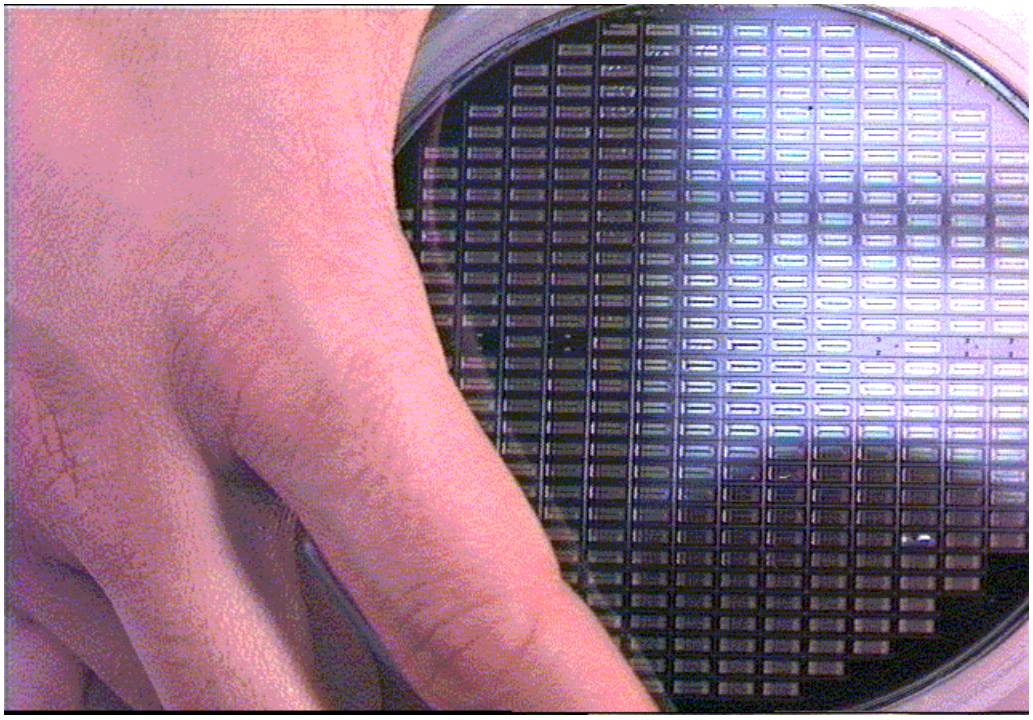
Overview

This paper describes:

Recent advances in the fabrication of thin-film multijunction thermal converters (FMJTCs)

Ac-dc transfer difference data for some of the new FMJTCs

A model of the ac-dc transfer difference at high-frequencies and methods for ir



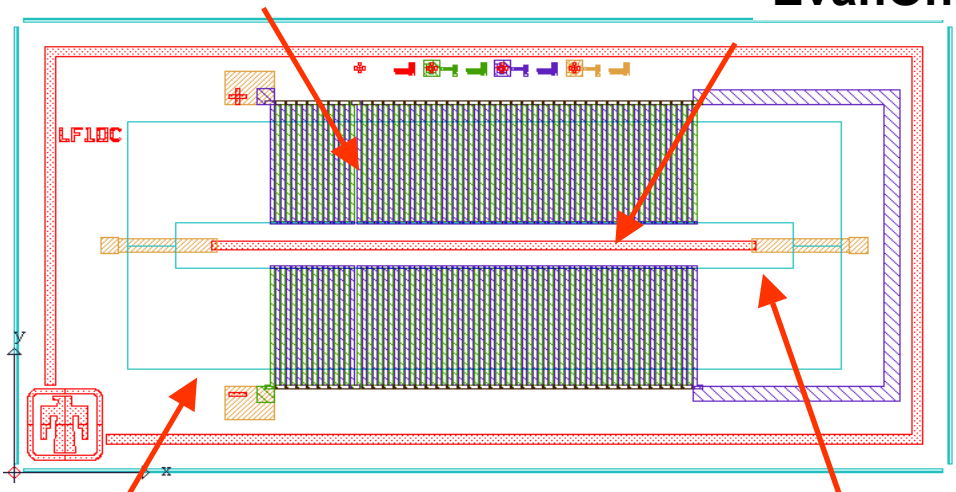
Methodology

- Eliminate time consuming wet-chemical steps through use of photoresist lift-off and use of High Aspect Ratio Silicon Etching (HARSE/Bosch*)
- Develop a method of formation for a silicon obelisk compatible with Bosch etching
- Create thermal and electrical models of various structures
- Develop structural elements to optimize performance at both low and high frequencies
- Provide a vacuum packaging methodology

Coaxial Thermal Converter

100 series connected thermocouples

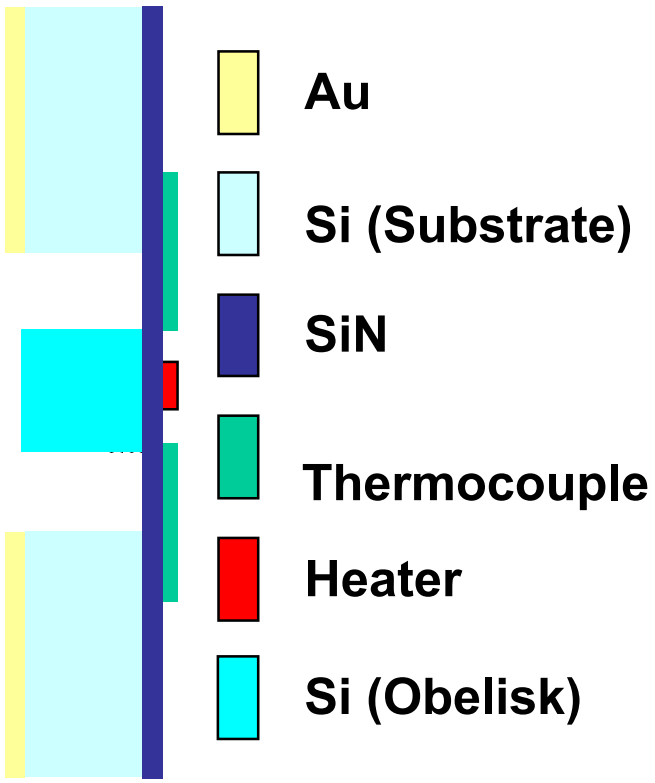
EvanOhm* heater



Membrane Boundary

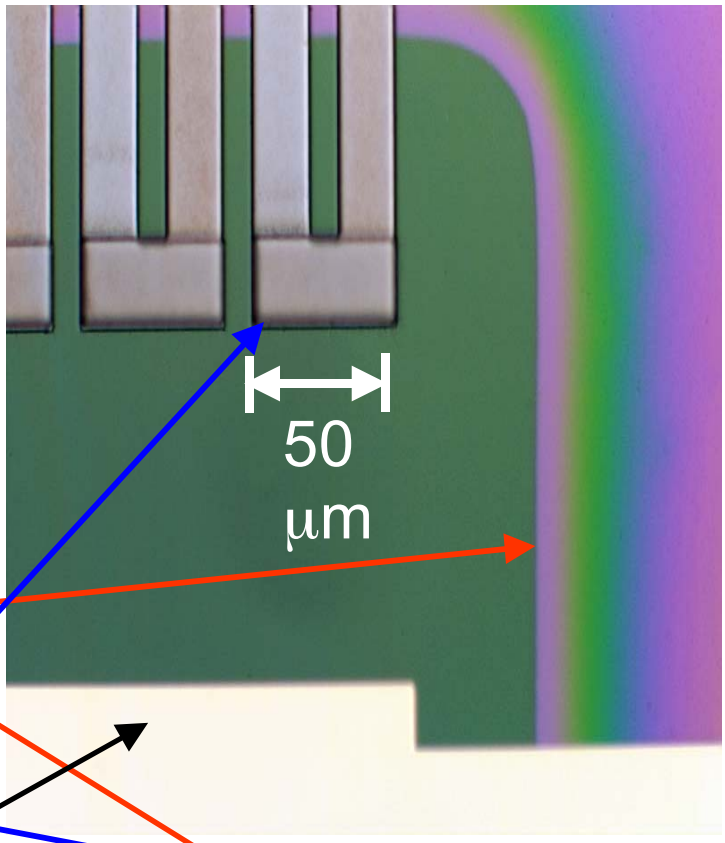
Silicon obelisk

Cross section of chip



Obelisk Formation

Frontside View



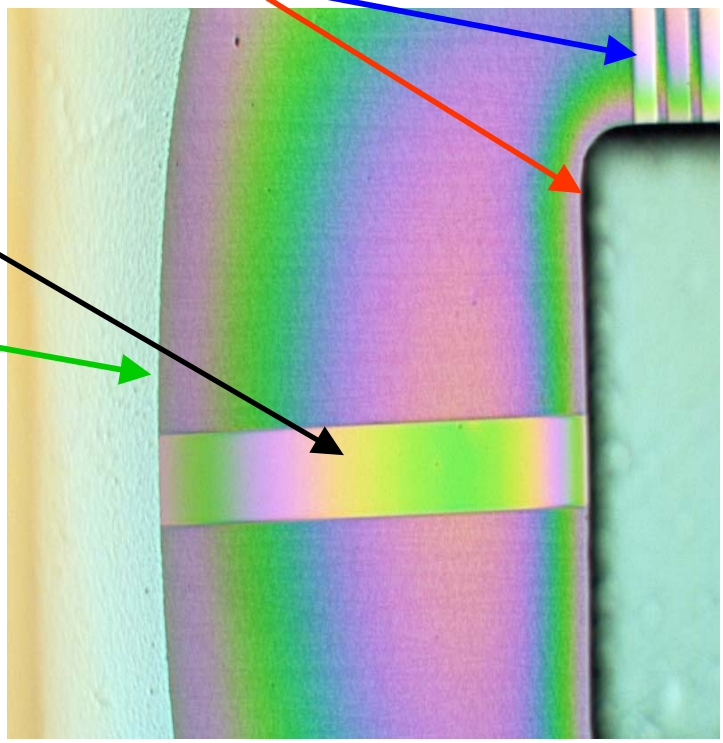
Si Obelisk Boundary

Thermocouples

Heater

Inner Substrate Edge

Backside View



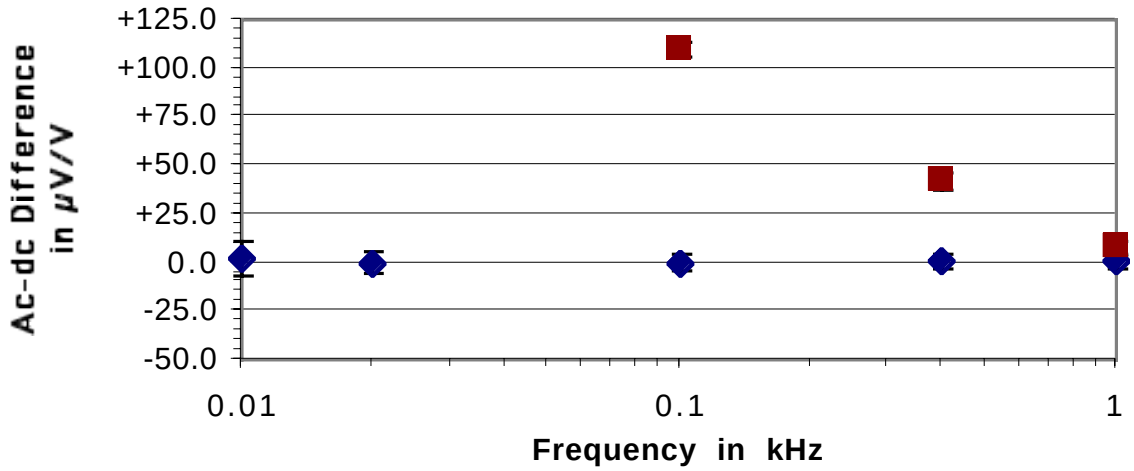
Model Of The Ac-dc Transfer Difference At High Frequencies

- Klonz, Laiz and Kessler have shown that the capacitance to the substrate and the capacitance from the heater to the thermocouples are insufficient to account for effect

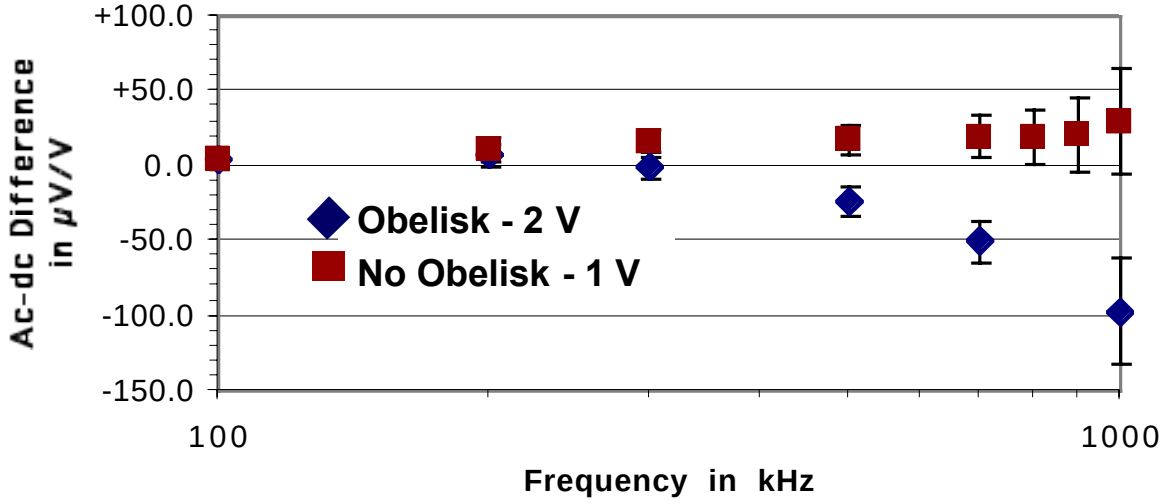
- New model addresses increased heating on ac excitation due to a coupling of the ac signal through the dielectric membrane into the silicon obelisk

Effect of Obelisk on Ac-dc Difference

- Silicon obelisk reduces ac-dc differences at low frequencies by increasing thermal time constant



- Obelisk has a detrimental effect on ac-dc difference at high frequencies



Future Plans

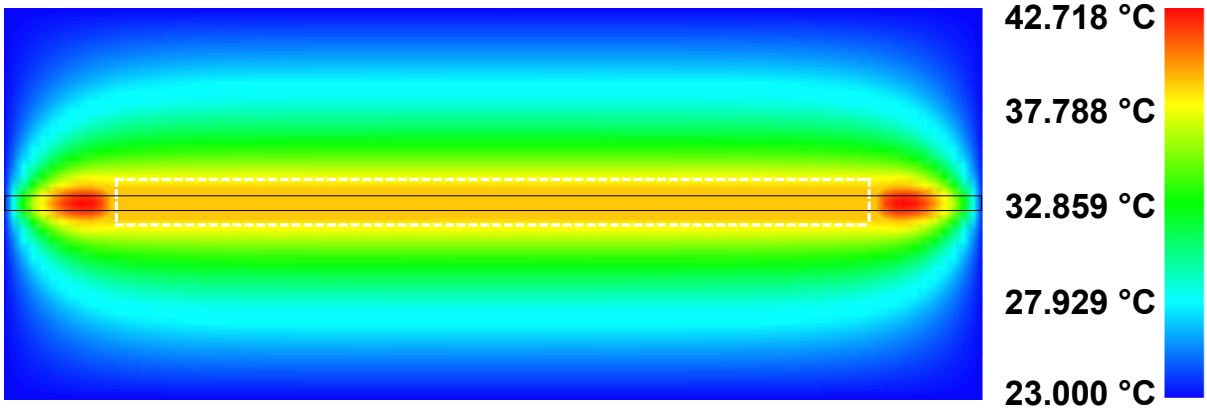
- Perfect vacuum sealed package
- Perform additional electrical and thermal modeling
- Continue characterization of completed devices
- Evaluate thermal current converters and high current chip and multi-chip assemblies

Summary

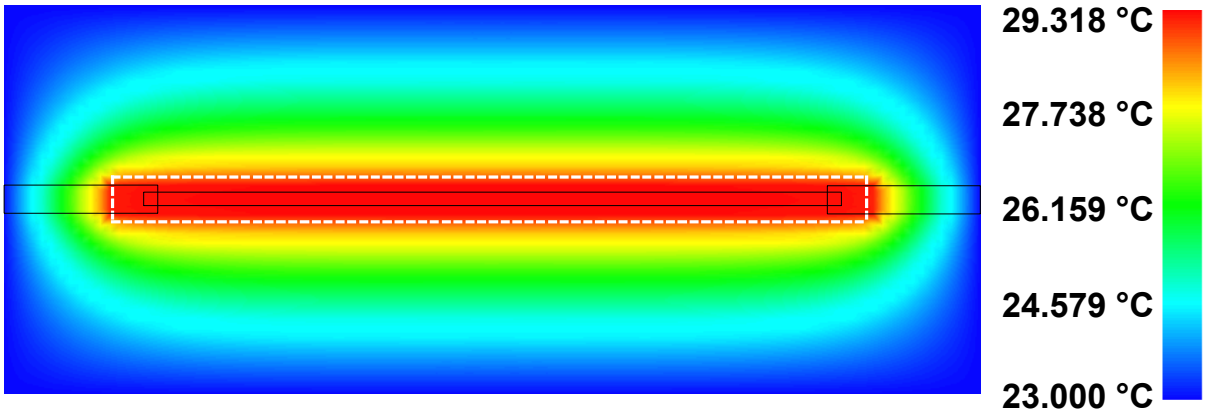
- High performance thermal converters fabricated in a reduced design/fabrication cycle time and at lower cost
- Thermal and electrical modeling partially completed
- Models confirm possible method to improve high-frequency performance
- Characterization of devices underway

* Identification of commercial equipment, instruments, and/or materials does not imply recommendation or endorsement by NIST or Sandia, nor does it imply that the material or equipment identified is necessarily the best available for the specified purpose.

Steady State Simulation Result for Two Heater Styles



LF10a (Straight Coaxial Heater)
375 Ω @ 2 V



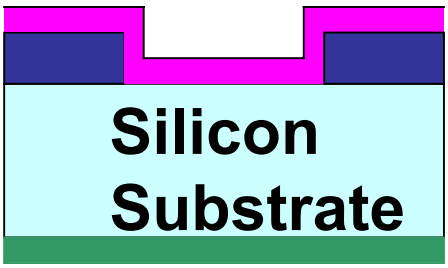
LF10c (Gold Leads to Heater)
350 Ω @ 2 V

- Simulation shows membrane region. Simulation is 3D, obelisk extends into the page beneath heater
- Low-frequency performance improved through elimination of residual heating effect in region between obelisk and substrate edges
- No additional mask layer (as in compensation technique)

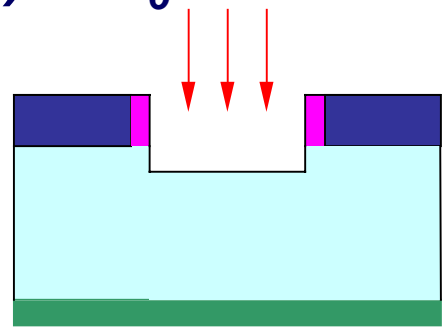
HARSE/Bosch* Etching

- SF6/Ar reactive ion etching alternating with fluorocarbon conformal passivation to prevent sidewall etching
- High-aspect ratio >20:1
- High Si etch rate 3 mm/min
- Good selectivity to photoresist (>50:1) and other materials
- Compatibility with standard processes like CMOS

1) Passivation

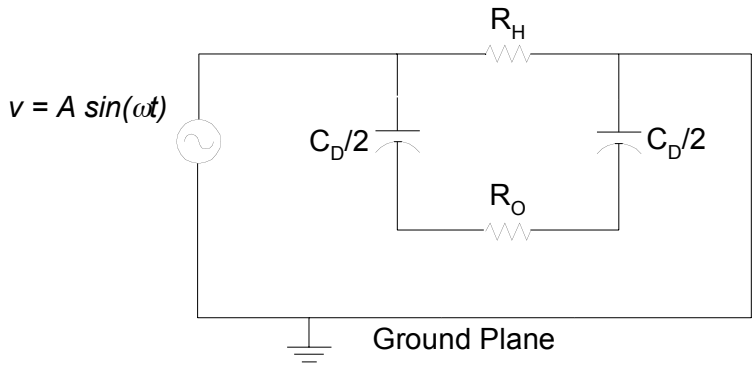


2) SF_6/Ar Etch



High-frequency Effect of Silicon Obelisk

For the simple model shown:



It can be shown that the ac-dc difference, d is given approximately by

$$\delta \approx -\frac{1}{2}\frac{R_O R_H \chi_C}{\left(R_O^2 + \chi_C^2\right)^{3/2}}, \text{where} \qquad \chi_C = \frac{4}{\omega C}$$

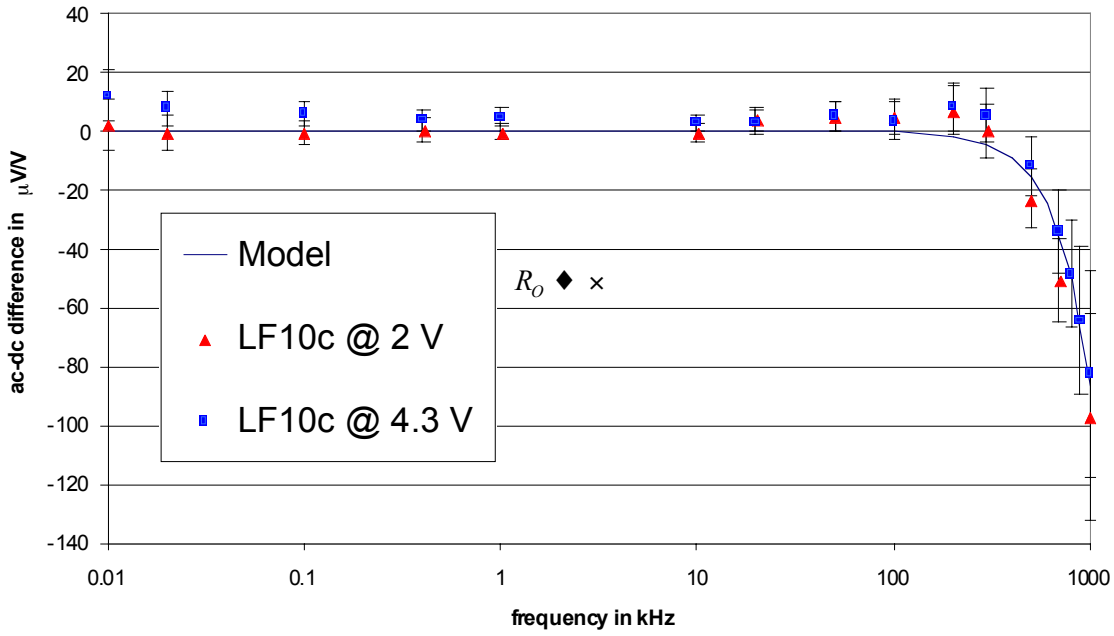
Note the following:

- **Predicts independence of voltage**
- **Slight voltage dependence observed can be explained by negative TCR of Silicon**
- **The value of d is smaller in magnitude with a decrease in R_H as observed (see, Klonz, Proc. of the Conf. on Microtechnology in Microsystems, Delft, p. 9, 2000)**

High-frequency Effect of Silicon Obelisk (cont.)

For R_O, we must consider that the current flows along the top surface and is confined by the skin depth, x_s. R_O is frequency dependent as

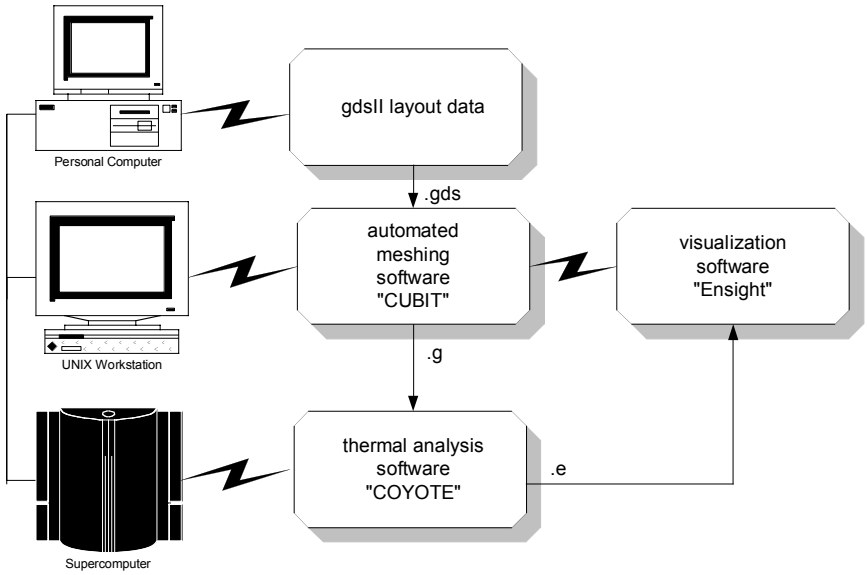
$$R_0 = \frac{\rho l}{\chi_s w} \quad \text{where} \quad \chi_s = \sqrt{\frac{2\rho}{2\pi f}}$$



At least three solutions exist:

- **$R_O \to \infty$ (non-conductive substrate)**
- **$R_O \to 0$ (highly-conductive substrate)**
- **Decrease R_H (this requires a positive δ from skin effect to compensate to get $\delta=0$ and will not fully compensate across all frequencies**

3D Thermal Simulation Tools



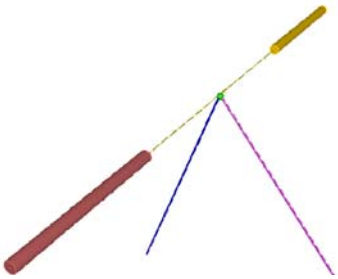
FULL PHYSICS THERMAL MODEL CAPABILITY

- **Thermal Conduction (temperature dependent material properties)**
- **Radiation Heat Loss**
- **Gas Conduction (through heat transfer coefficient, h=k/d)**
- **Thermoelectric Effects**

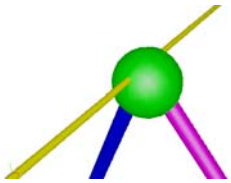
ADVANCED COMPUTATIONAL CAPABILITY

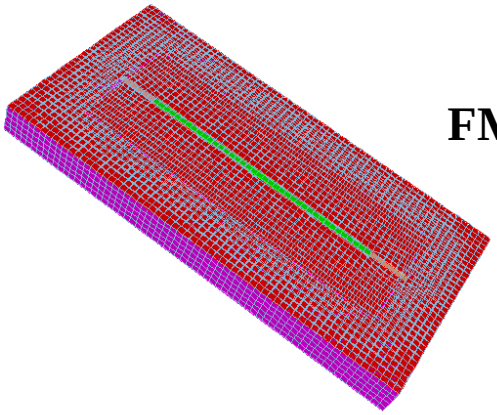
- **Massively Parallel Computers**
- **Automated Mesh Generation Software**
- **Parallel Optimized Thermal Analysis Software**
- **Advanced Visualization (post processing)**

Solid Modeling and Automatic Meshing "CUBIT"

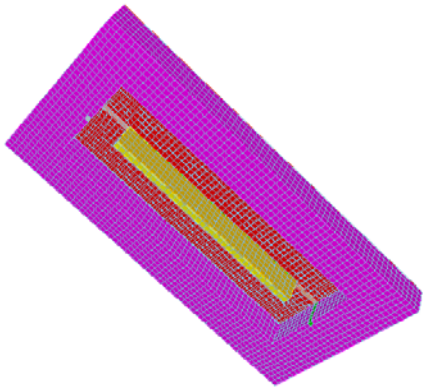


SJTC





FMJTC



Journal Files Simplify Changes in Geometry

```
## D:/Program Files/Cubit/Program/Cubit.exe, Cubit Vers
## Command Options:
## -warning = On
## -information = On
### FULL 3D MODEL FOR TVC3a ##################
############### GEOMETRY ###################
# Heater (body 1)
create brick x 4120 y 80 z 0.
## Obelisk (body 2)
create brick x 3120 y 120 z 400
## Dielectric (body 3)
create brick x 5240 y 2720 z 1
## Substrate (body 4)
create brick x 5240 y 2720 z 400
########## POSITION BODIES ##################
body 1 move 0 0 0.75
body 2 move 0 0 -200.5
body 4 move 0 0 -200.5
########## TOOL BODIES ######################
# Heater (tool body 5)
create brick x 4120 y 80 z 900
# Obelisk (tool body 6)
create brick x 3120 y 120 z 900
# Back Etch opening (tool body 7)
```

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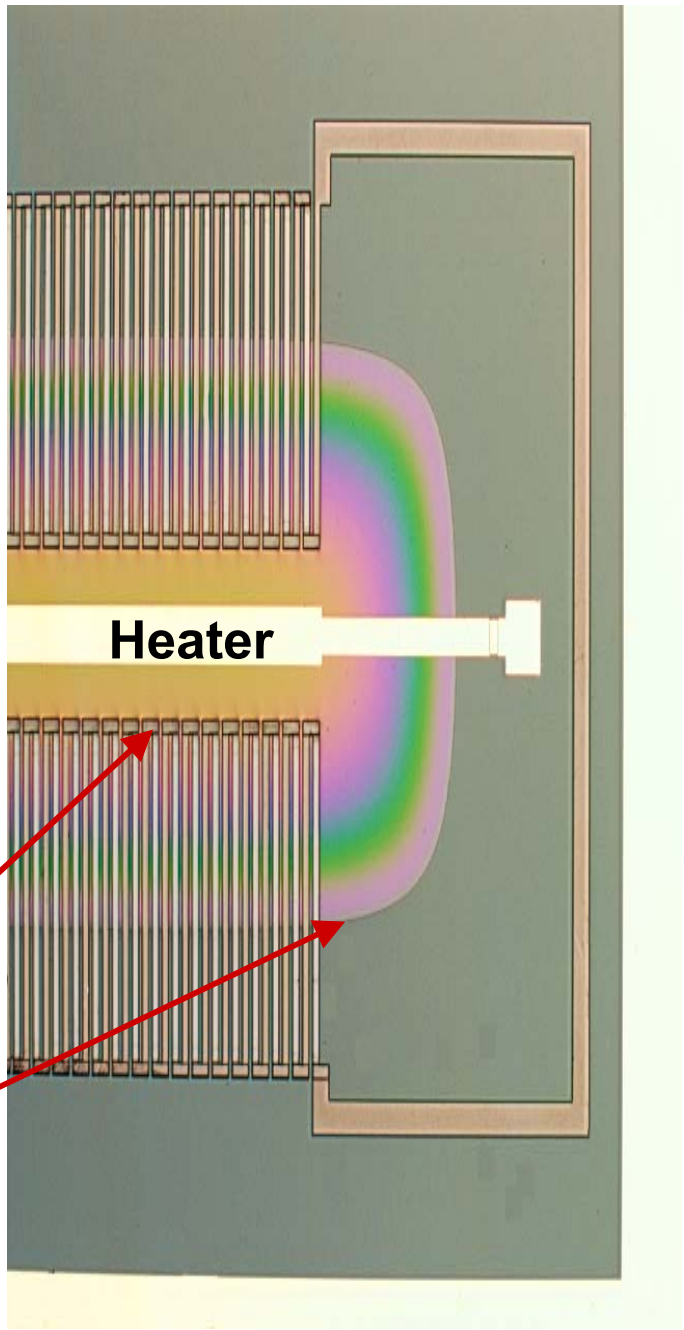
Klonz, Laiz and Kessler have shown that the capacitance to the substrate and the capacitance from the heater to the thermocouples is insufficient to account for effect

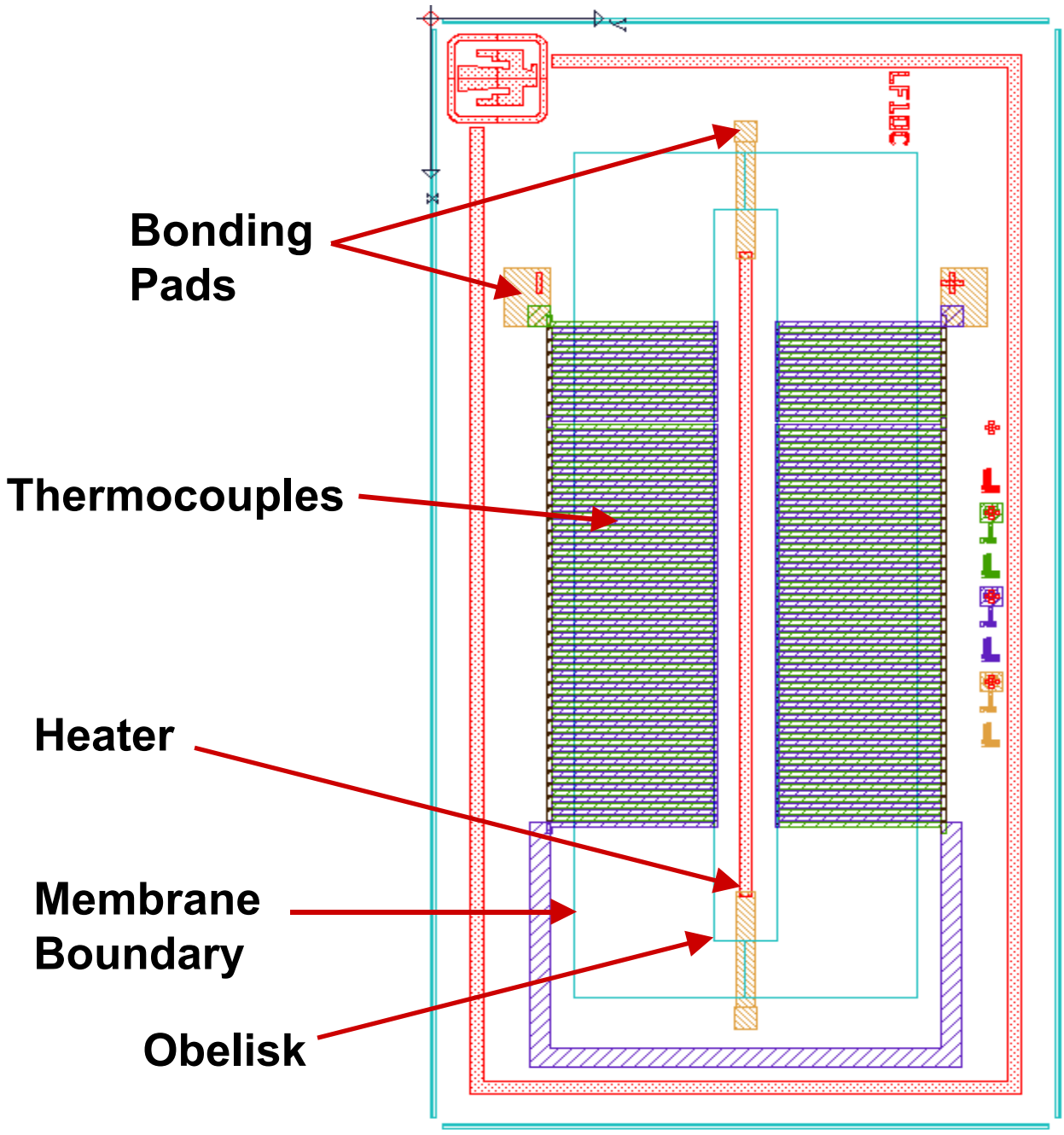
New model addresses increased heating on ac excitation due to a coupling of the ac signal through the dielectric membrane into the silicon obelisk

Fabricated TVC Die

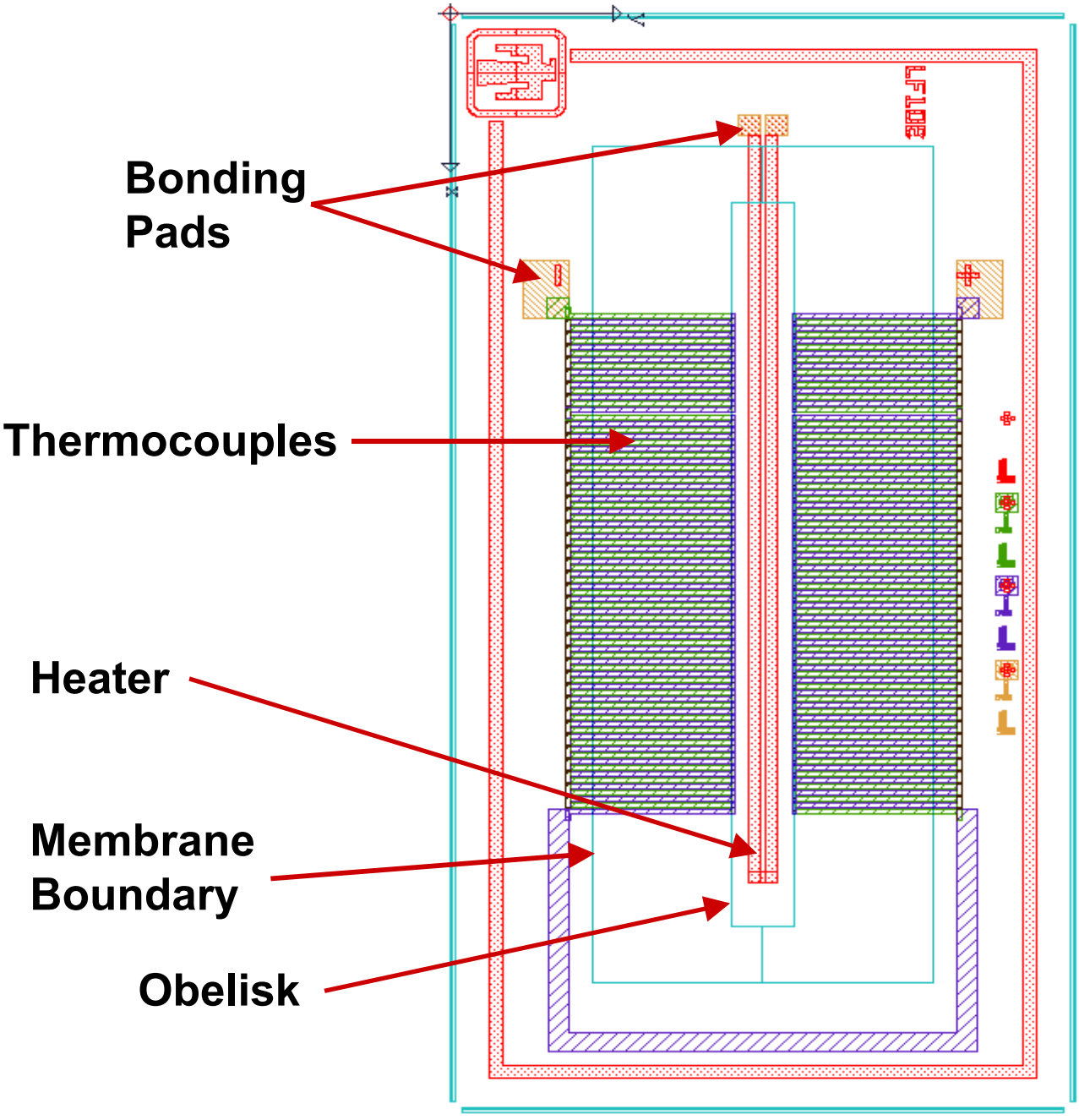
- EvanOhm* heater for TVC (200 Ω to 1000 Ω)
- Gold heater for TCC (0.1 Ω to 5 Ω)
- Examining new designs for high current



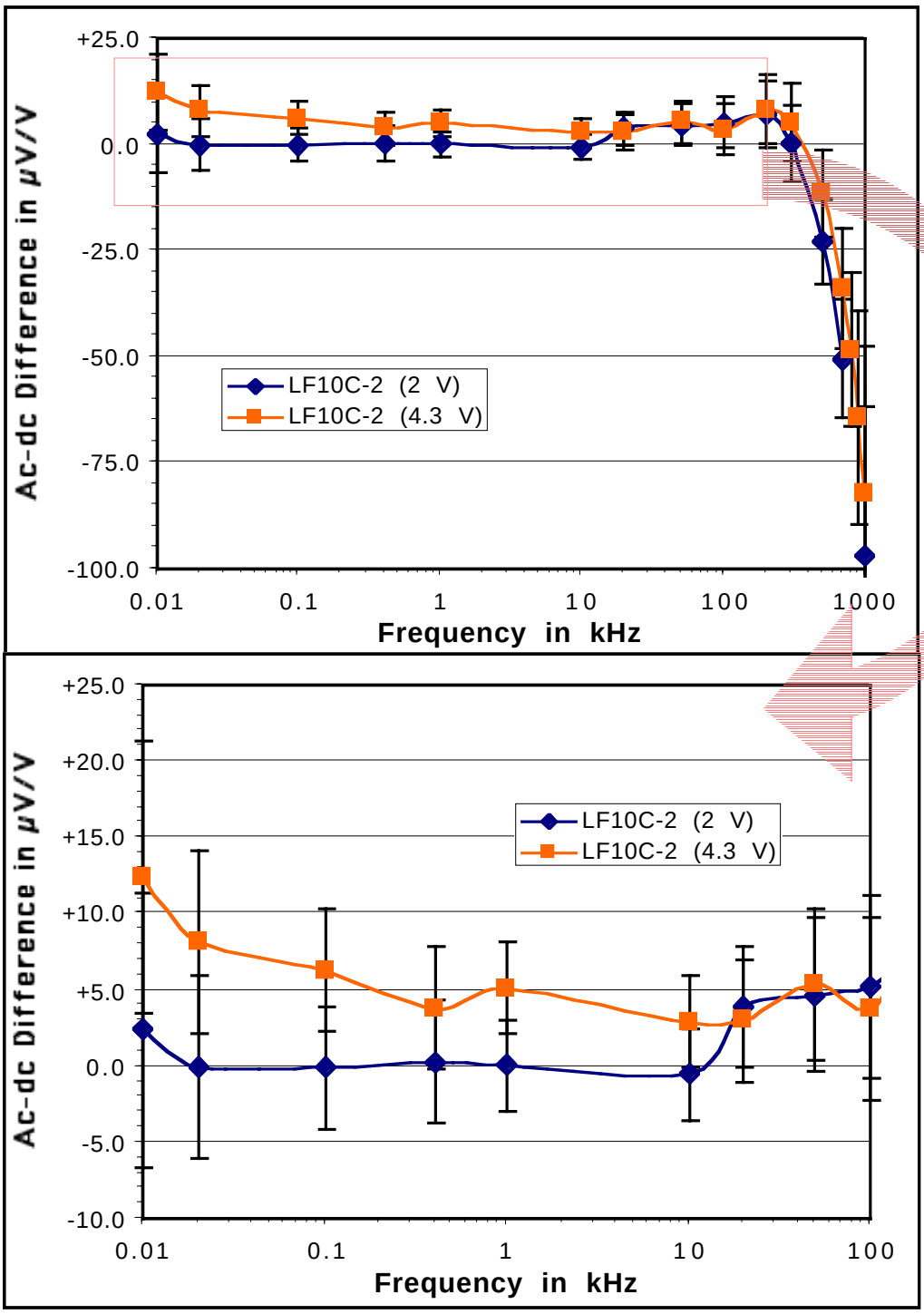
LF10c Coaxial FMJTC



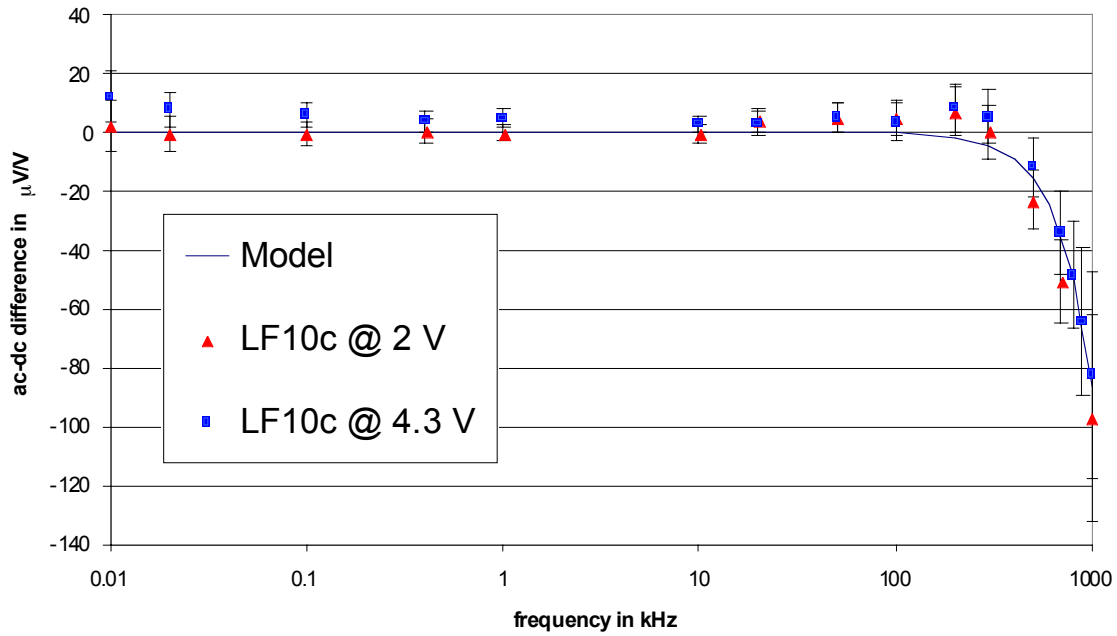
LF10b Bifilar FMJTC



Results - LF10c



High-frequency Effect of Silicon Obelisk (cont.)



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