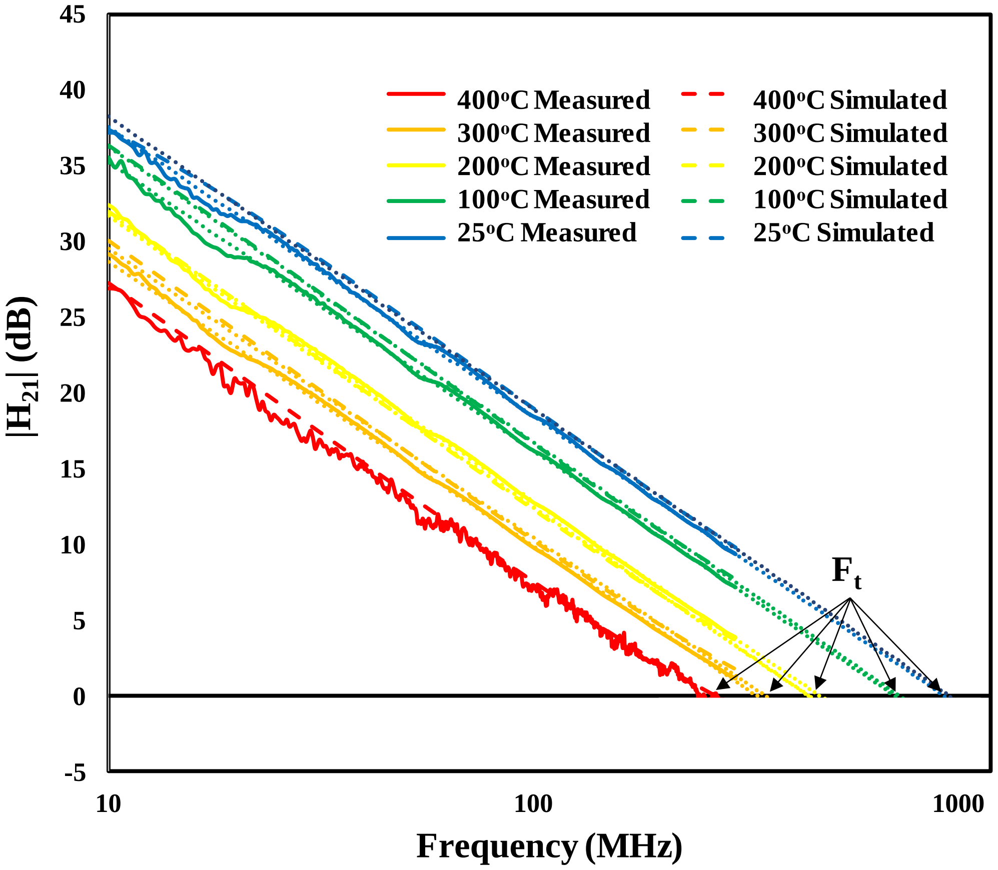
Transition (Cut-Off) Frequency (f_t)

Determination and of transition frequency from three data sources

Details

- Range of Simulated and Measured Data: 20-300 MHz.
- Linear extrapolation used for frequencies above 300 MHz.
- Calculated with expression and compared to modeled and measured values.

$$f_t = \frac{g_m}{2\pi C_{gs} + C_{gd}}$$

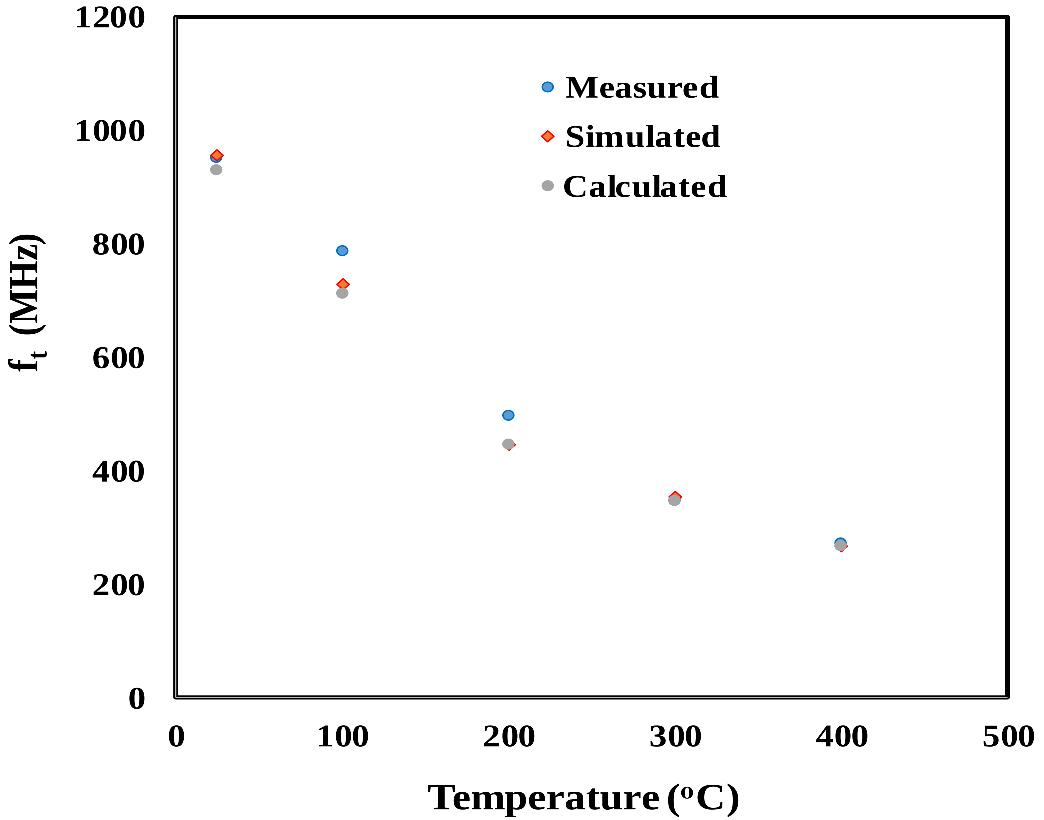


Simulated and Measured Transition Frequencies as a Function of Temperature

Transition (Cut-Off) Frequency (f_t)

Comparison of the transition frequency from three data sources

Simulated, Calculated, and Measured Transition Frequencies from 25°C to 400°C



- Range of Simulated and Measured Data: 20-300 MHz.
- Difference between all transition frequency values at 400°C: 1.8 %
- Largest difference: 10.6% at 200°C

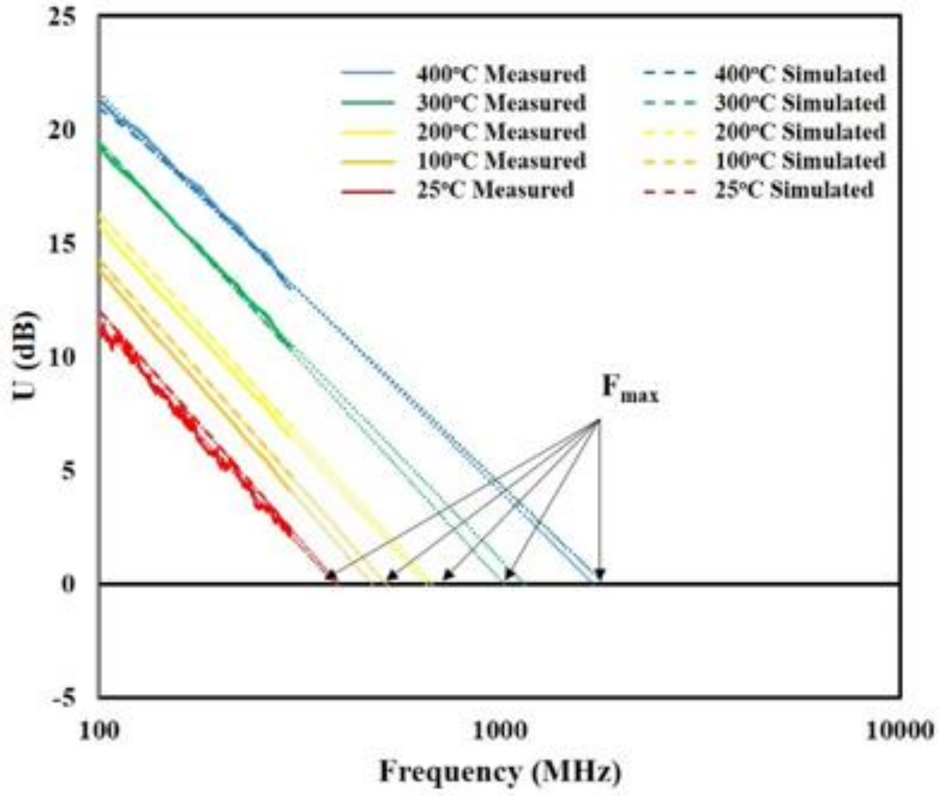
Maximum Frequency (f_{max})

Comparison of the maximum frequency using measured and simulated data

Details

- Range of Simulated and Measured Data: 20-300 MHz.
- Linear extrapolation used for frequencies above 300 MHz.
- Calculated with expression and compared to modeled and measured values.
- At 400°C, the f_{max} from the measured S-parameters is 396 MHz while that from the simulated is 386 MHz, a difference of only 2.5%

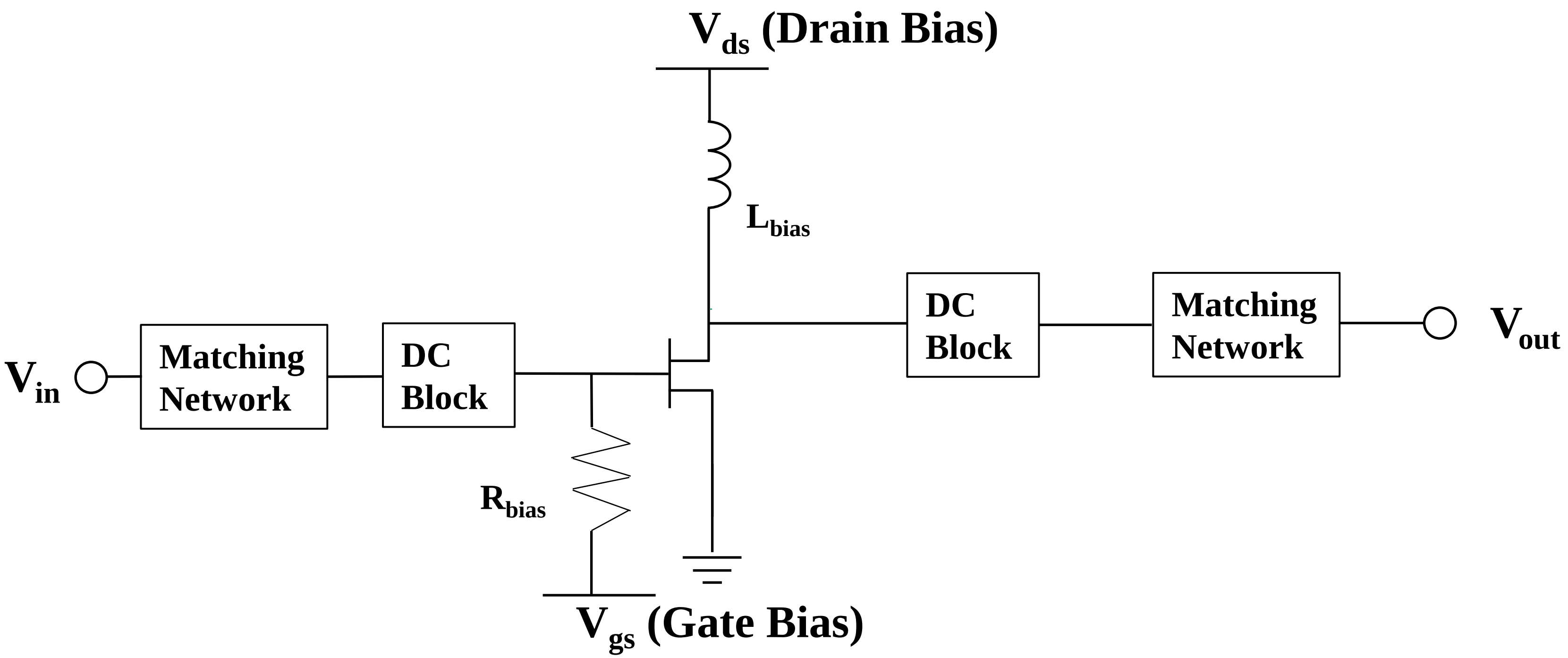
Simulated and Measured F_{max}



This analysis further supports the accuracy of the small signal model of the SiC SIT

Amplifier Design

Class-A Amplifier was selected for this application

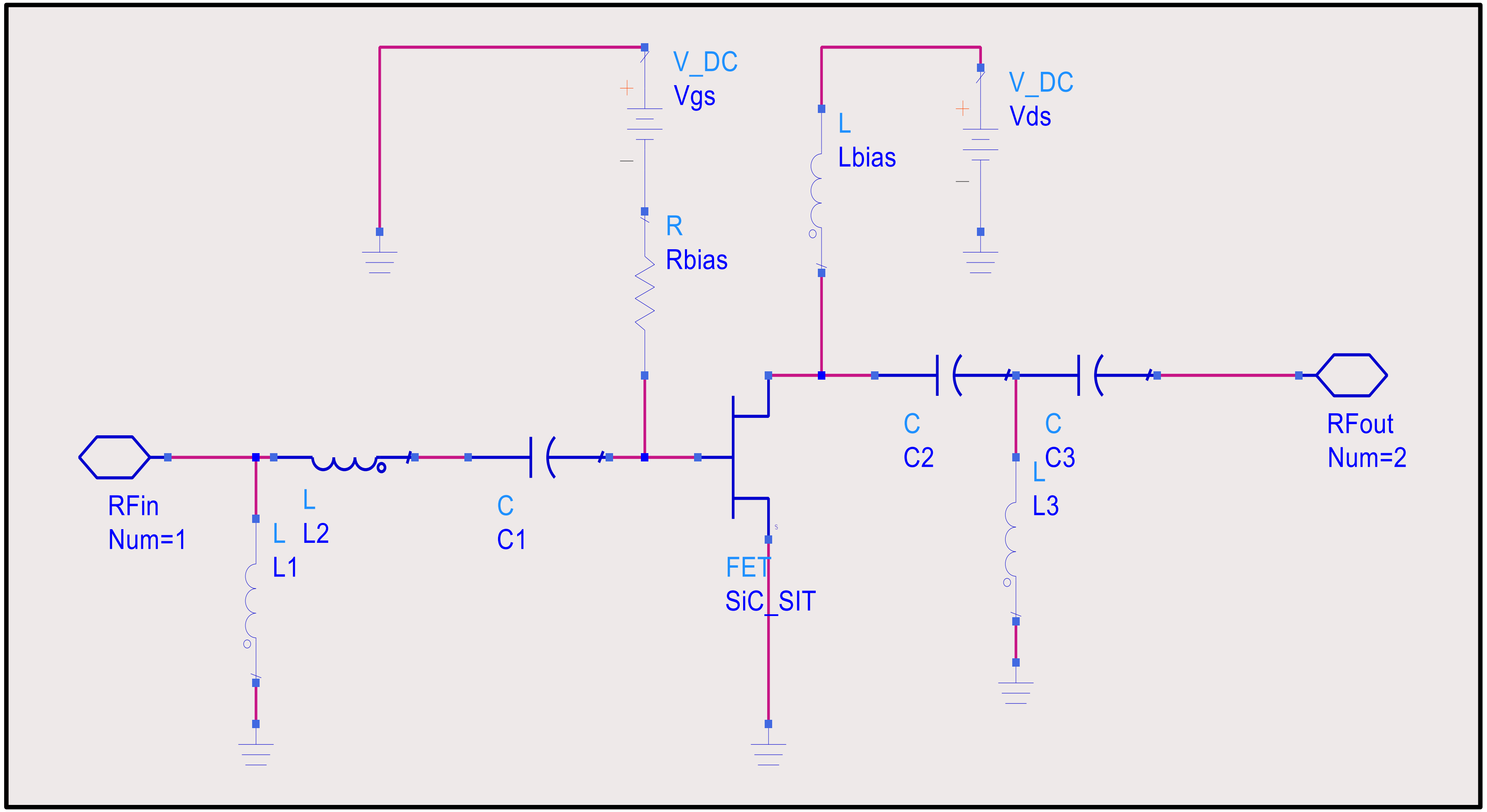


Circuit schematic with matching networks and DC Blocks

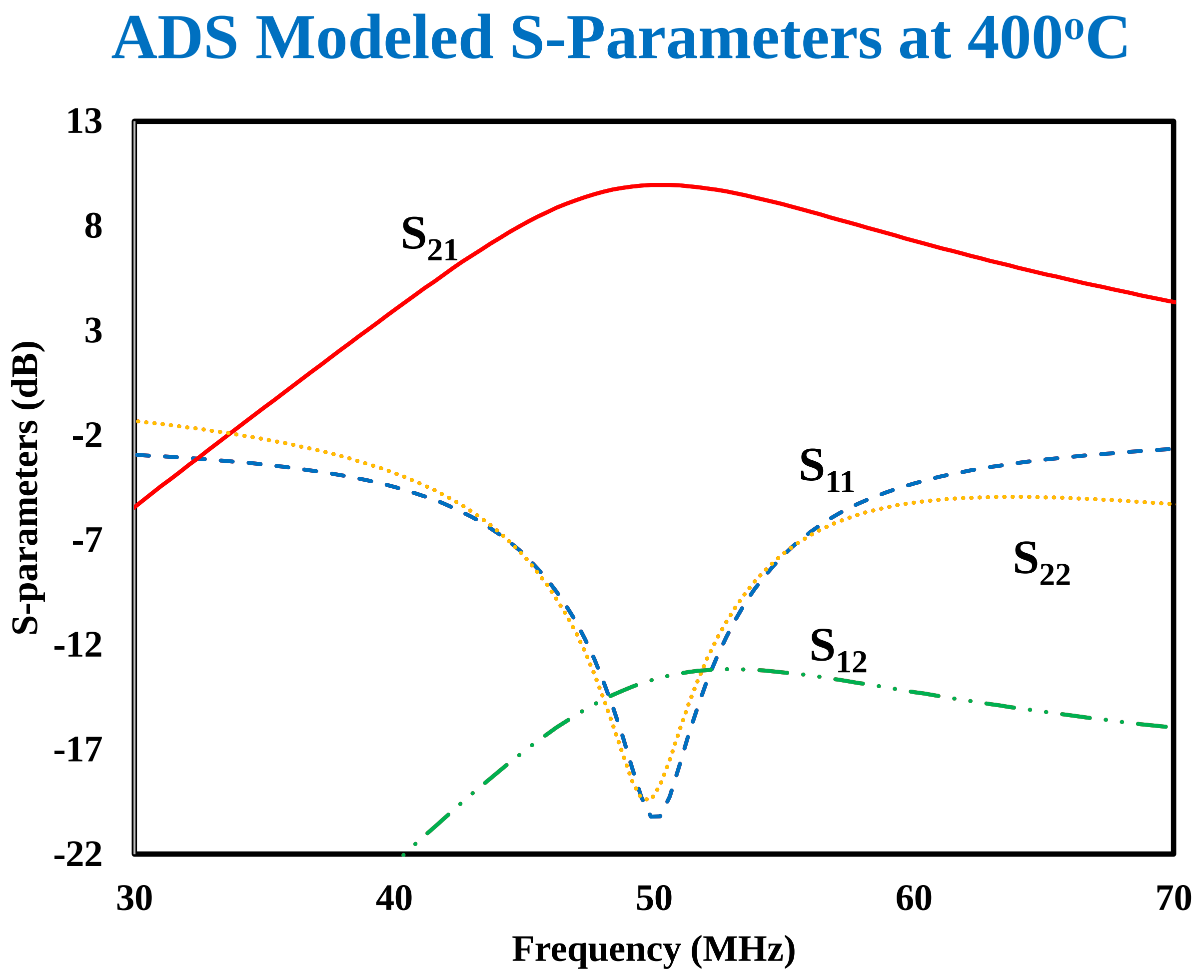
- Simplistic Design – Limiting the number of component failure
- Largest Signal Conduction (360^{O})
- Highest linearity

ADS Amplifier Design

ADS Model for the High Temperature Class-A Amplifier



Modeled Amplifier S-parameters



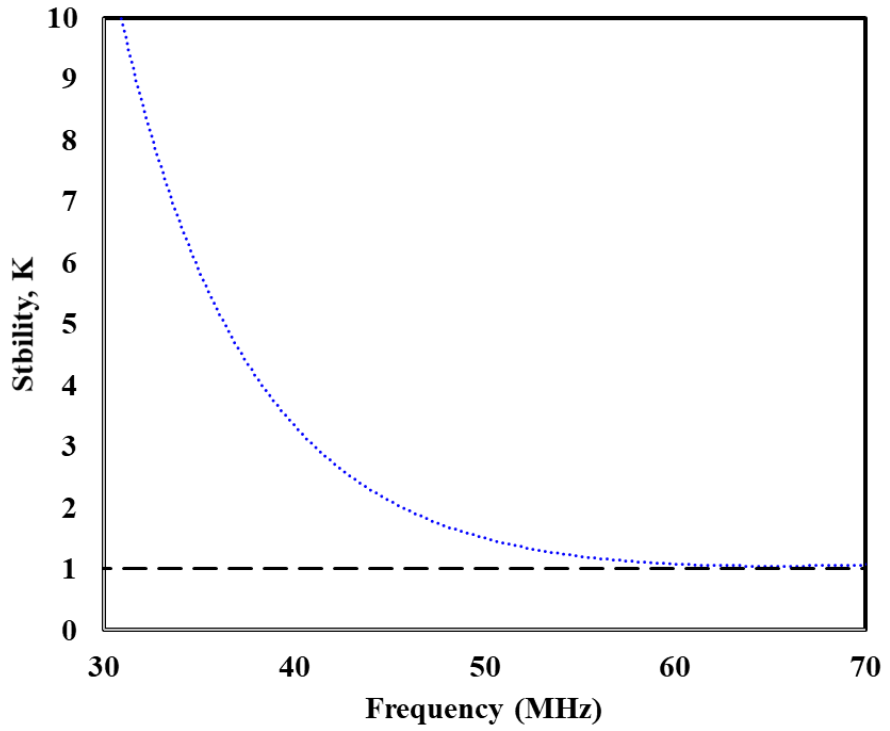
Simulated Data from 30-70 MHz

- **S_{21}: 9.95 dB S_{12}: -13.65 dB S_{11}: -20.1 dB S_{22}: -19.4 dB @ 50 MHz**

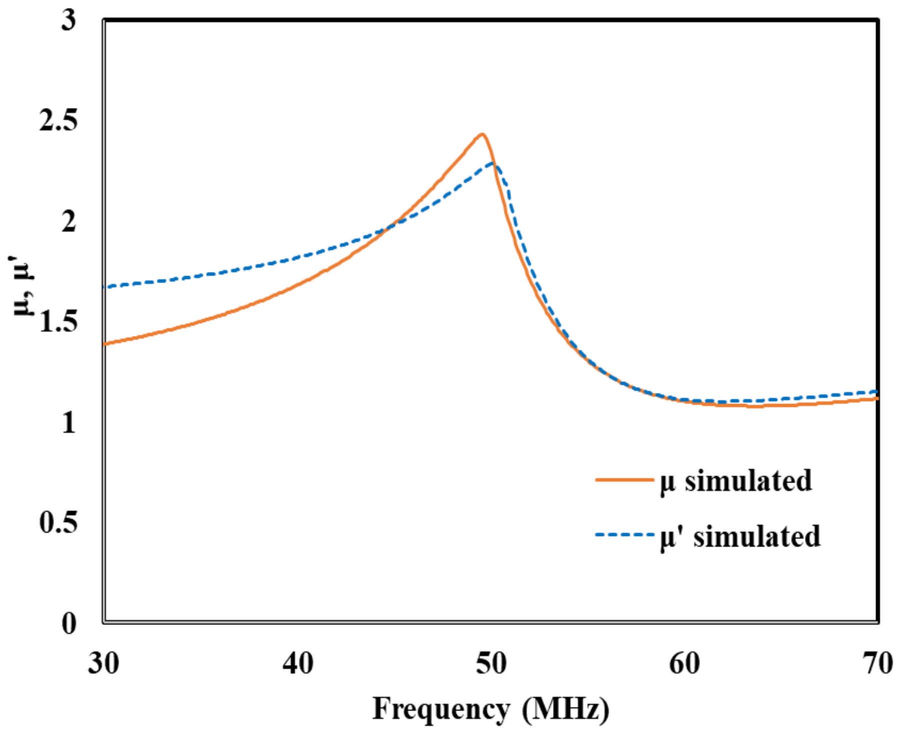
Modeled Amplifier Stability

ADS Modeled Stability for the Amplifier

Simulated K-Factor at 400°C



Simulated μ-Factor at 400°C

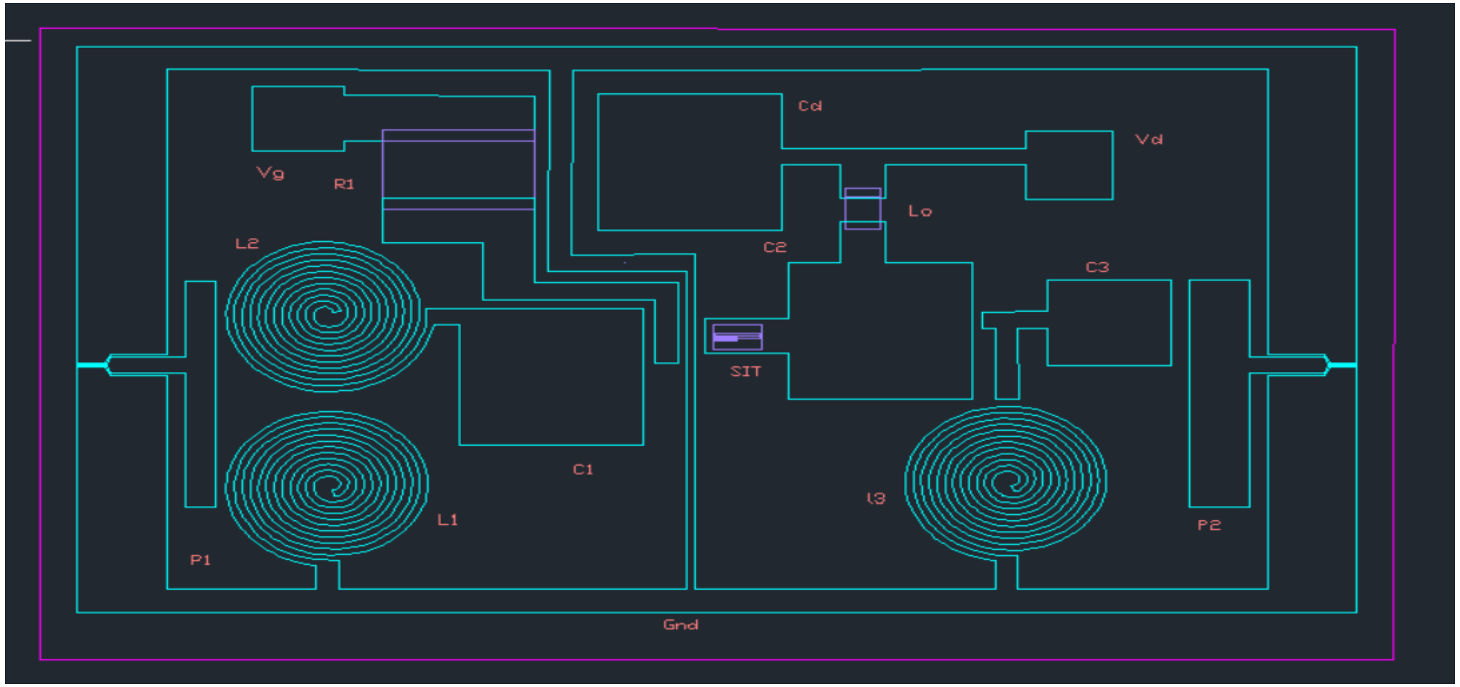


Simulated Data from 30-70 MHz

- K, if greater than 1 at a defined stability = Unconditionally stable
- μ, μ’, if greater than 1, unconditionally stable while providing information about which matching network has a higher stability likelihood

Amplifier Design

SiC SIT-based Class-A Amplifier Layout



CAD Layout

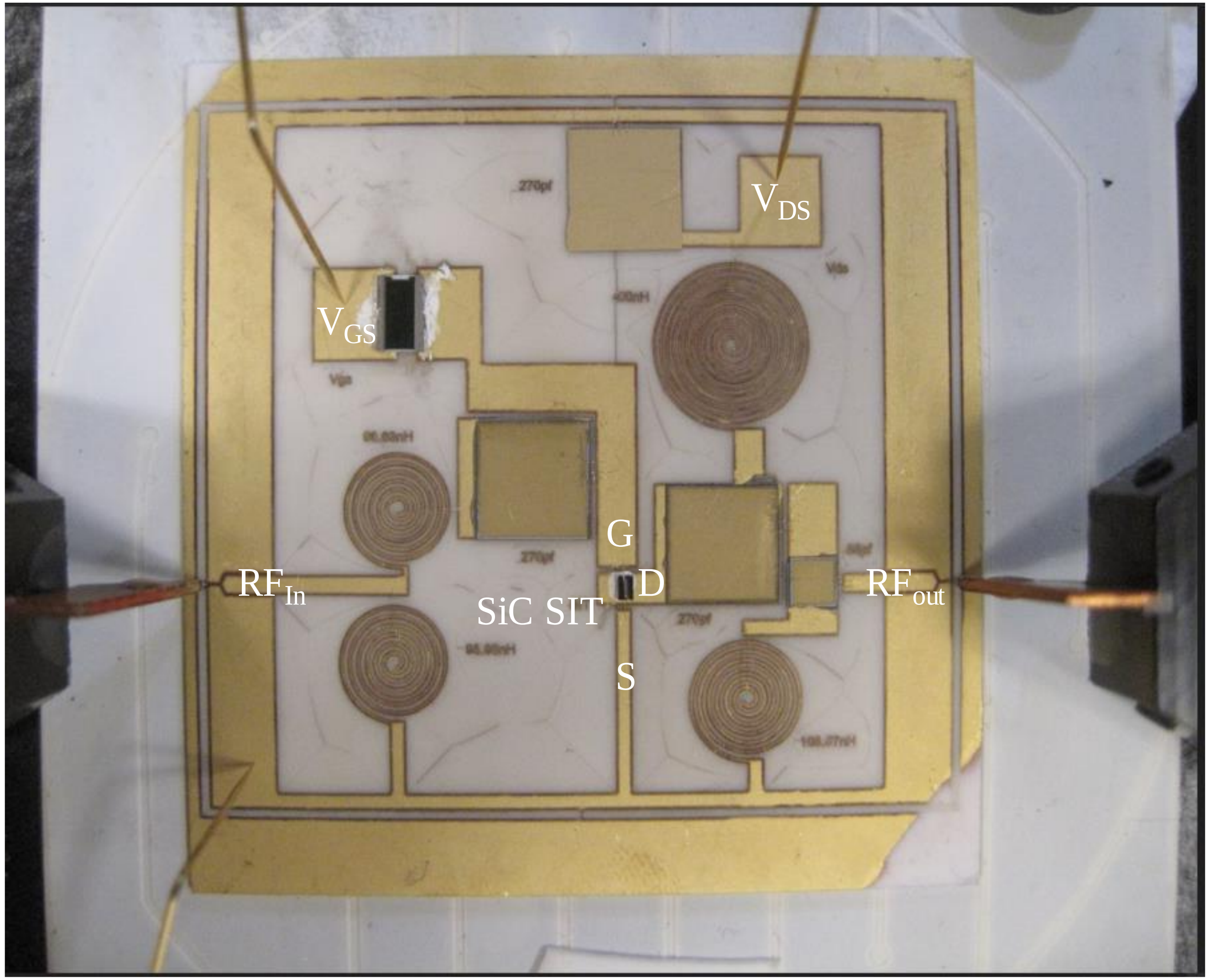
	Value
C_1 (pF)	270
C_2 (pF)	270
C_3 (pF)	50

L_{bias} (nH)	400
L_1 (pH)	96
L_2 (pH)	100
L_3 (nH)	100

R_{bias} (kΩ)	10
R1(Ω)	8.5
R2(Ω)	10.5
R3(Ω)	9.5

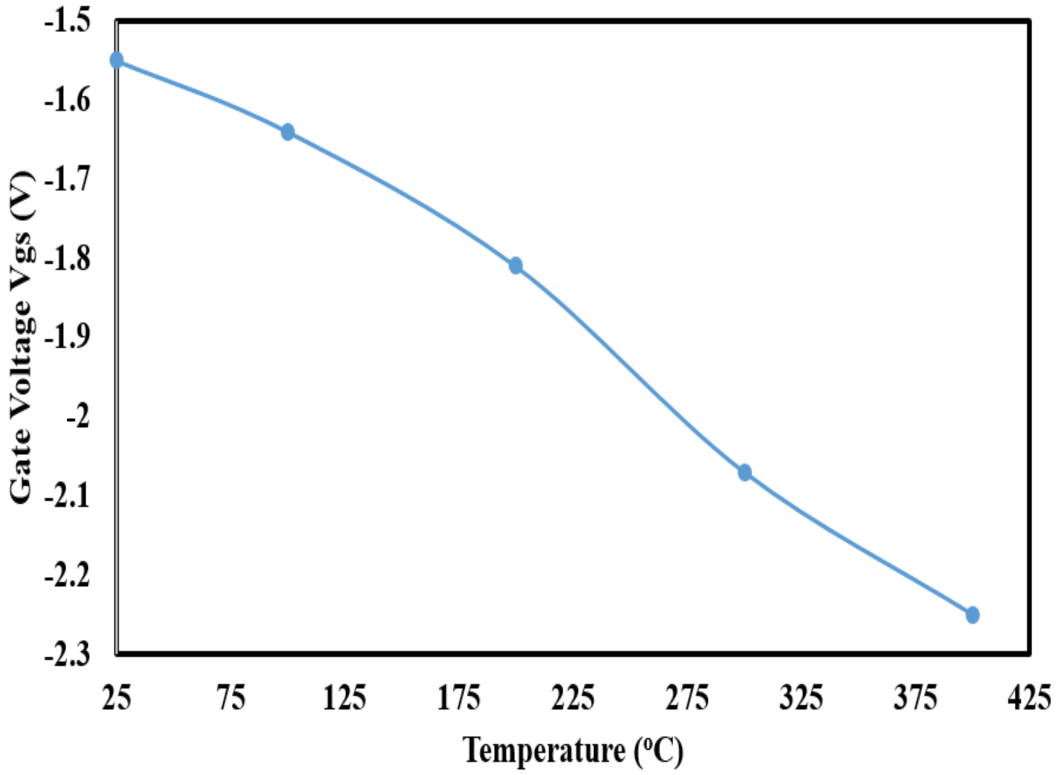
Fabricated Amplifier Design

Photograph of Amplifier on High Temperature Probe Station



Amplifier Biasing

Gate voltage between 25°C and 400°C

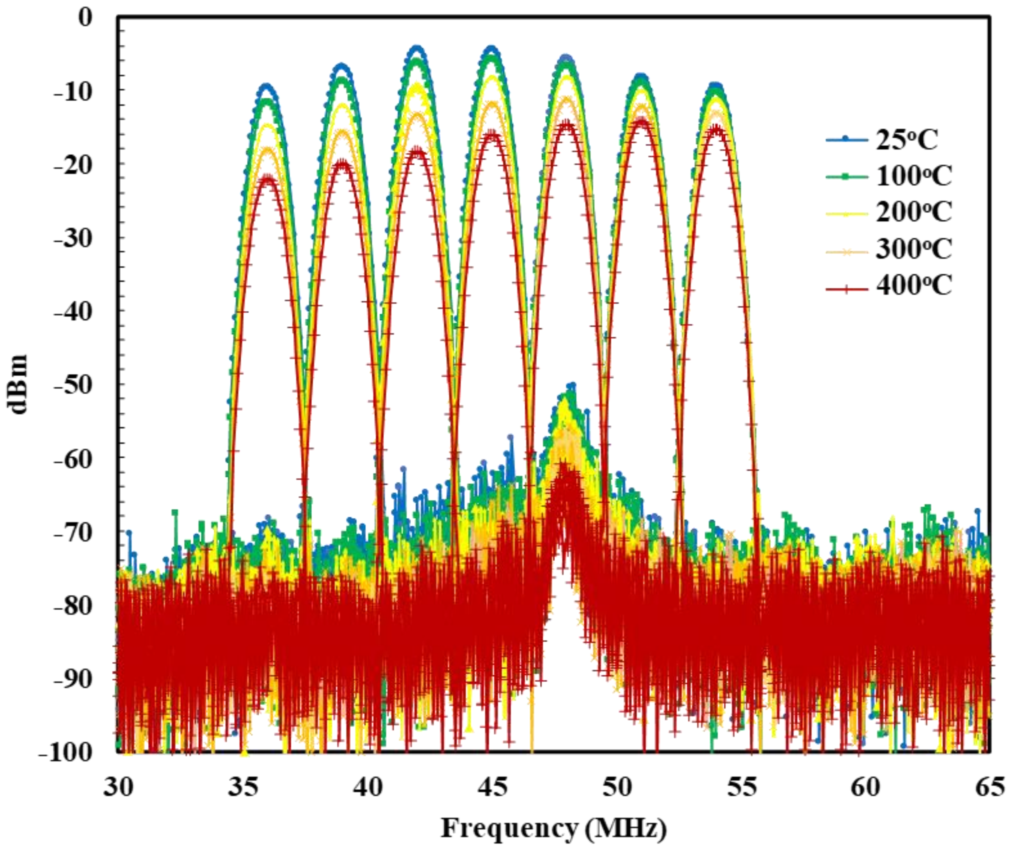


Gate voltage was required to maintain operational current

- **To achieve a constant 40 mA, a variable gate voltage, V_{gs}, was required**
- **Gate voltage decreased from -1.56 V at 25ºC to -2.23 V at 400ºC, a difference of 42%**

Spectrum Power Output

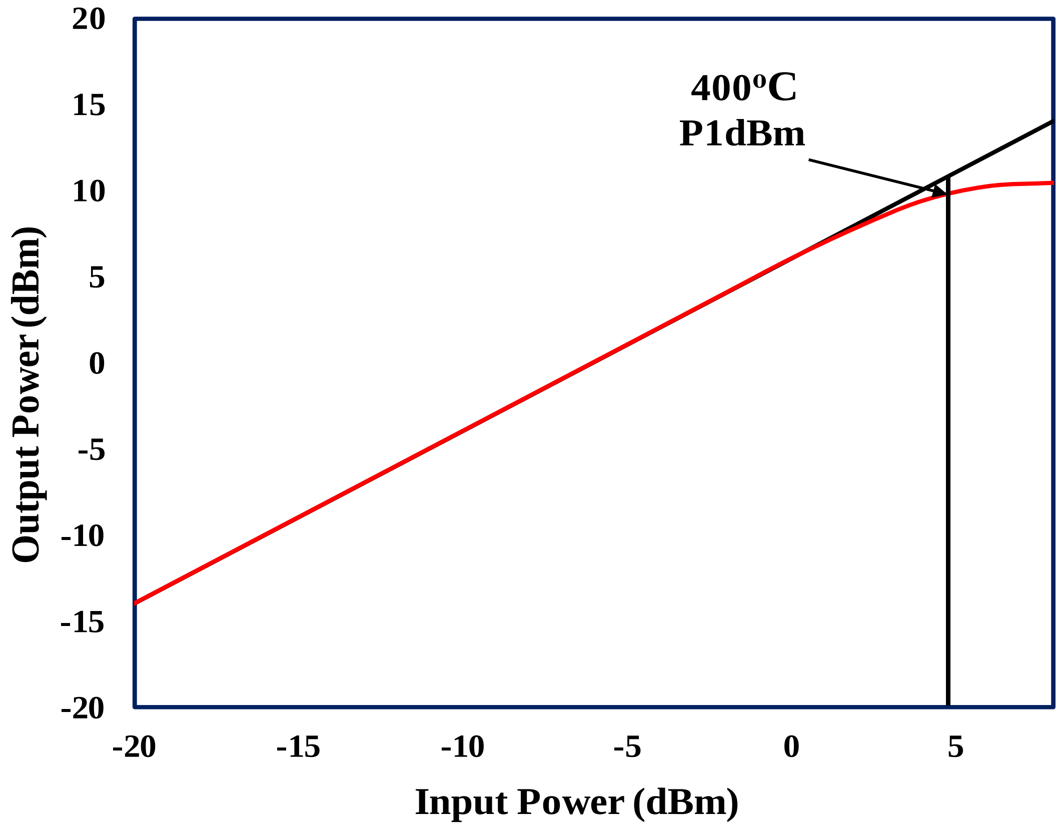
Output power as a function frequency between 25°C and 400°C



- **Measurements made using an E8244A Agilent Series Signal Generator and an Agilent N9020A MXA Signal Analyzer**
- **-20 dBm input at the following frequencies: 36, 39, 42, 45, 48, 51, and 54 MHz**

Linearity and Compression

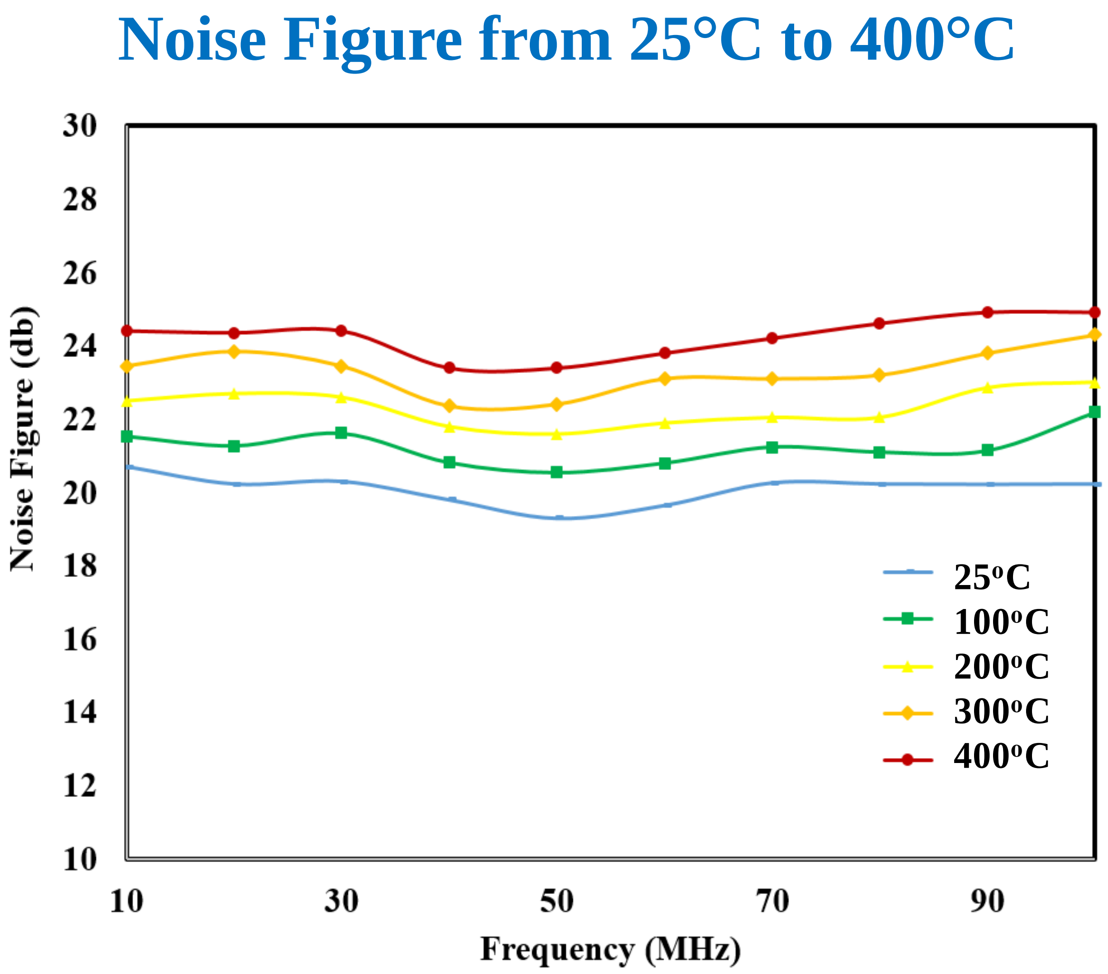
Output power as a function of input power at 400°C



1-dBm compression for device linearity

- Input power swept from -20 to 8 dBm
- Temperature: 400°C
- Good Linearity until 1-dBm compression: ~4 dBm

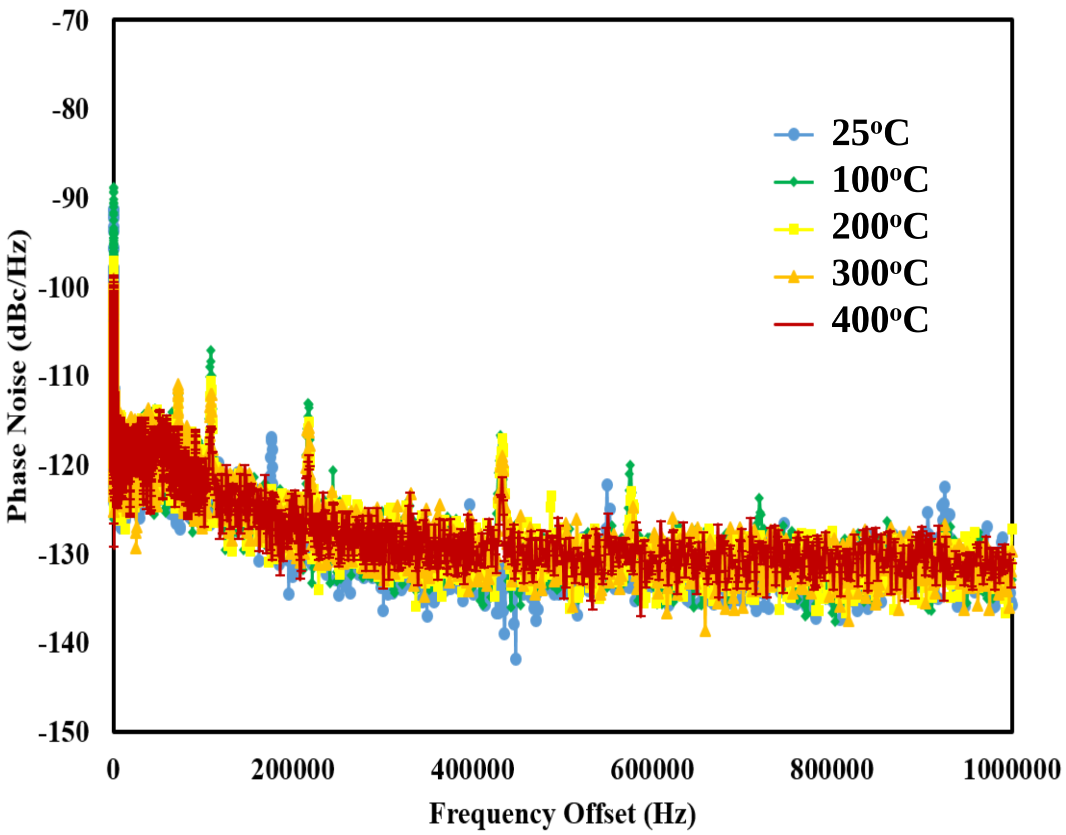
Noise Figure



- Measurements made using an E4448A Agilent spectrum analyzer and a HP 346A Noise Source
- 21.2% increase at an operational frequency of 50 MHz

Phase Noise

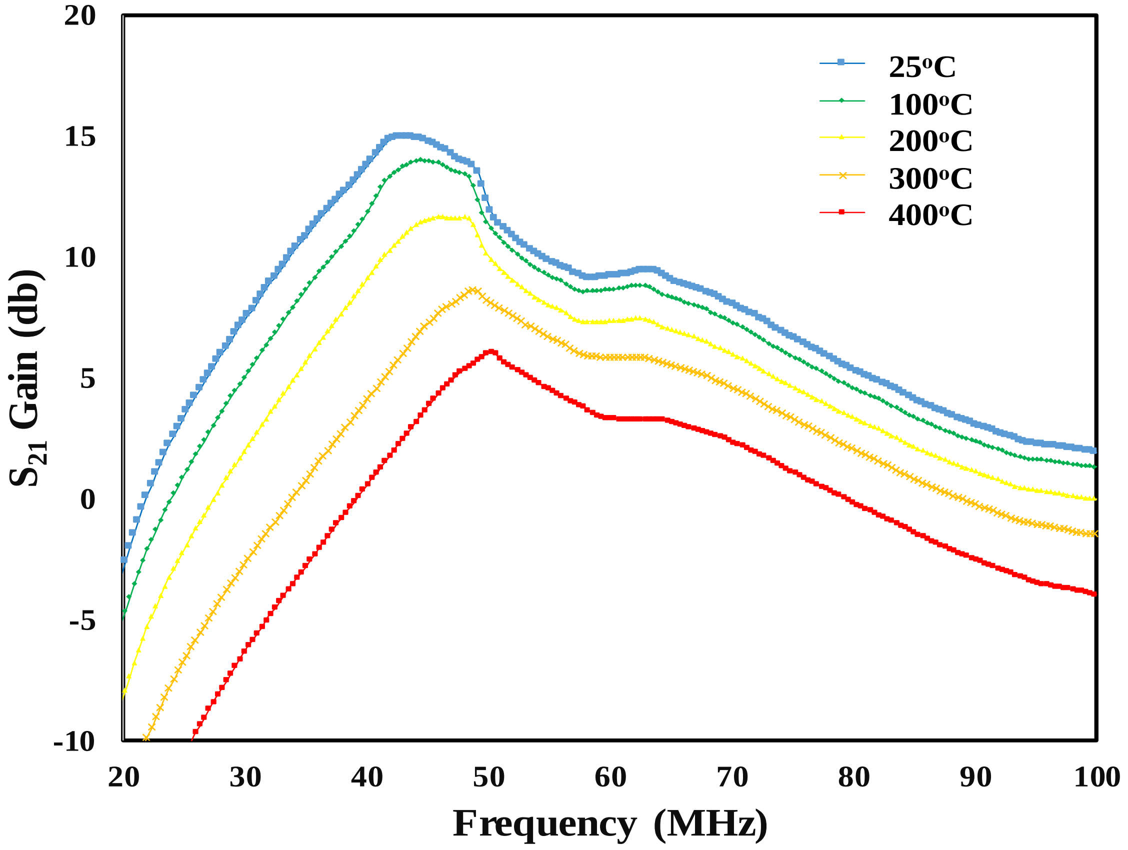
Phase Noise from 25°C to 400°C



- Measurements made using an E8244A Agilent Series Signal Generator and E4448A Agilent Spectrum Analyzer
- 100 kHz offset frequency - input carrier signal was less than -110 dBc/Hz

Amplifier S-parameters and Gain

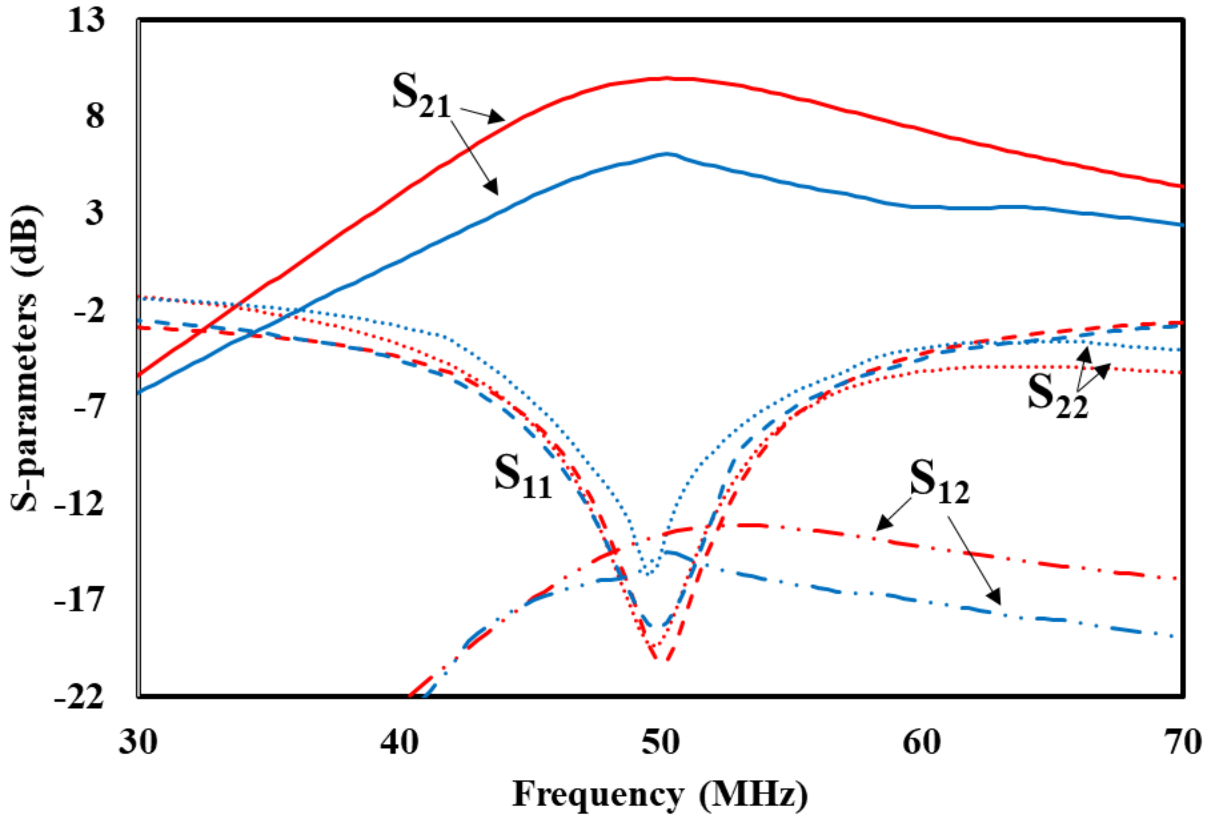
Gain, S_{21}, of the Amplifier from 25°C to 400°C



- **Temperature: 25-400°C**
- **Peak frequency shift is observed attributed to the matching network, loss in transconductance, and decrease in carrier mobility**

Amplifier S-parameters

Measured and Simulated S-Parameters of the Amplifier at 400°C

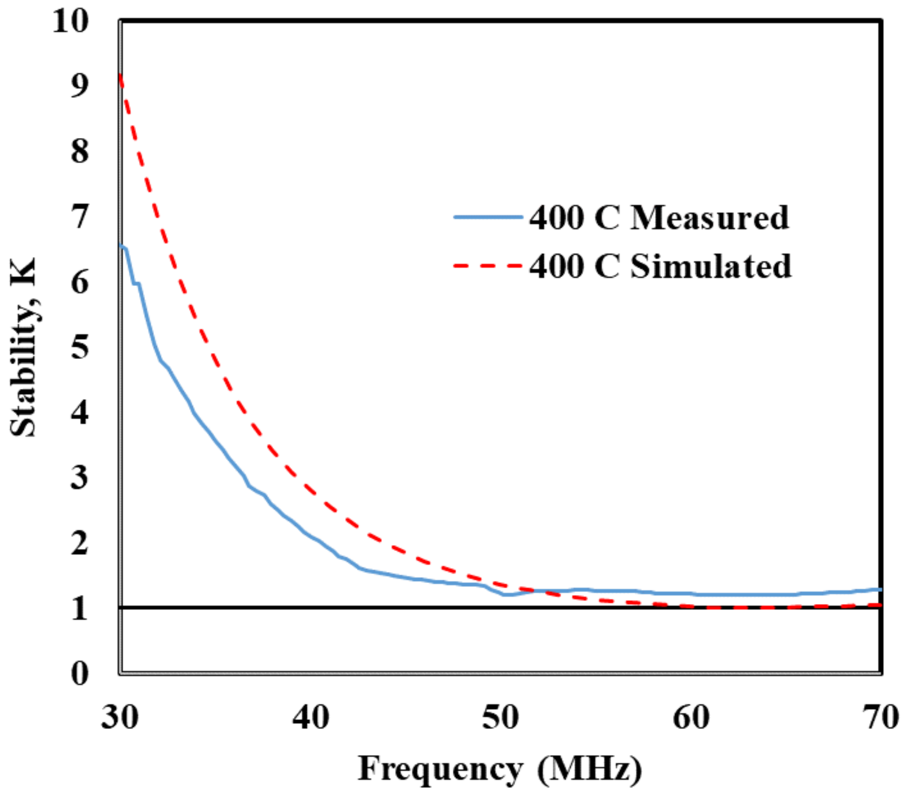


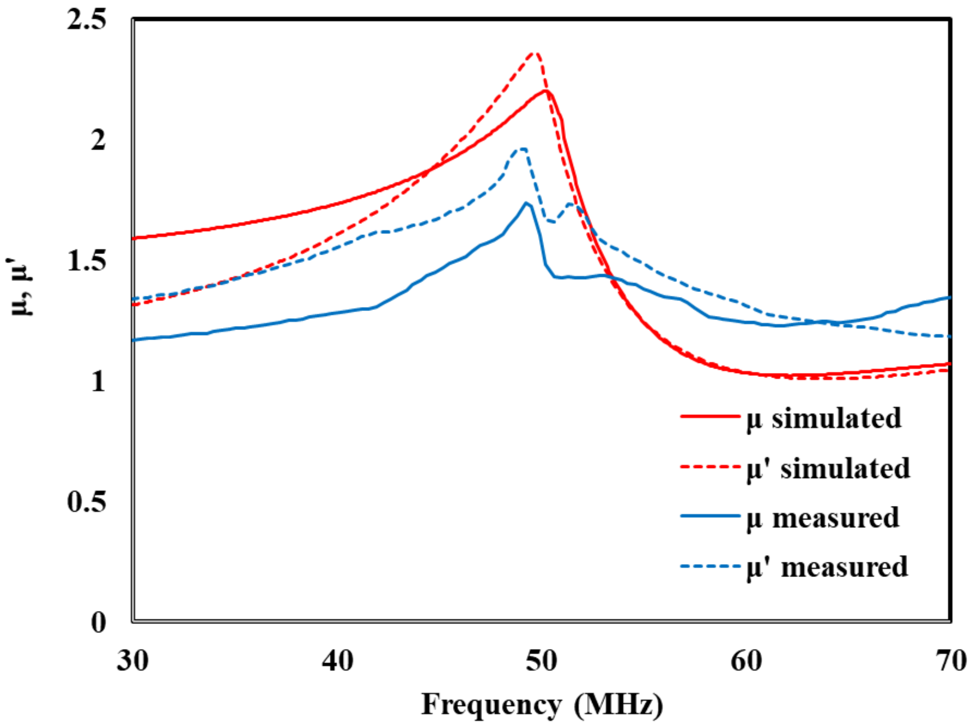
Simulated and Measured from 20-100 MHz

- **S_{21}: 9.95 dB, 6.01 dB (% Loss of 39.5% at 50 MHz)**
- **S_{12}: -13.6 dB, -14.4 dB (5.88%)**
- **S_{11}: -20.1 dB, -18.5 dB (7.96%)**
- **S_{22}: -19.5 dB, -15.2 dB (22.1%)**

Stability

Simulated vs Measured Stability of the Amplifier at 400^{o}C





Data from 30-70 MHz

- K is greater than 1 indicating unconditional stability at the designed frequency
- μ, μ’, if greater than 1, indicating that the system is unconditionally stable

Conclusion

Amplifier Achievements:

- Characterized the SiC SIT at temperatures up to 400^{o}C and frequencies of up to 300 MHz

- Developed a small signal model for the SiC SIT up to 400^{o}C

- Developed suitable high temperature passive components

- Designed a Class-A amplifier for harsh environment wireless application testing

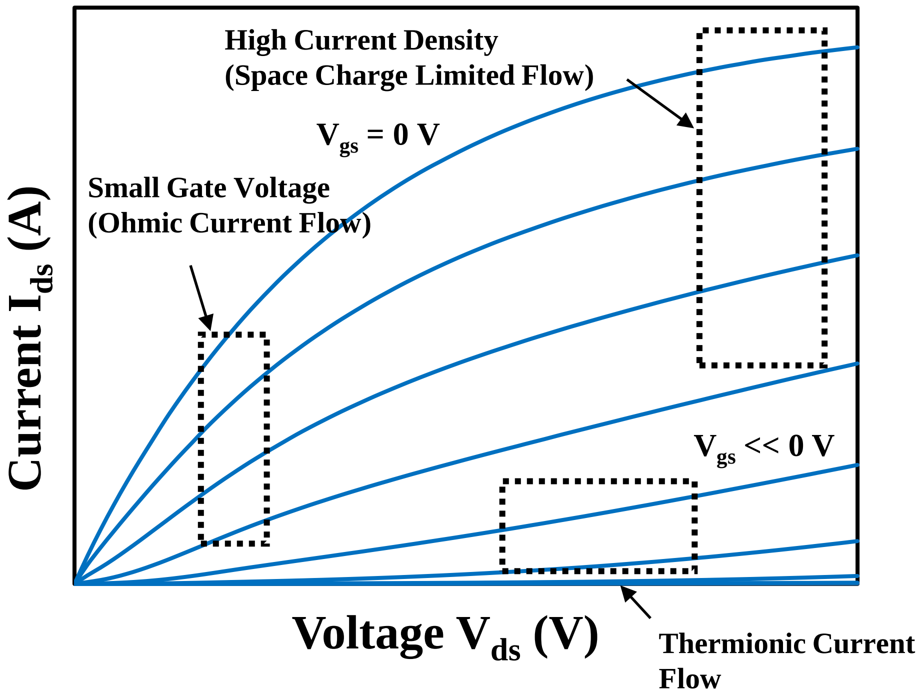
- Fabricated and bench-tested the device and amplifier to test for prototype viability and SiC SIT function

Back-up Slides

Static Induction Transistors

SITs are vertically normally-on devices with 3 conducting modes

Operational Conduction Regimes

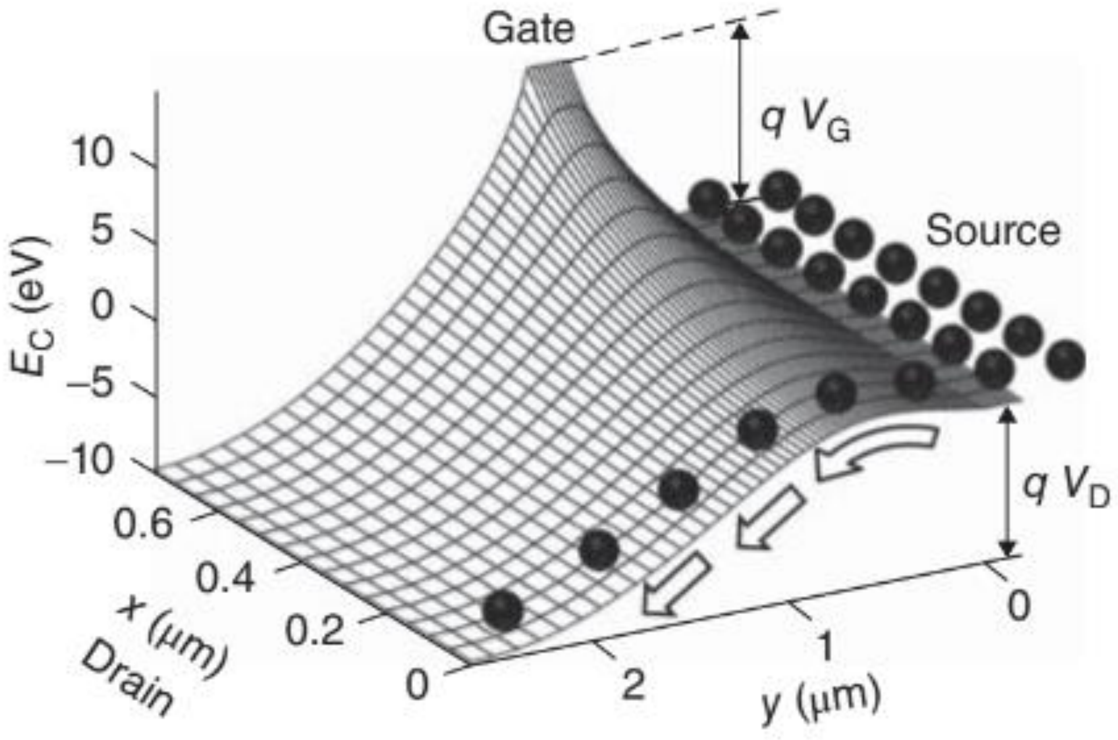


- Gate Length $L_g \ll a$: Current does not saturate like MESFET & JFET
- (1) Ohmic: Channel Open (Gate Controlled)
- (2) Thermionic: Large gate bias - Current increases exponentially as potential barrier is lowered. Drain modulation due to small gate electrode
- (3) Space Charge: electron density in the channel exceeds the doping density, and the electrons drift at their saturated drift velocity

In the SIT geometry, the potential the barrier is modulated by both the gate voltage and the drain voltage

Static Induction Transistors

SITs are Modulated by Both Gate and Drain Bias

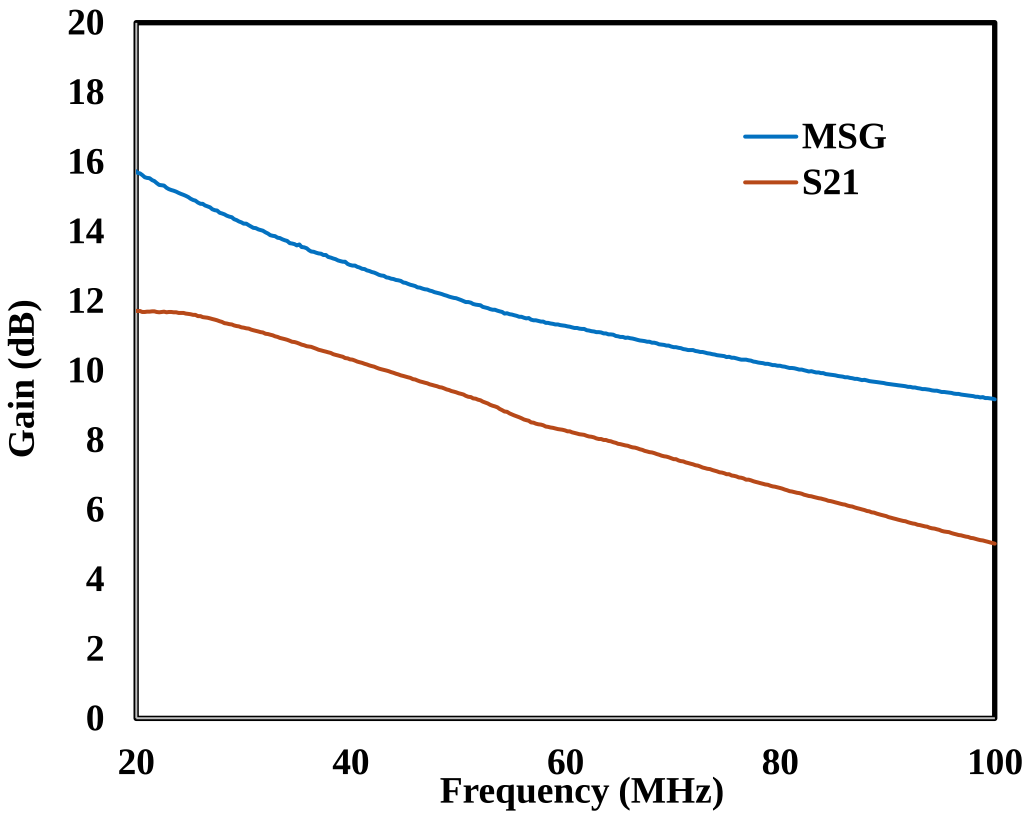


Conduction Band for Half of the Channel of the SiC SIT

RF Measurements

S-parameter, S_{21}, at 400°C and Maximum Stable Gain

MSG and S_{21} of at 400°C as a function of frequency



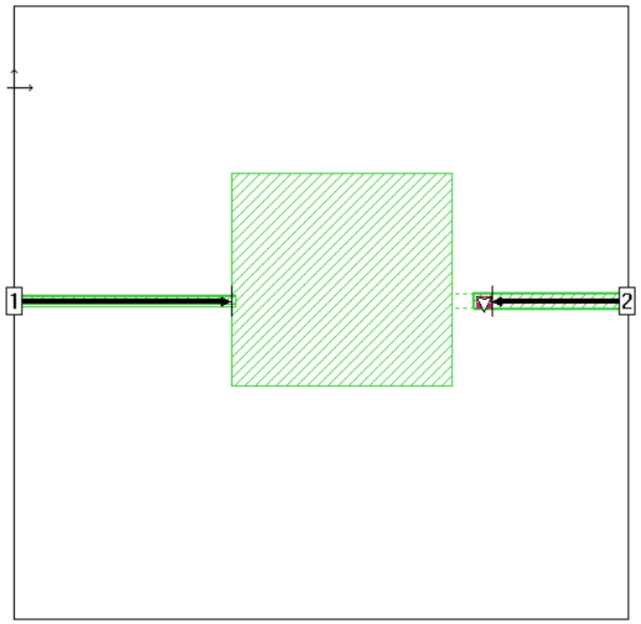
Constant Drain Current, I_{ds}

- 400°C Operational Temperature, MSG = $|S_{21}| / |S_{12}|$
- Constant Current at I_{ds} = 40 mA

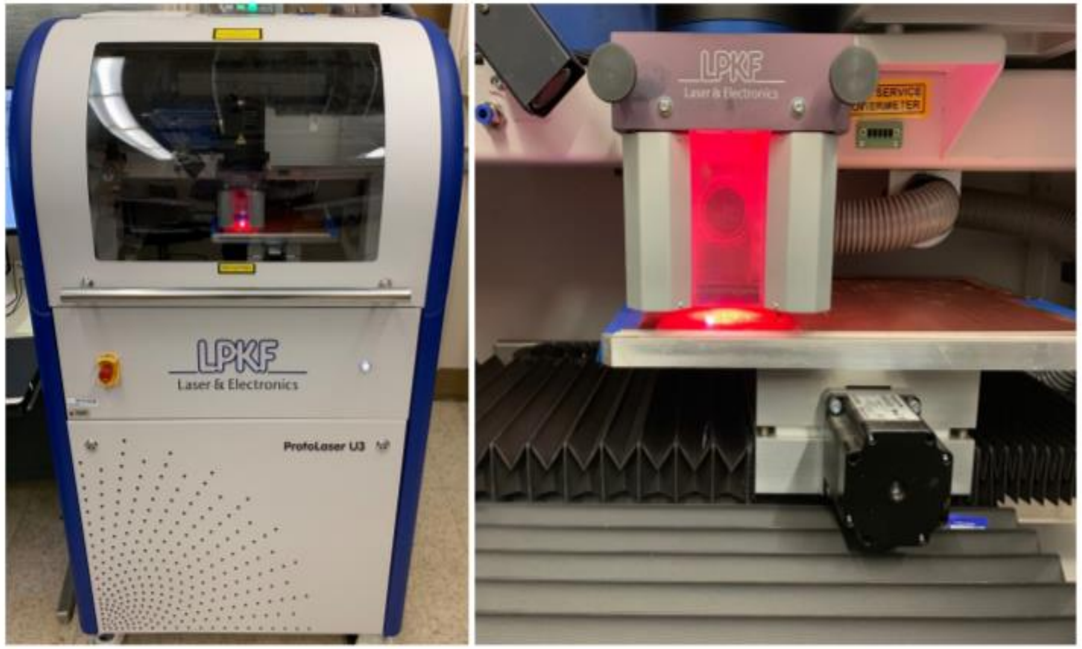
Metal-Insulator-Metal Capacitors

Sonnet EM Computational Software used to design the capacitors

- **Capacitors: design, fabrication and characterization between 25 to 400°C for a frequency range from 1 to 100 MHz.**
- **Used LPKF ProtoLaser U3 for Fabrication.**

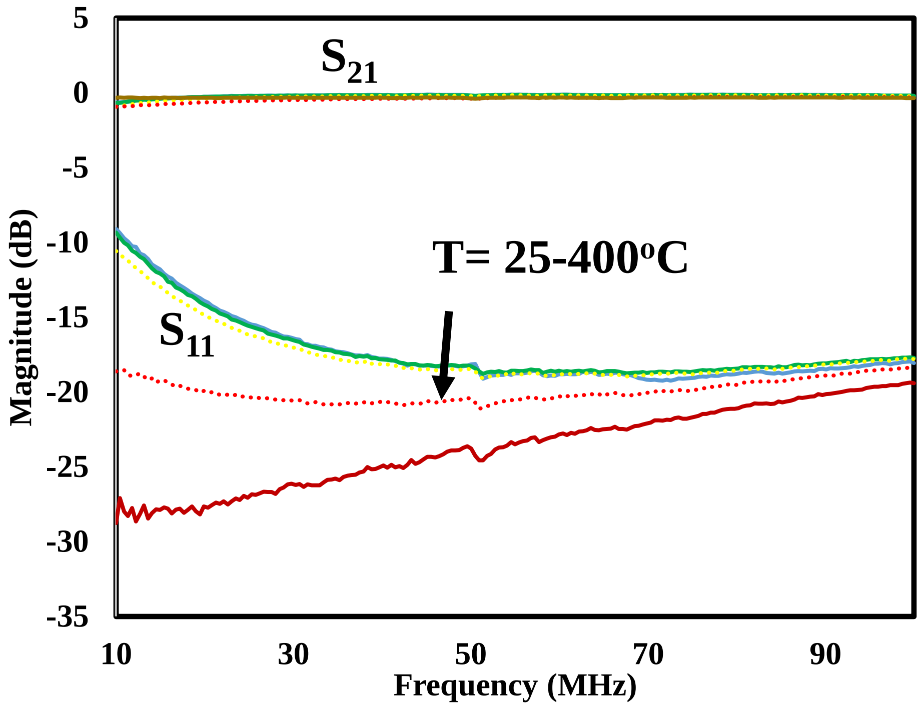


Plan-view of a 200 pF Capacitor

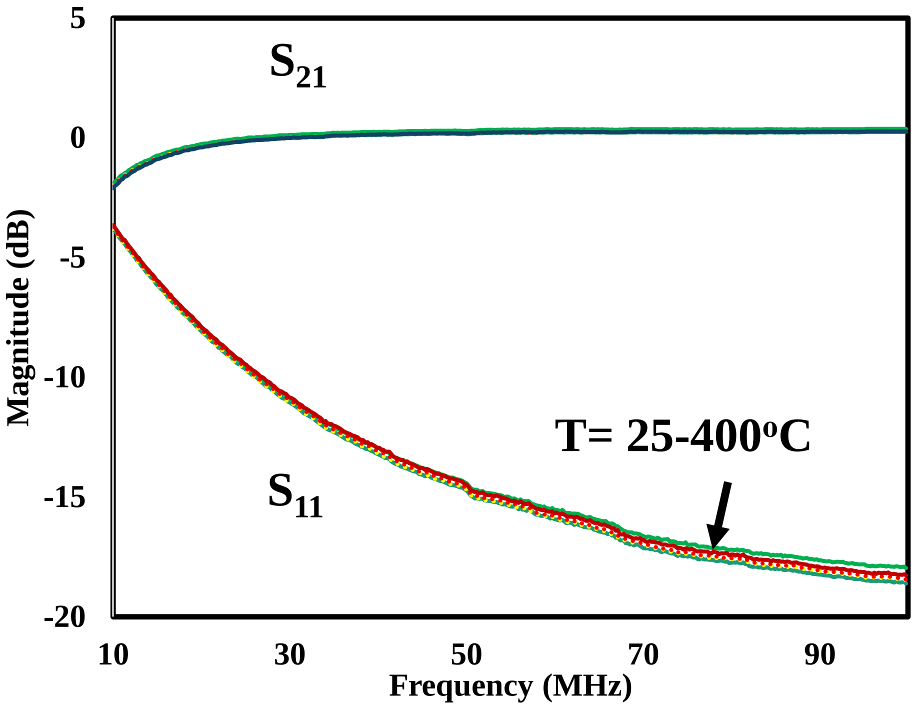


LPKF ProtoLaser U3

Metal-Insulator-Metal Capacitors



Compex MIM Designed 194 pF Capacitor



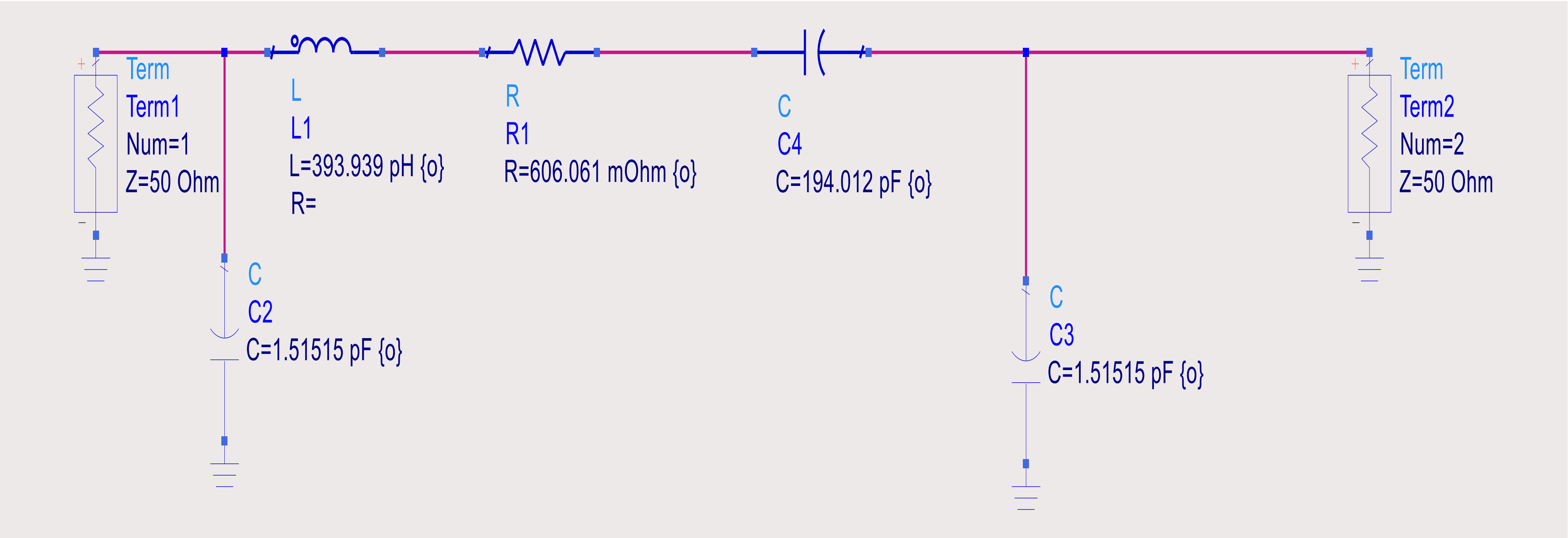
110 Maruwa MIM Designed 194 pF Capacitor

S-parameter Measurements of CPW Dielectric MIM Capacitor Candidates for High Temperature:

- Use LPKF ProtoLaser U3 for Fabrication.
  - Compex MIMs, easy fabrication, but indicate instability
  - Maruwa 110 MIMs are more difficult to machine, but show high stability at temperature

Metal Insulator Metal Capacitor

MIM Capacitor Model



First order lumped element circuit model used for capacitors

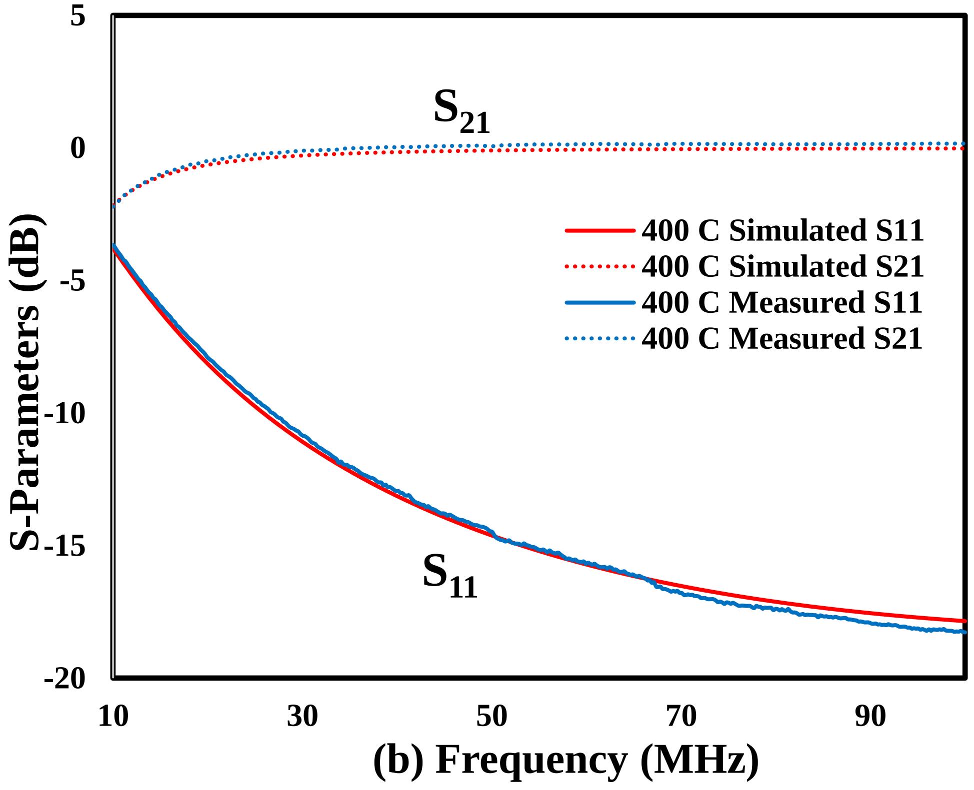
Metal Insulator Metal Capacitor

Measured and simulated S_{11} and S_{21} values at 400°C

Details

- S-parameter of Modeled MIM Capacitor @ 400^{O}C vs Measured
- Modeled 194 pF Capacitor
- Simulated and Measured from 10-100 MHz

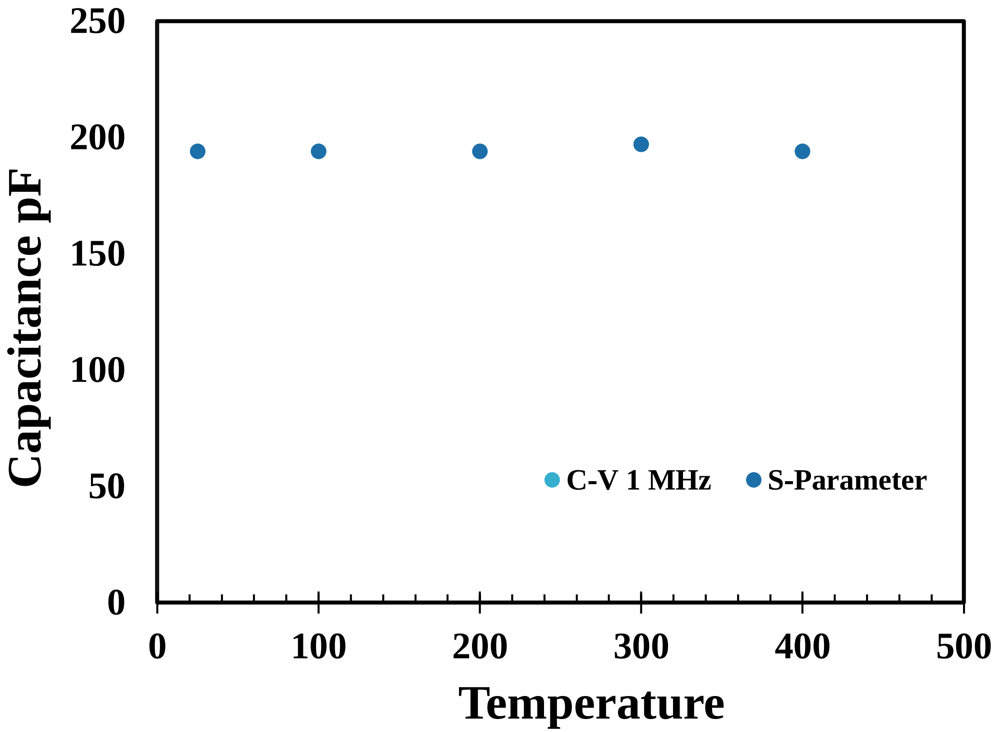
Simulated vs Measured S-Parameters at 400^{o}C



Strong overlap between modeled and measured indicates agreement with expected values

MIM Capacitor Data

Measured C-V vs Modeled Series Capacitance Data



- S-Parameter data seen in the table proves MIM stability for high temperature capacitors from 10-100 MHz
- 5 Samples/measurement for repeatability. (194.5 Avg capacitance at 400^{o}C)

Extrapolated and Measured Capacitance

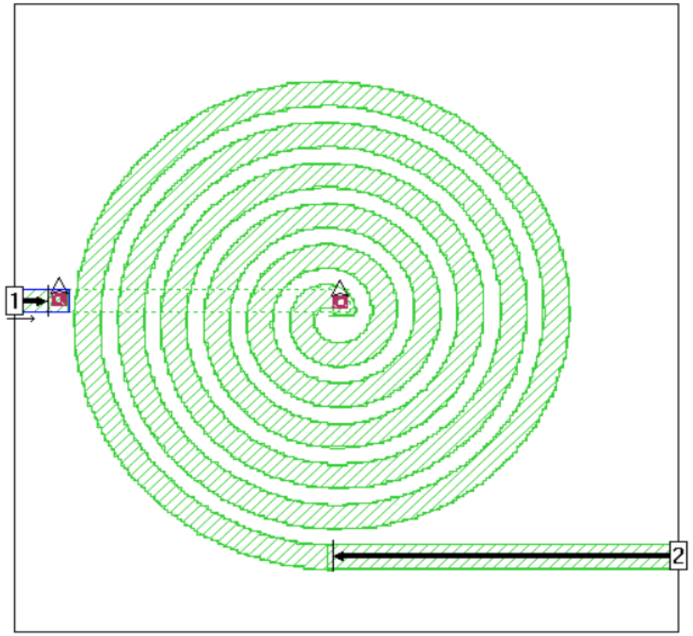
M110 S-Parmater Data	Ls (pH)	Rs (mΩ)	Cs (pF)	Cp1 (pF)	Cp2 (pF)
25^{o}C	393.939	606.061	194.013	1.51515	1.51515
100^{o}C	393.939	666.667	194.156	1.81585	1.81585
200^{o}C	393.939	666.606	194.263	1.81515	1.81515
300^{o}C	393.939	660.601	197.285	1.51515	1.51515
400^{o}C	393.939	660.606	195.152	1.51515	1.51515

Thin Film Spiral Inductors

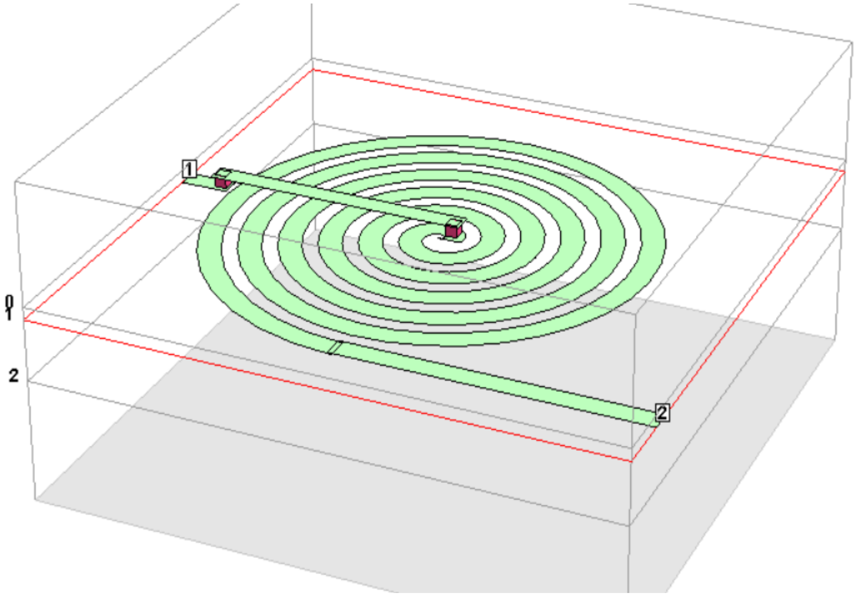
Sonnet used to design the inductors for the matching network

Use LPKF ProtoLaser U3 for Fabrication.

- **Inductors: design, fabrication and characterization over 25 to 400°C and over a frequency range from 10 to 100 MHz.**



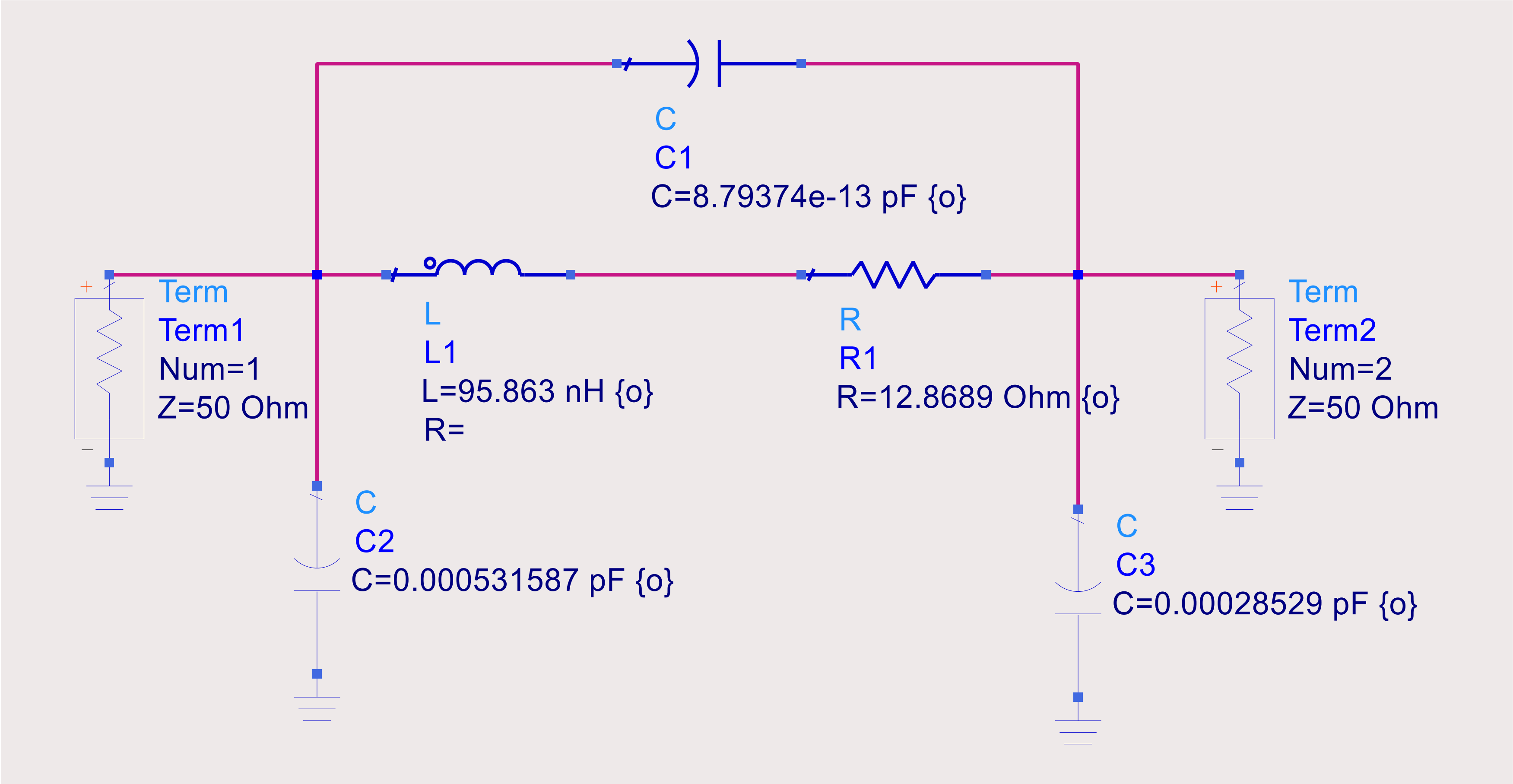
Plan-view of a 94 nH Inductor



3-D Rendering of the 94 nH Inductor

Thin Film Spiral Inductors

Spiral Inductor Model



First order lumped element circuit model used for Inductors

MIM Capacitor Data

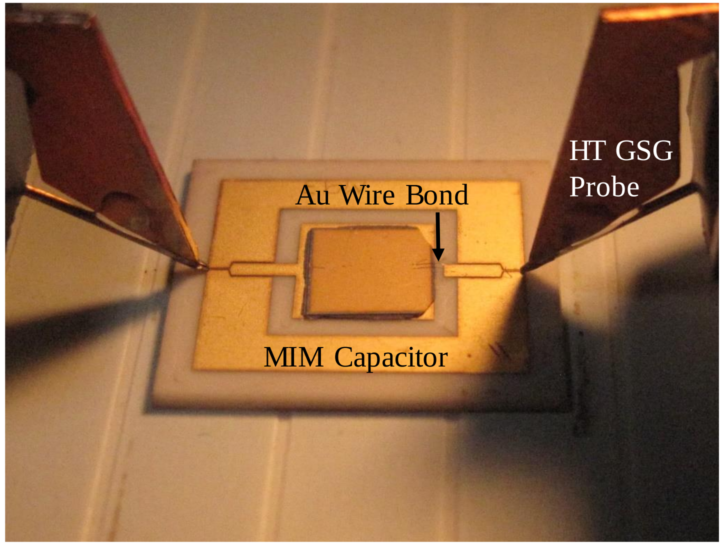
Measured C-V data for Maurwa MIM Capacitors

Temperature	1 MHz C-V (pF)
25°C	99.00
100°C	103.0
200°C	106.0
300°C	102.0
400°C	102.0

Temperature	1 MHz C-V (pF)
25°C	194.0
100°C	194.0
200°C	194.0
300°C	197.0
400°C	197.0

Measured C-V Capacitance

- ✓ 1 MHz DC C-V Measurement using B1505A Power Analyzer
- ✓ 96.06 pF designed MIM Capacitor
- ✓ 194.01 pF designed MIM Capacitor



MIM Capacitor with RF probes

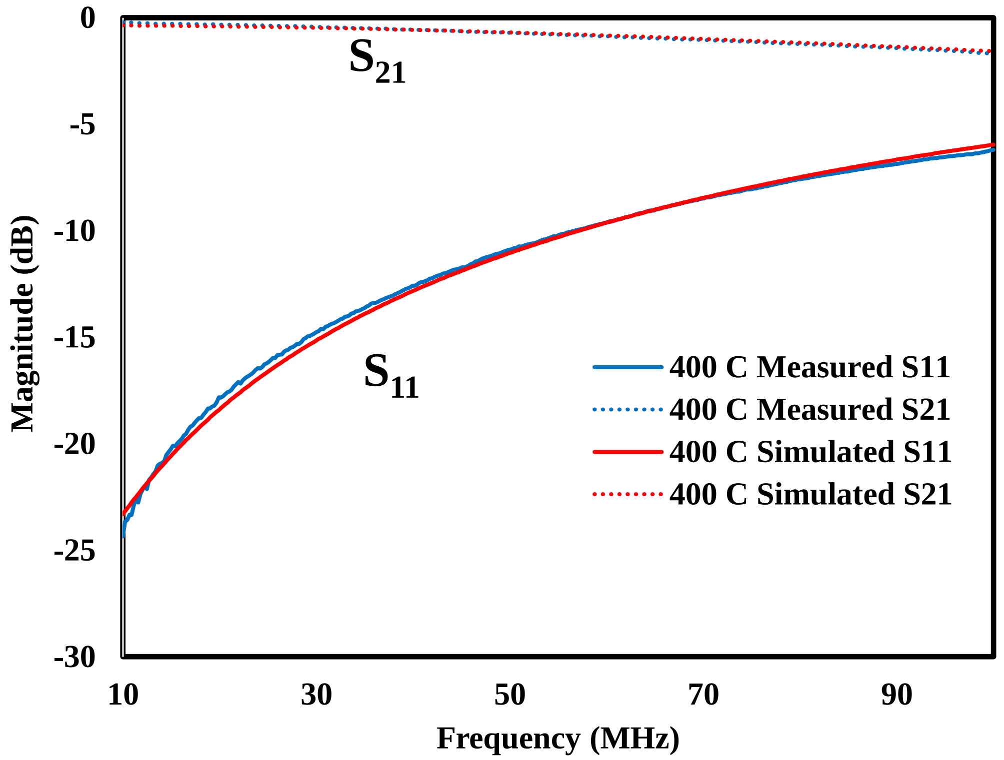
Thin Film Spiral Inductors

Inductor Modeling at 400°C

Details

- S-parameter of Modeled Thin Film Spiral Inductor @ 400^{O}C vs Measured.
- Modeled 94 nH Thin Film Spiral Inductor.
- Simulated and Measured from 10-100 MHz.

Simulated vs Measured S-Parameters



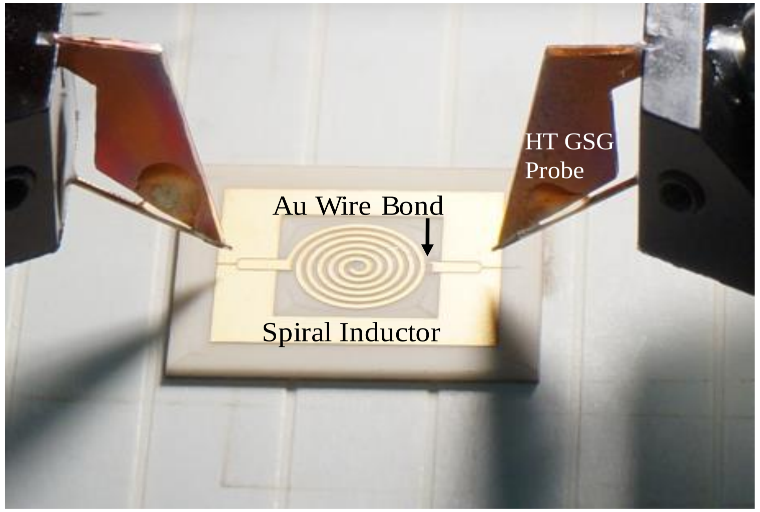
Strong overlap between modeled and measured indicates agreement for designed values

Thin Film Spiral Inductors

Inductor Modeling Results From 25°C to 400°C

Listed lumped elements from 25 to 400^{O}C.

- **Simulated and Measured from 10-100 MHz.**
- **1.8% Increase in Inductance.**
- **3 Samples/measurement for repeatability (94.7 nH)**



Spiral Inductor with RF probes

M110 S-Parmater Data	Ls (pH)	Rs (mOhm)	Cs (pF)	Cp1 (fF)	Cp2 (fF)
25^{o}C	94.171	3.7373	0.8793	0.5318	0.2853
100^{o}C	94.223	4.5632	0.8793	0.5318	0.2853
200^{o}C	94.556	6.1435	0.8793	0.5318	0.2853
300^{o}C	95.112	9.5489	0.8793	0.5318	0.2853
400^{o}C	95.863	12.838	0.8793	0.5318	0.2853

Thick Film Resistors

Thick Film Resistor Measurements

Resistance as a function of Temperature

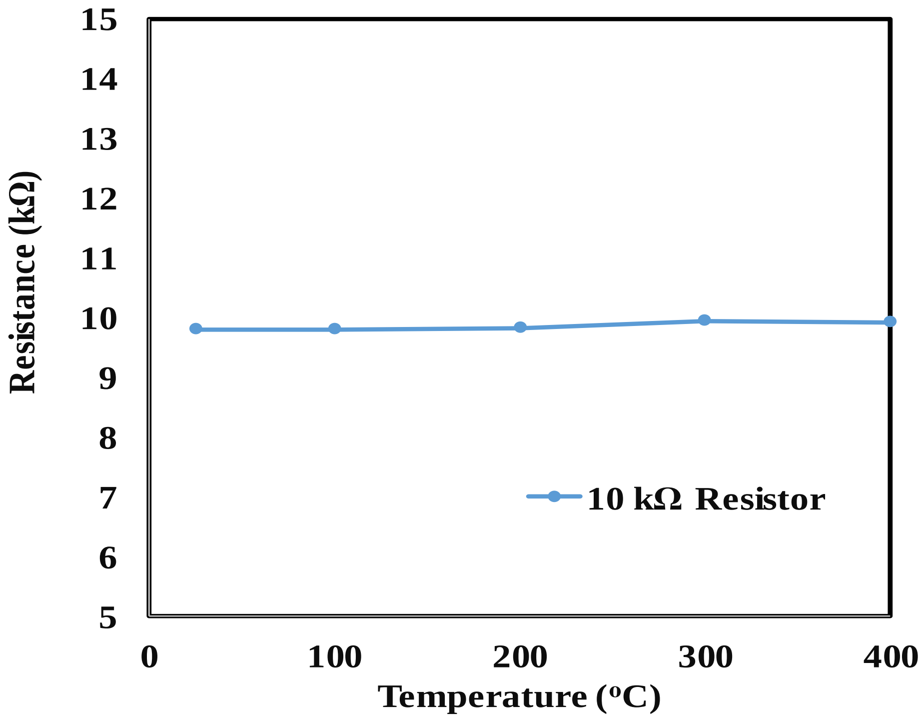
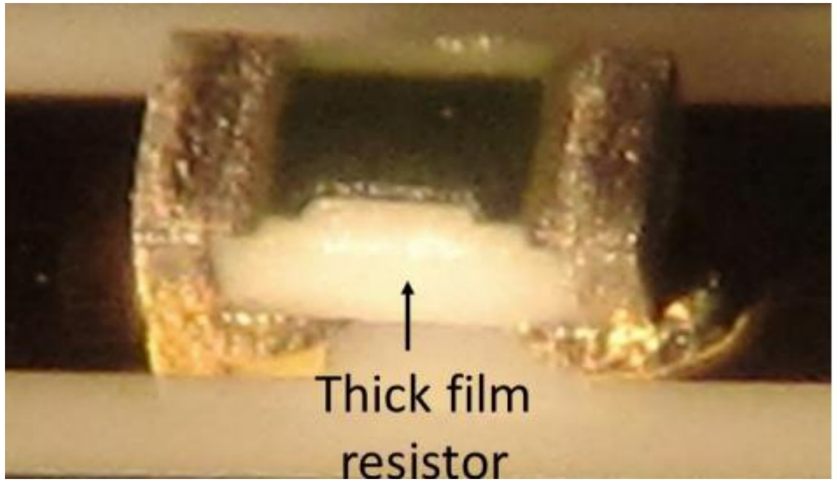


Photo of a Thick Film Resistor



Measurements made using a Keysight 34401A Multimeter from 25 to 400ºC

- Commercially available from MiniSystems Inc
- Ruthenium alloy with a voltage and power rating of 40V and 1 W
- 1.2% Increase in Resistance
- DC Au/W Probes were used for measurement