Thermal Signature of a Resistor

And Problems Encountered Along the Way

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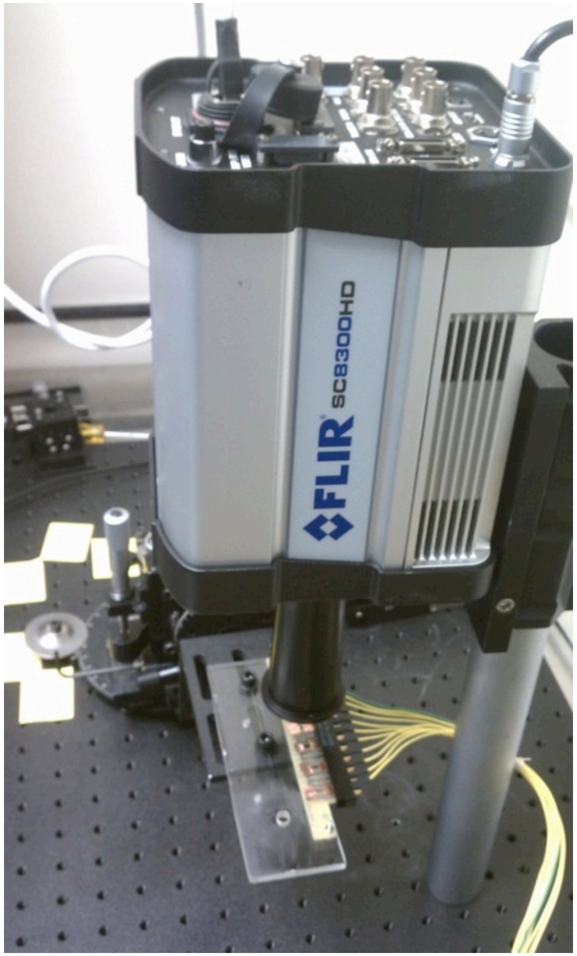
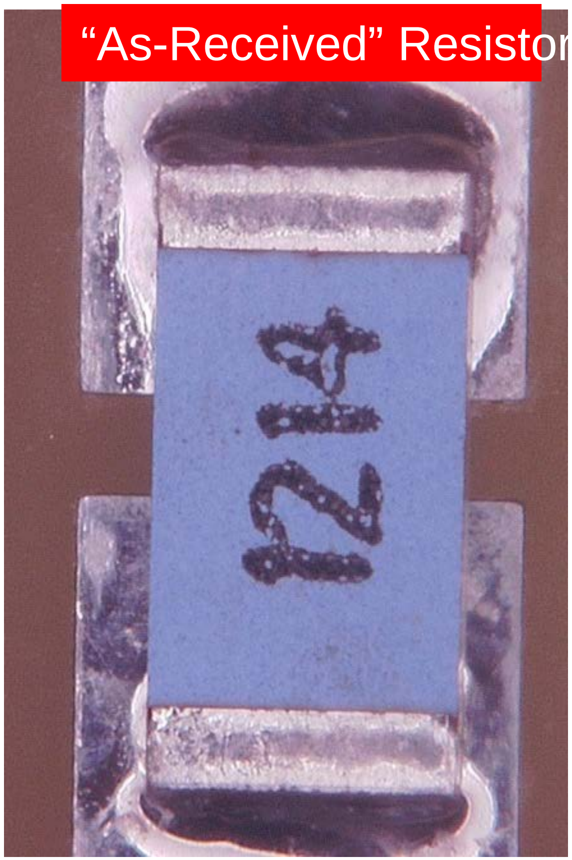
Deliverable to NASA Electronic Parts and Packaging (NEPP) Program to be published on nepp.nasa.gov originally presented at the 2016 NEPP Electronics Technology Workshop (ETW), Goddard Space Flight Center, Greenbelt, Maryland, June 13–16, 2016.

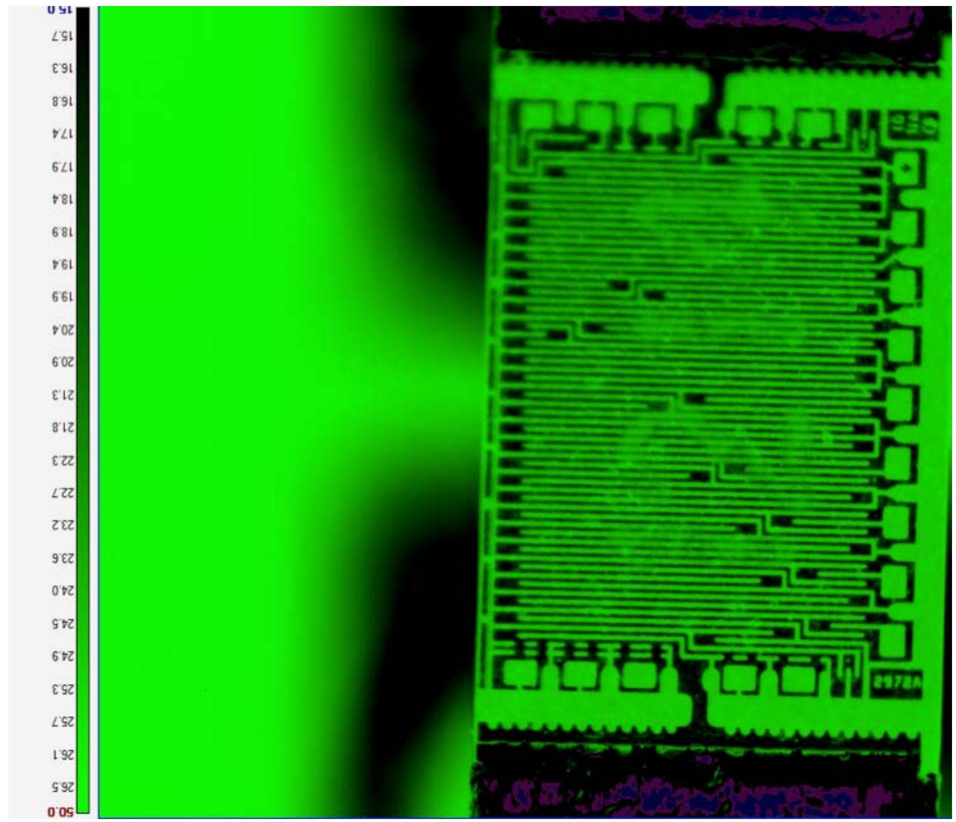
FLIR SC8300HD
High Resolution Infrared Camera
+ 4X Lens

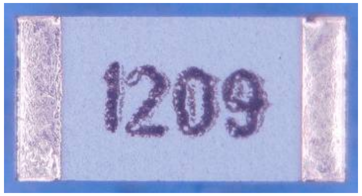


Surprise!!

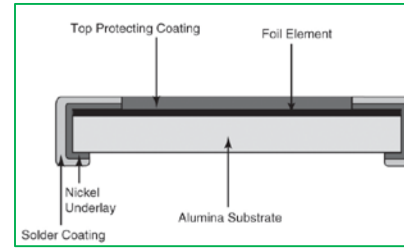
With This Particular Camera/Lens Configuration We Could See THROUGH THESE SPECIFIC External Coatings and Image the Resistor Pattern Even When Device is NOT POWERED

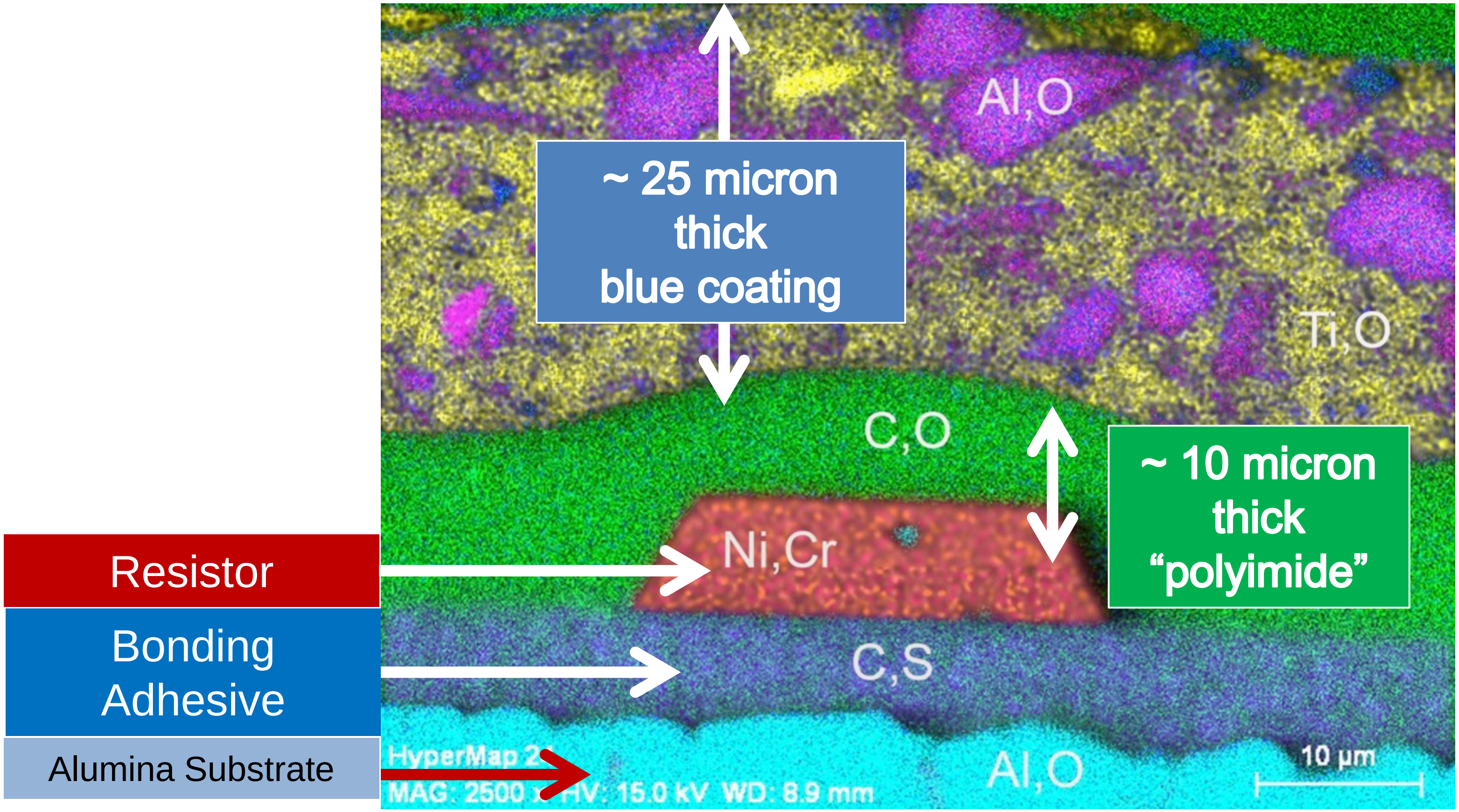






This is what we could "See Through" Cross Section of Resistor





An EDS map of a cross-sectioned resistive element resting on a carbon-sulphur compound on the alumina substrate of the device. The resistive element is coated with a hydrocarbon layer. The protective cover consists of aluminum and titanium oxide particles embedded in a polymer matrix.

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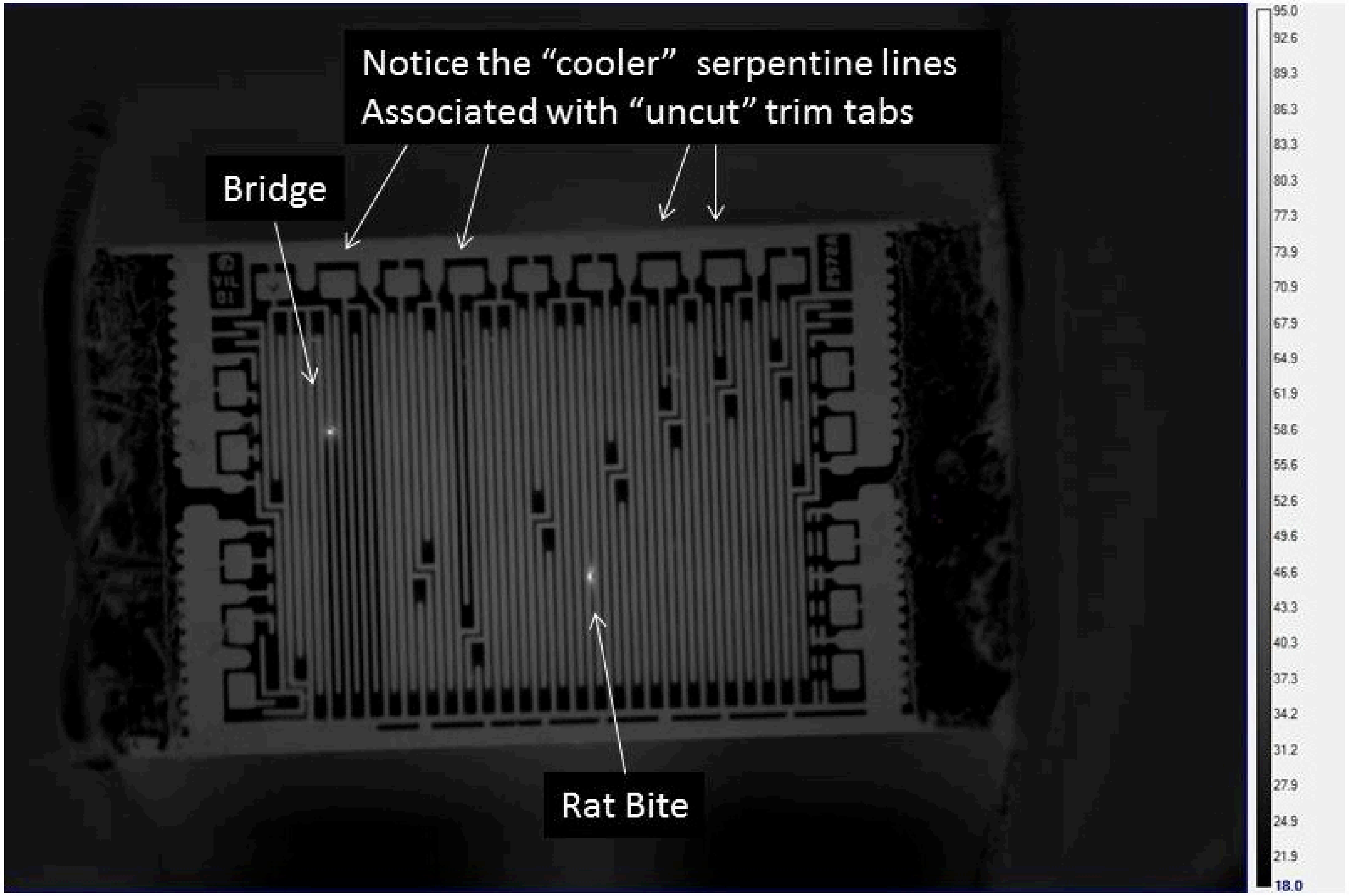
Infrared Image of a 2kOhm Size 1206 Foil Resistor Receiving Power



Why We Worry about a Resistor.

- Spacecraft are expensive to build and are usually one of a kind
- We want our spacecraft to last a long time
- **Sometimes…Parts fail!!!**
- Fixing a spacecraft once in orbit is almost always NOT POSSIBLE!
- Because of the above, ideally, we strive to employ effective screening tests to reduce in-flight failure rates by finding weak parts BEFORE they are used.

Why We Worry about a Resistor.

- Experience tells us that the resistor in question has some known failure modes DESPITE the use of several different screening tests. These screening tests are LEAKY and may allow a few weak parts through!!!

Can we find a better screening process to find weak parts?

Goal of this Paper

While working on a new screening process for precision foil resistors, there were issues between the IR camera and the test article that all came together in textbook fashion. This paper talks about some of those issues.

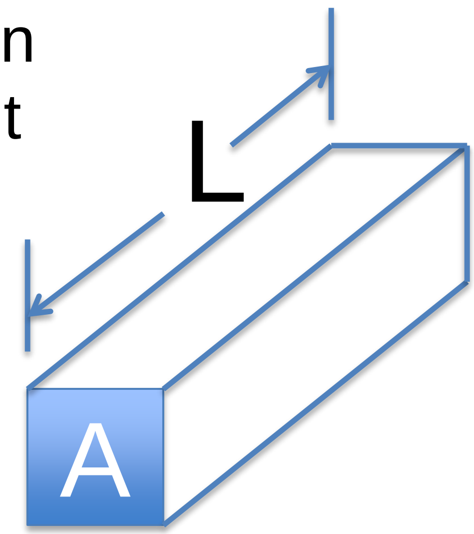
In this paper

- What is a foil resistor?
- Unavoidable problems
- Why Thermal Imaging
- The need for a microscope and the problems it represents
- Problems encountered
  - Size and wavelength limitations
  - Moiré patterns
  - Pixel size limitations
  - Emissivity and reflections

There is nothing new or unusual about these problems but they come together when working on the resistor.

What is Resistance

The electrical resistance of an electrical conductor is the opposition to the passage of an electric current through that conductor.



$$R_{\cancel{\Omega}} = \rho_{\cancel{\Omega m}} \frac{L_{\cancel{m}}}{A_{\cancel{m}^{\cancel{2}}}}$$

ρ for Copper = 0.000,000,016,78 Ωm =16.78e-9 Ωm
ρ for Silver = 0.000,000,015,87 Ωm = 15.87e-9 Ωm

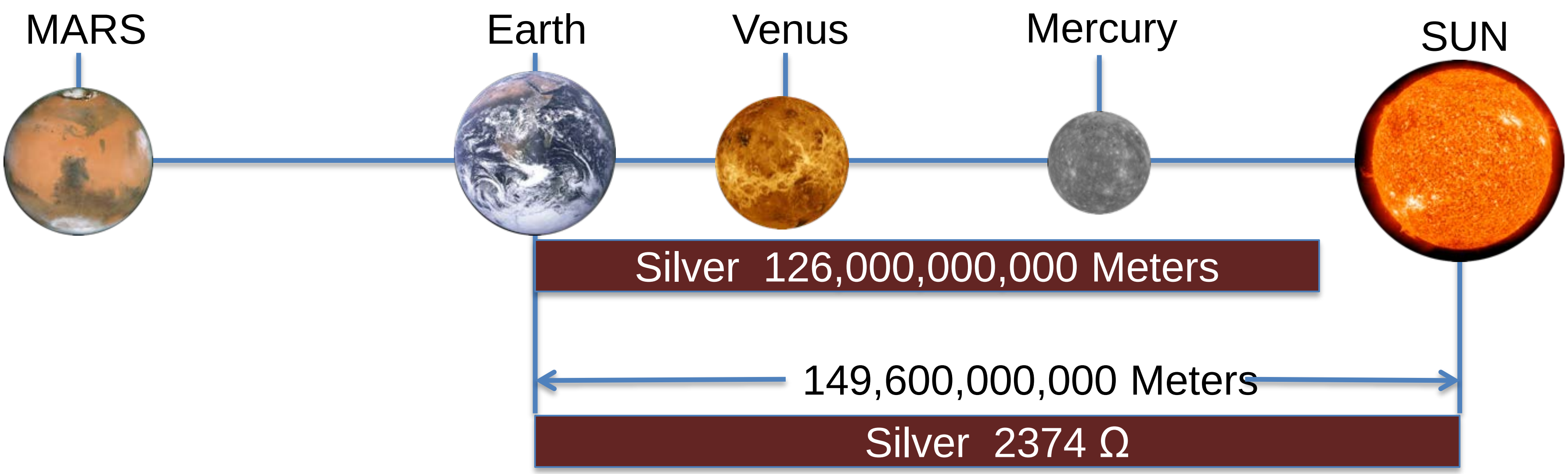
Where
- R = resistance (ohms)
- ρ = resistivity of the material (ohms · meters)
- L = length of the material (meters)
- A = cross sectional area of the material ($meters^2$)

How to Build a 2000 Ω Resistor

Starting with a block of Silver that is 1 meter wide by 1 meter thick (i.e., 1 m^2 Cross Sectional Area), How LONG would the block have to be to make a <u>2000</u>Ω Resistor?

ρ for Copper = 0.000,000,016,78 Ωm =16.78e-9 Ωm
ρ for Silver = 0.000,000,015,87 Ωm = 15.87e-9 Ωm

$$R_{\Omega} = \rho_{\Omega m} \cdot \frac{L_{m}}{A_{m^2}}$$



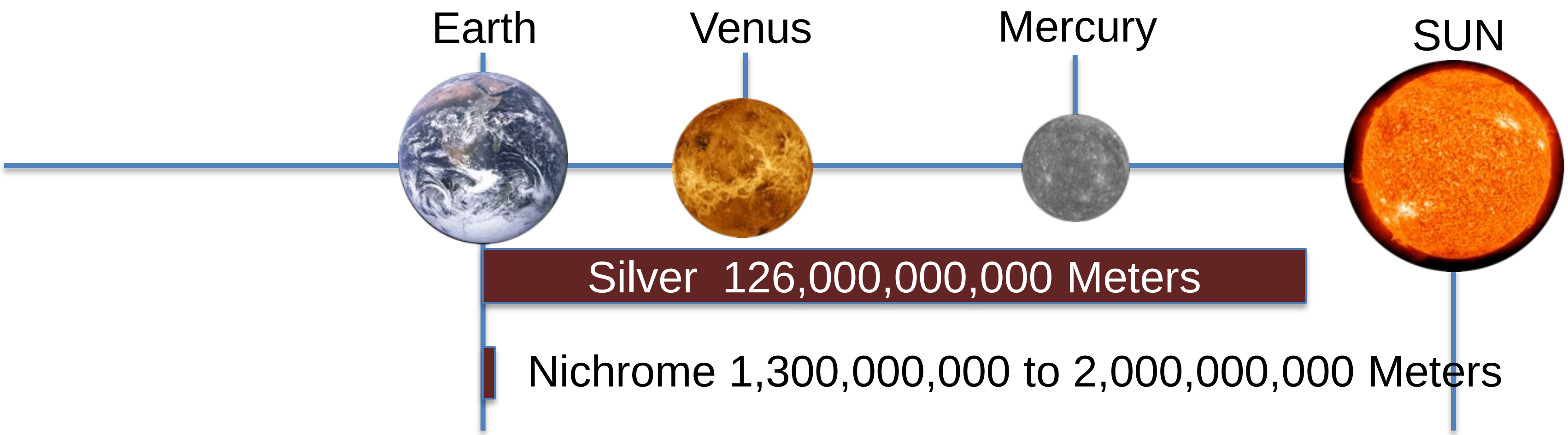
Improvements in the Size – Part I

Choose a Different Material with a different RESISTIVITY!!!

Nichrome (Nickel Chromium Alloy) alloys are commonly used to make resistors.

$$R_{\Omega} = \rho_{\Omega m} \cdot \frac{L_{m}}{A_{m^2}}$$

ρ for Nichrome = 1 e-6 to 1.5 e-6



A factor of approximately 100 better!

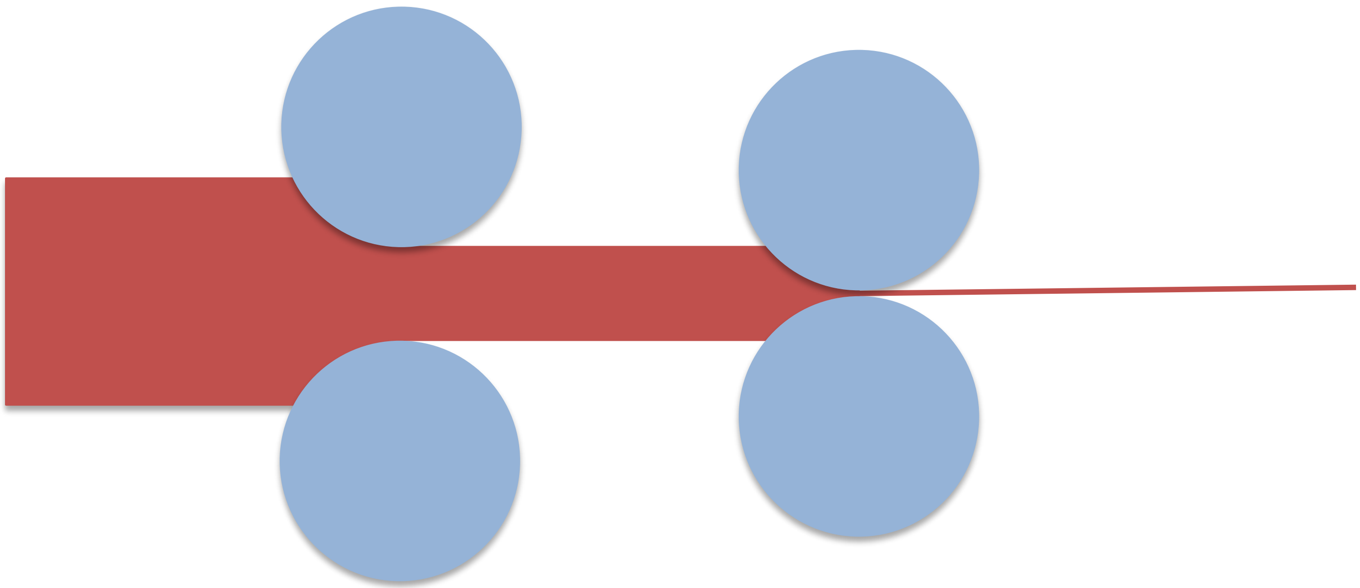
But that is still 4.3 times the distance from the earth to the moon!

Improvements in the Size – Part II

Reduce the Cross Sectional AREA of the Conductor and it will NOT have to be So Long!!!

$$R_{\Omega} = \rho_{\Omega m} \cdot \frac{L_{m}}{A_{m^{2}}}$$

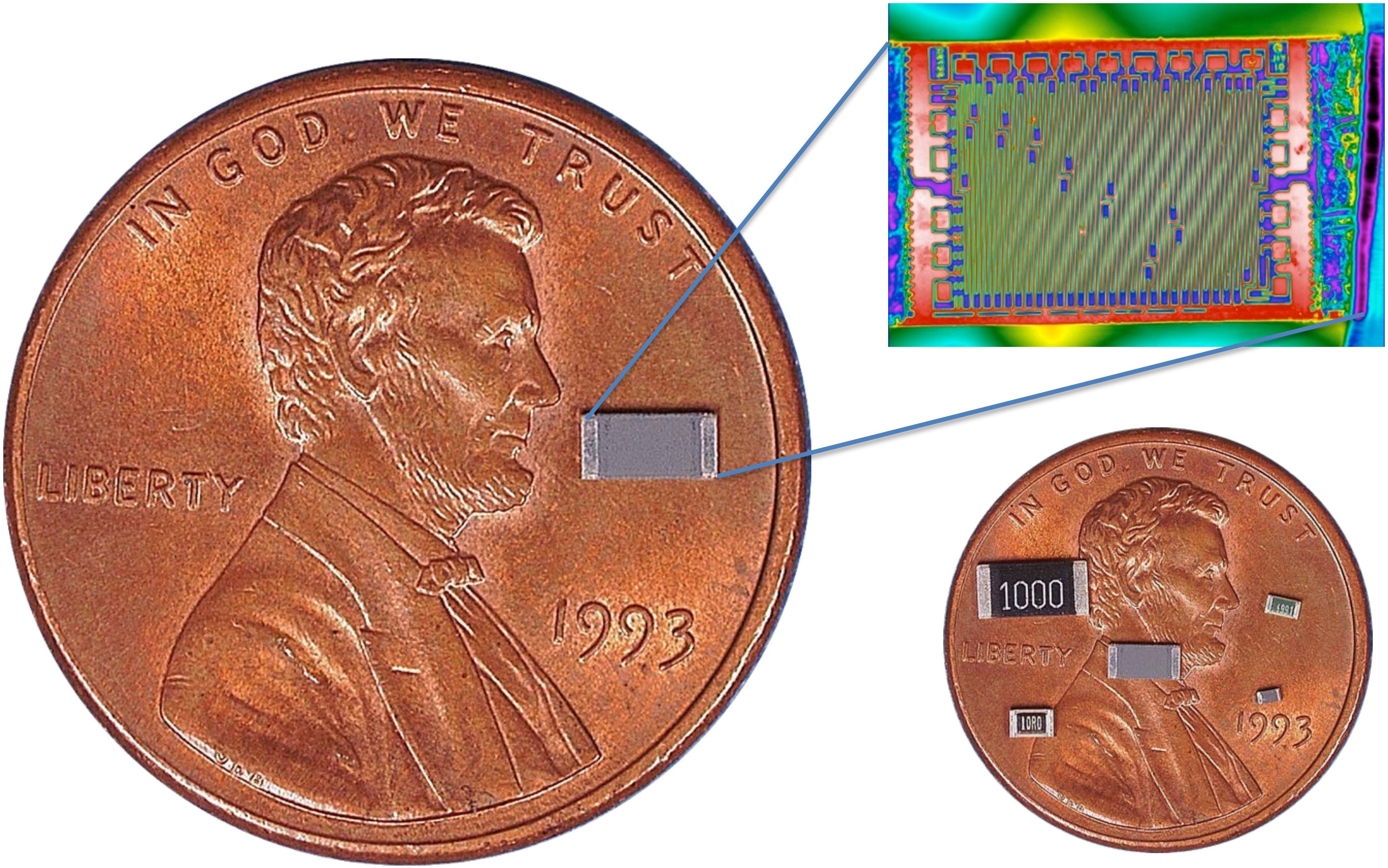
For this Resistor Technology the Nichrome can be reduced in width and thickness from 1 meter^2 down to ~0.000002 meter x 0.000002 meter, which means the length needed for 2000 ohms becomes **~ 1 cm long.**



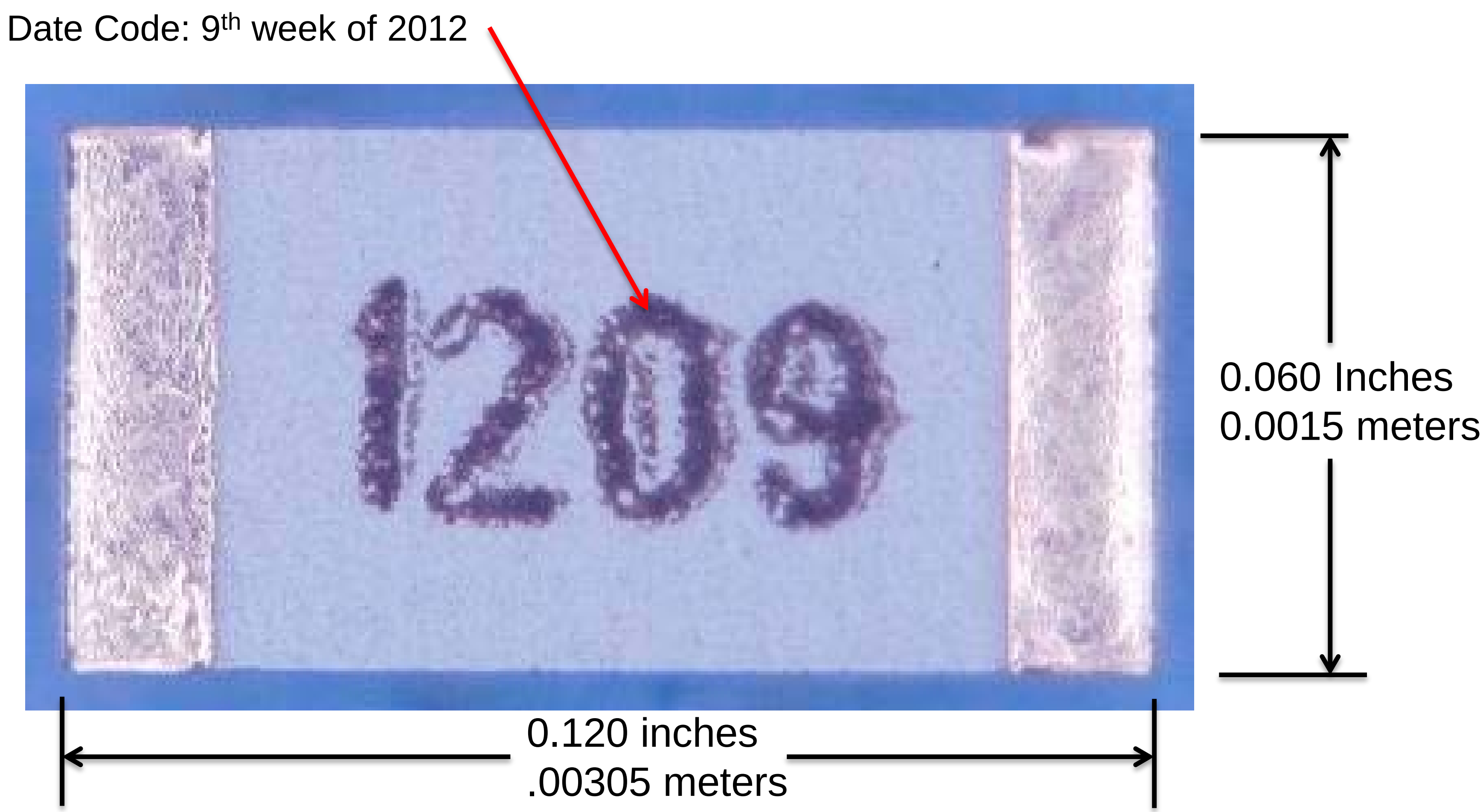
This is a reduction in area of **12 orders of magnitude**!

Now THAT'S Much More Practical!

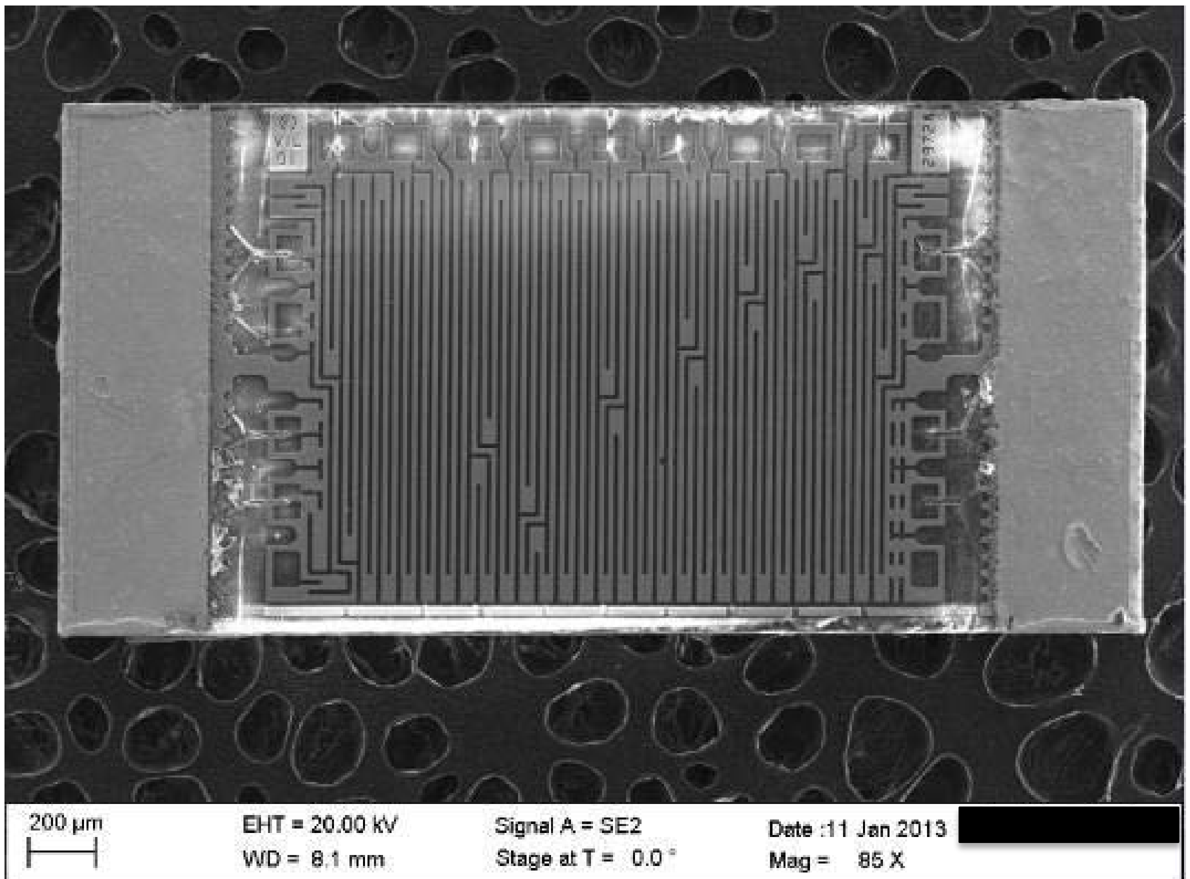
Resistor to Scale



Resistor Part of Interest

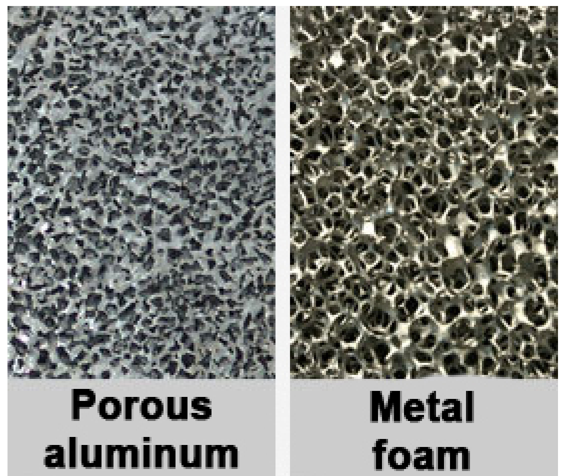


Scanning Electron Microscope (SEM) Image of Resistor Without Blue Coat

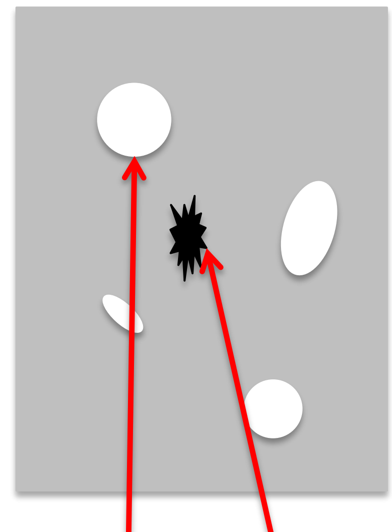


What Happens to Thin Metals

Household Aluminum Foil
0.000,016 meters thick



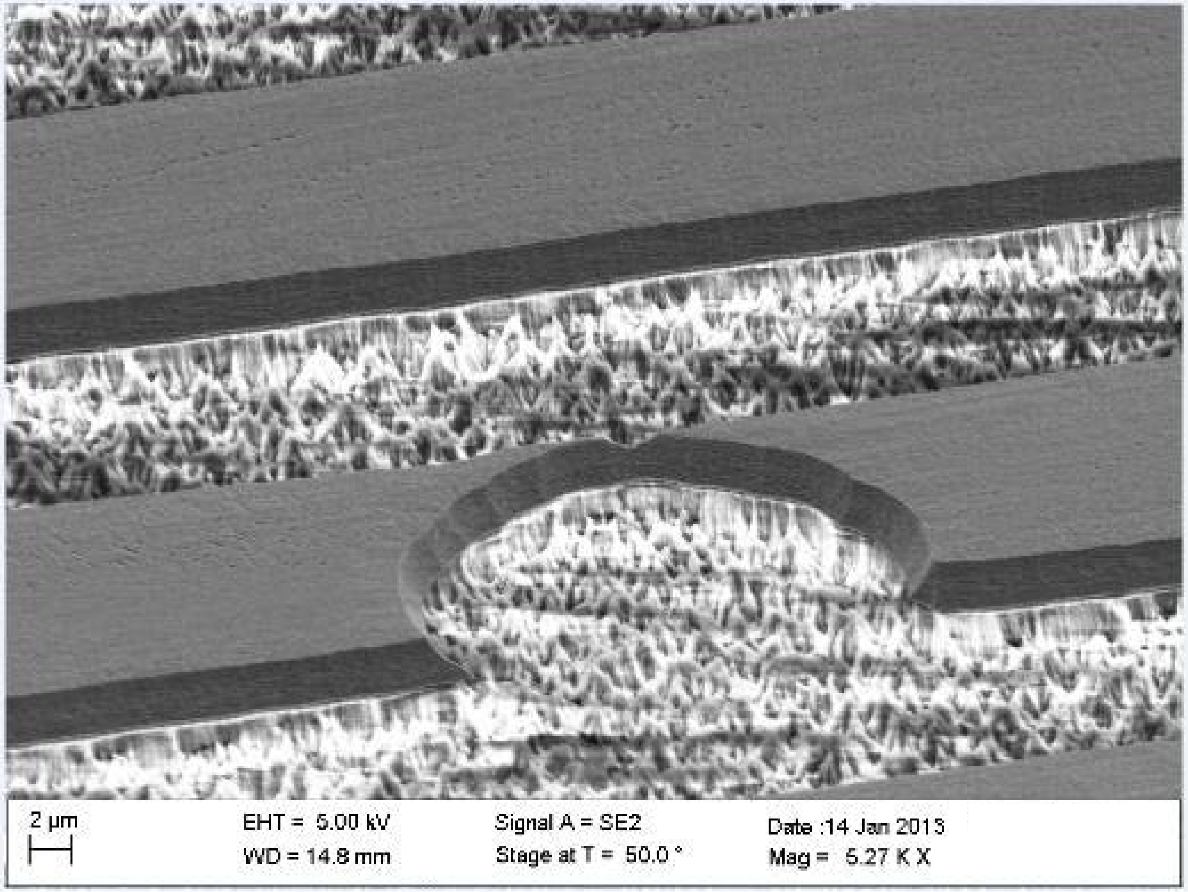
A foil 0.000,001 meters thick



http://b2bimg.bridgat.com/files/Porous_aluminum_An_Alternative_to_Sintered_Metals.jpg

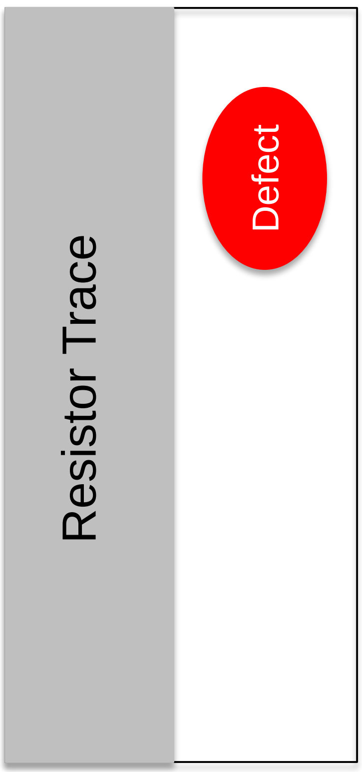
Metallurgists describe this as a metal becoming **porous**

Nichrome Foil Resistor with a “RAT BITE”
(May Be Caused by Working with a “Porous” Foil)

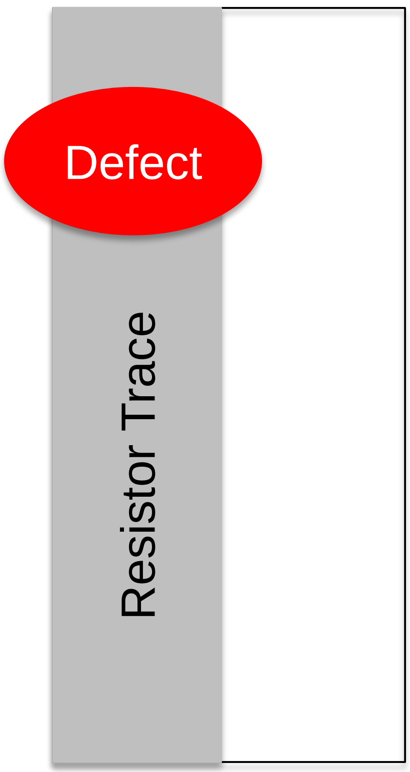


What do "Defects" do to Resistance?

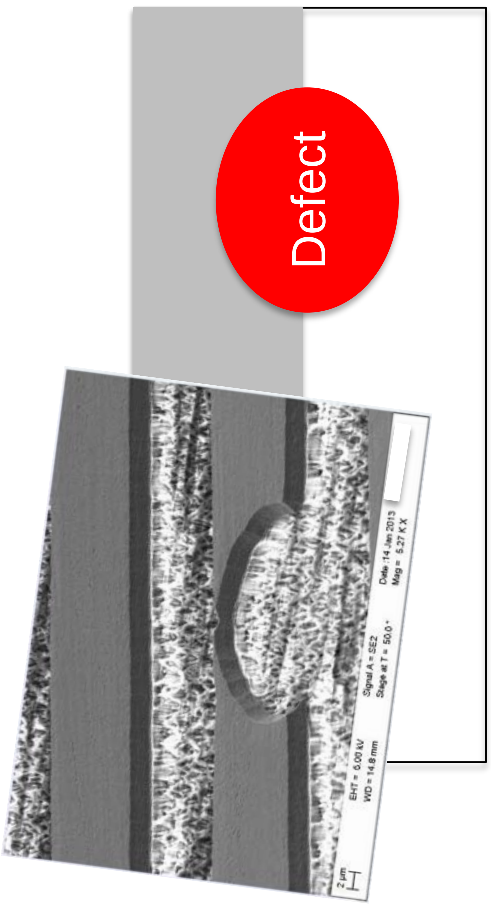
No Effect



Open Circuit
No Resistor

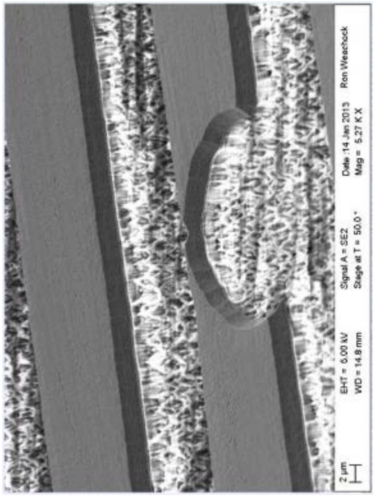


? See next slide



Change in Resistance

A rat bite at one location where 90% of a trace is missing before it can be electrically **detected** (Maybe*) .

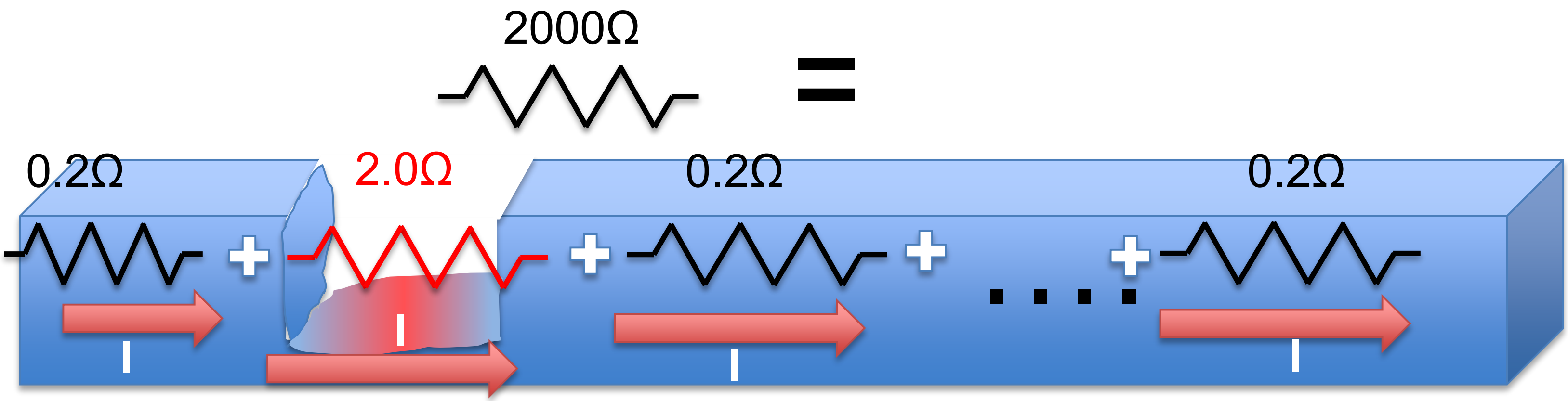


* In the case of a "Trimmed Part" the change in resistance is accounted for and the change becomes part of the final value.

A “Rat Bite” Has a Higher Resistance Due to the Smaller Cross Sectional Area

Example:
For a given Length (L) segment of resistor a 90% reduction in the Cross Sectional Area, Produces a 10x INCREASE in the resistance of the normal segment

The Same Electrical Current (I) in Amperes
Flows Through ALL Segments of this Resistor



But the POWER Dissipated in the “RAT BITE” is Higher Because its Resistance is Larger

$$P = I^2 * R$$

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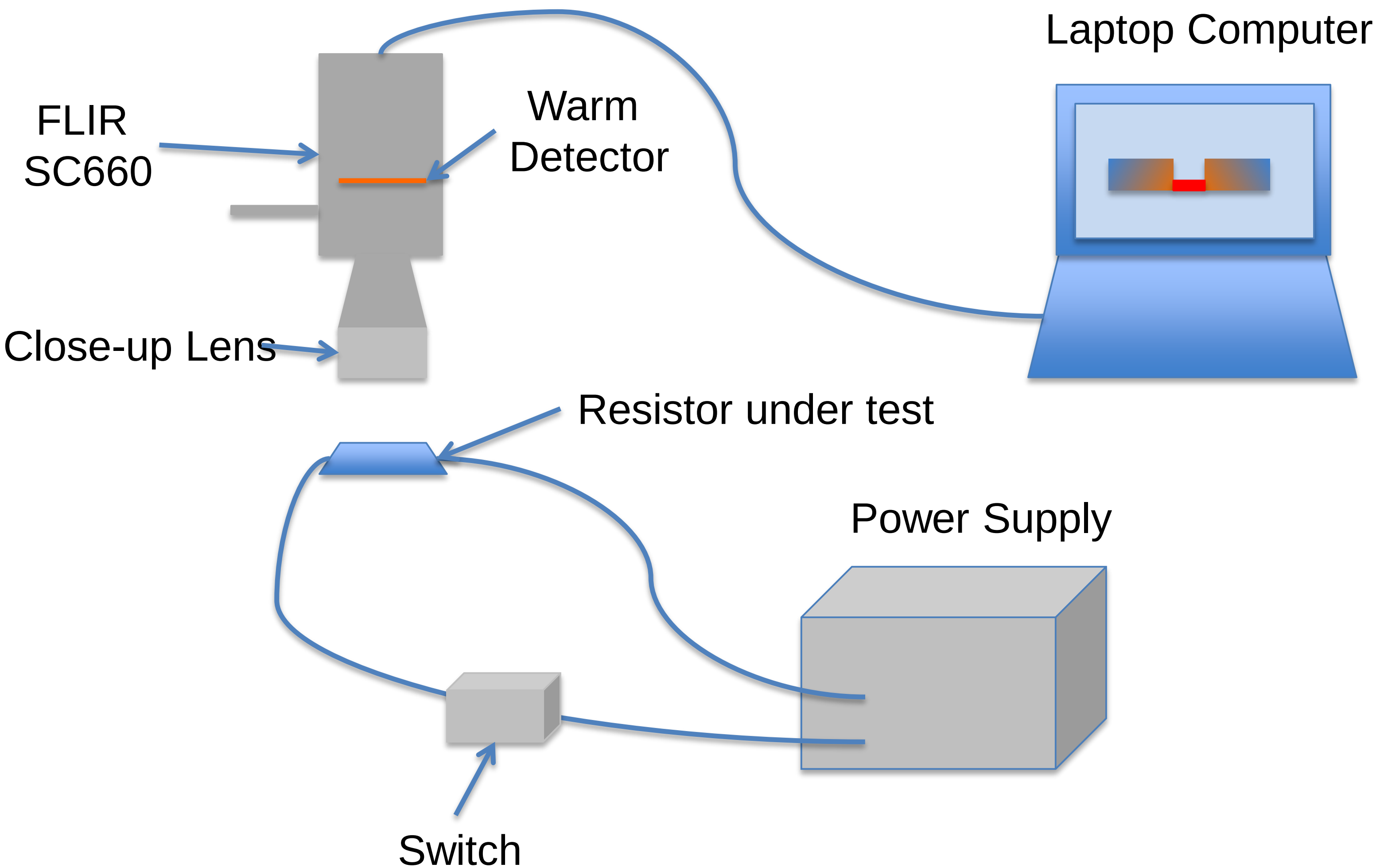
“Rat Bites” Get Hot Because

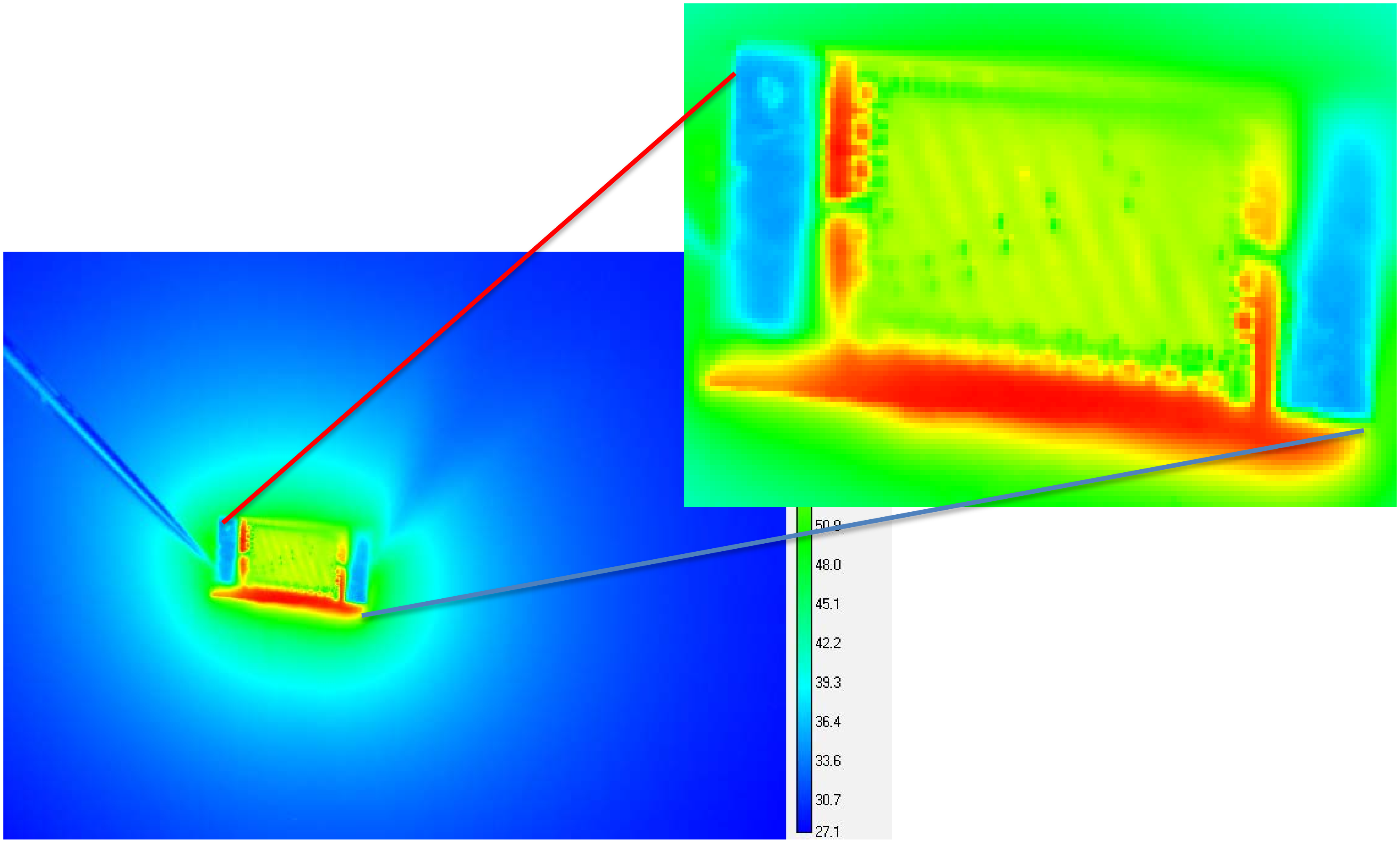
they
Dissipate MORE Power than Other Parts
of the Resistor

How hot does it get, how fast does it get hot and could it induce a failure?

Original Test Setup

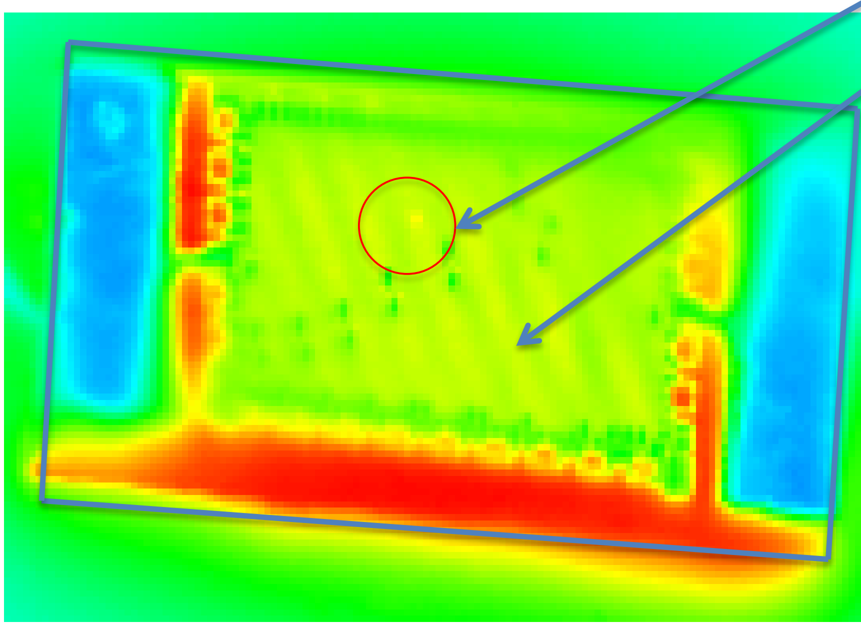


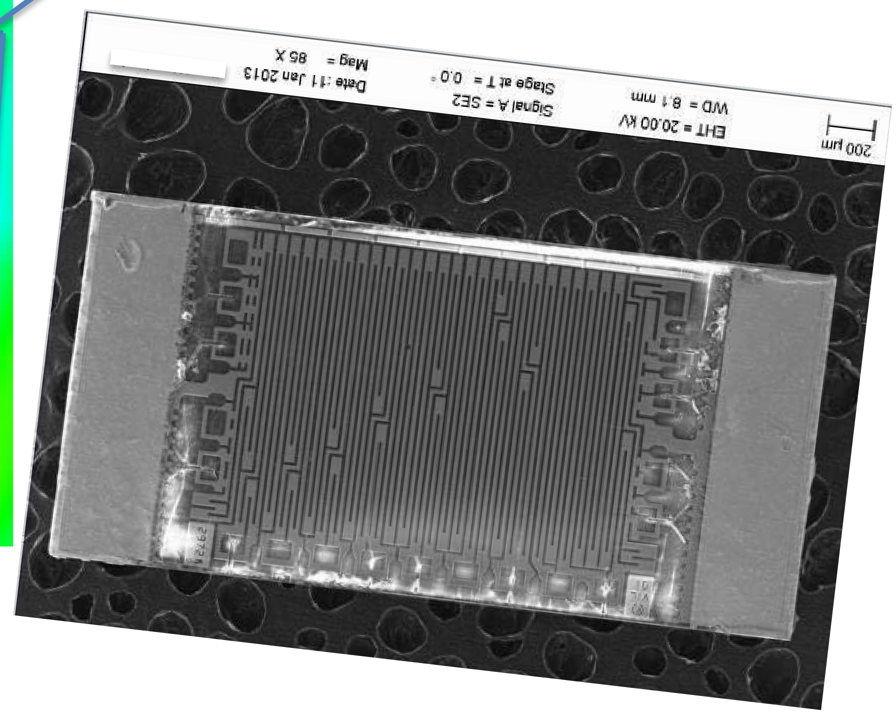
First Test Run



Items of Interest

Hot Spot
Stripes





Accomplishments of First Run

- Overall we could see the resistor was getting hot.
- Temperature rise at one spot was MAYBE 2C had expected a 60C rise.
- Expected to see 2 hot spots and saw maybe only 1.
- Saw "diagonal" stripes that were unexpected.

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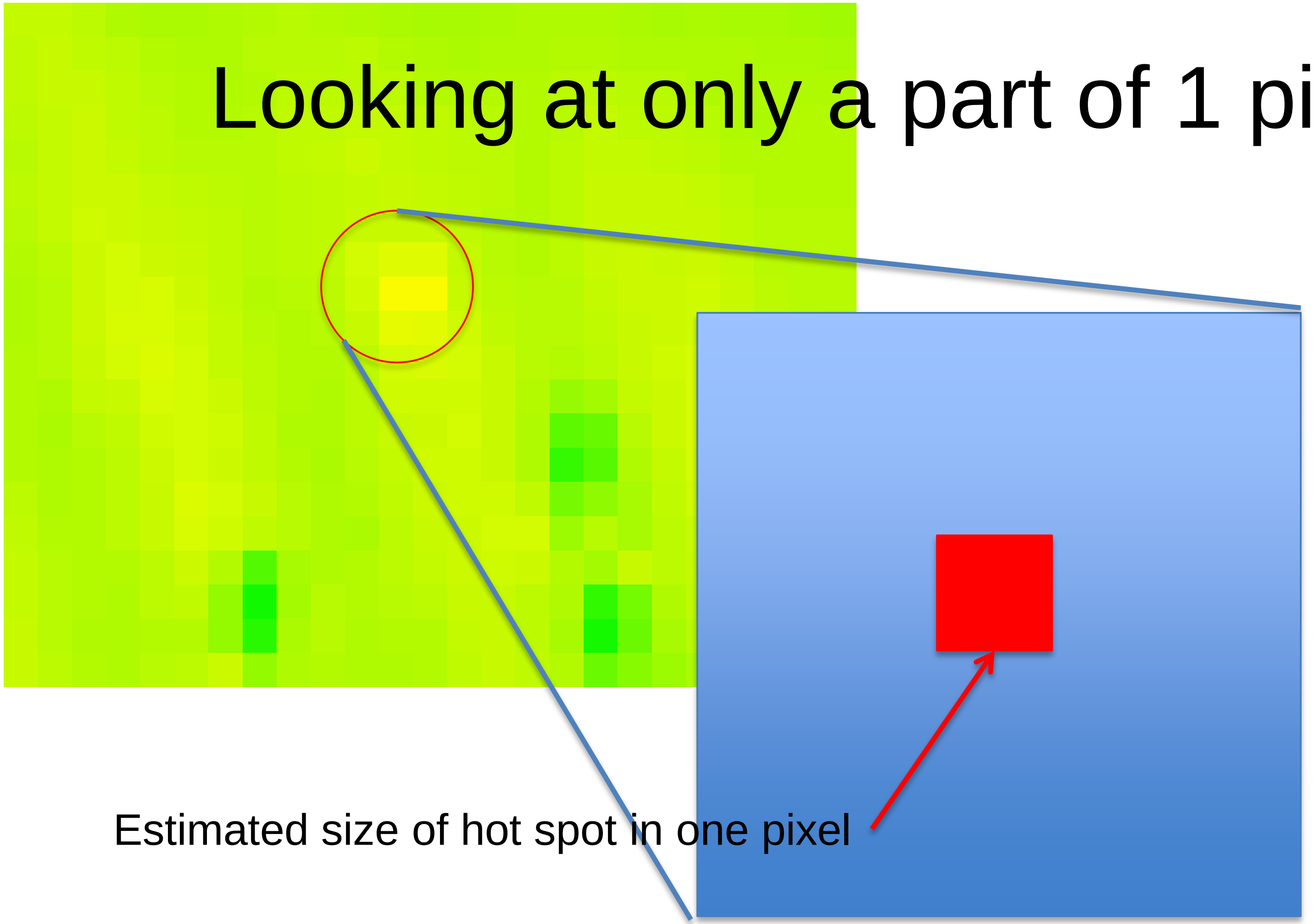
Disappointed, but What Went Right?



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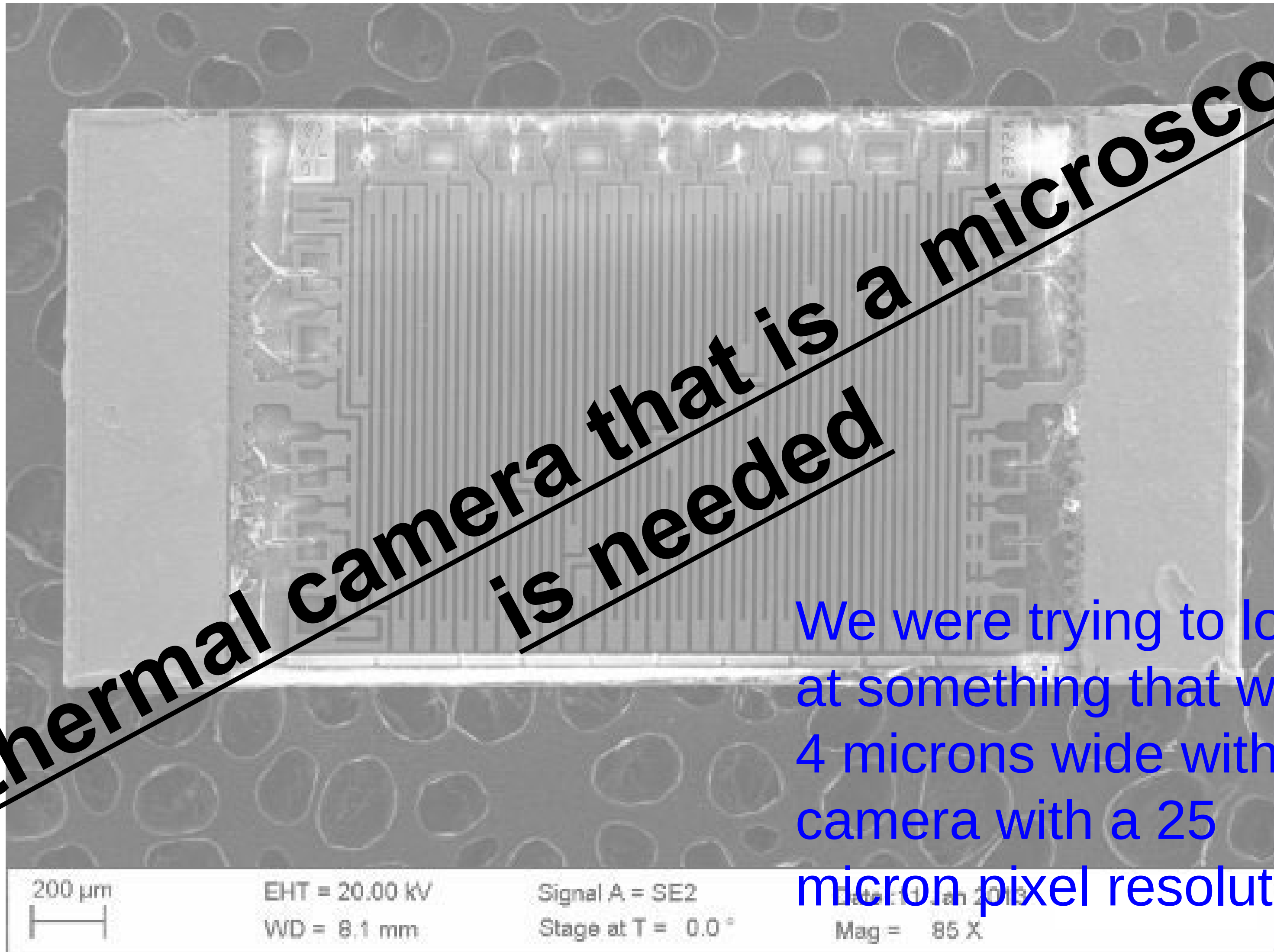
Disappointed, but What Went Right?

- Overall we could see the resistor was getting hot.
- With a quick calculation the expected temperature of the one pixel was about right.
  - This is hand waving at its finest
- Expected to see 2 hot spots and saw maybe only 1.
  - To be expected as the second hot spot was physically even smaller than the one we saw
- Saw diagonal stripes that were unexpected.
  - More on this later

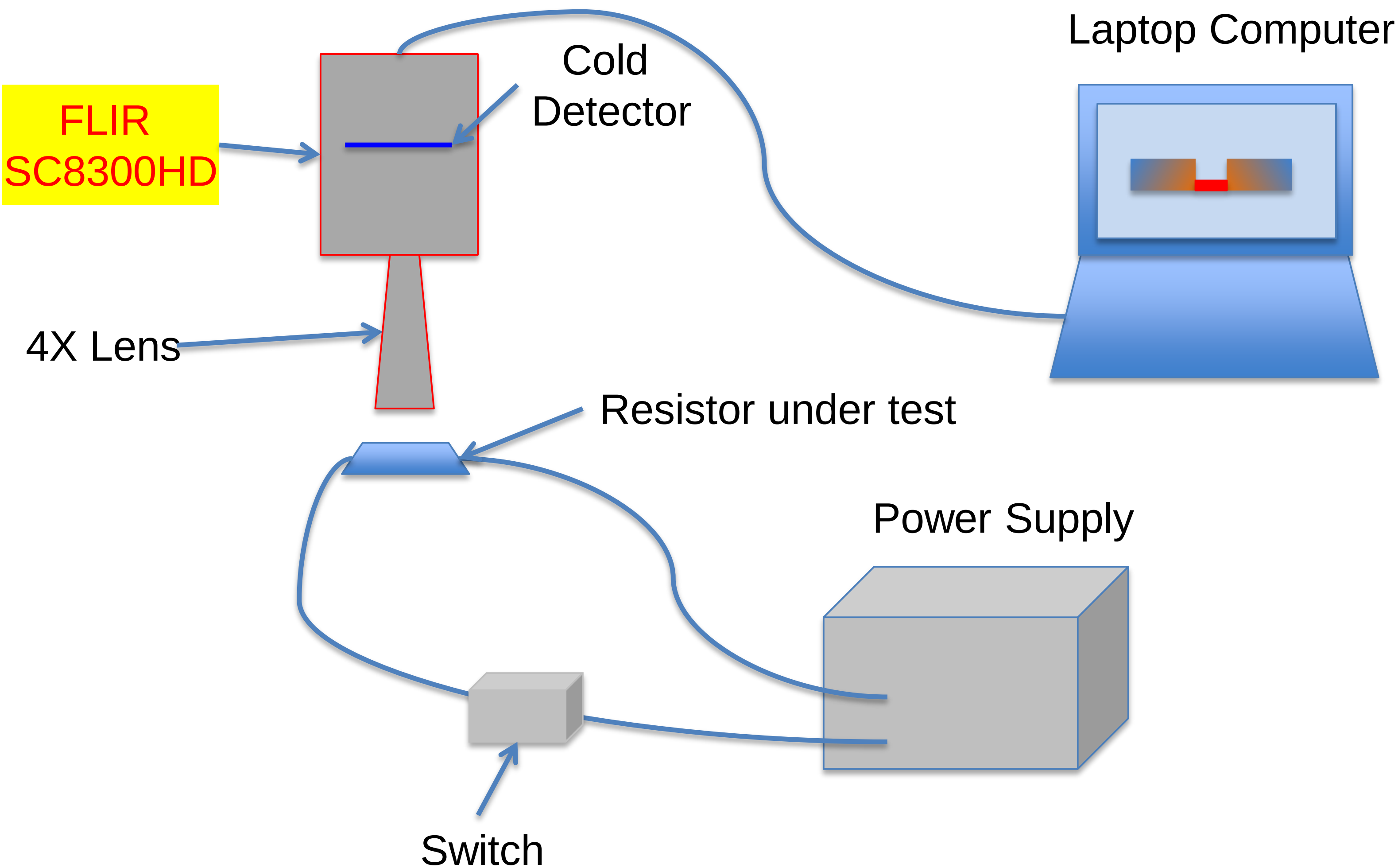
A Conclusion



A thermal camera that is a microscope is needed

We were trying to look at something that was 4 microns wide with a camera with a 25 micron pixel resolution.

New Test Setup



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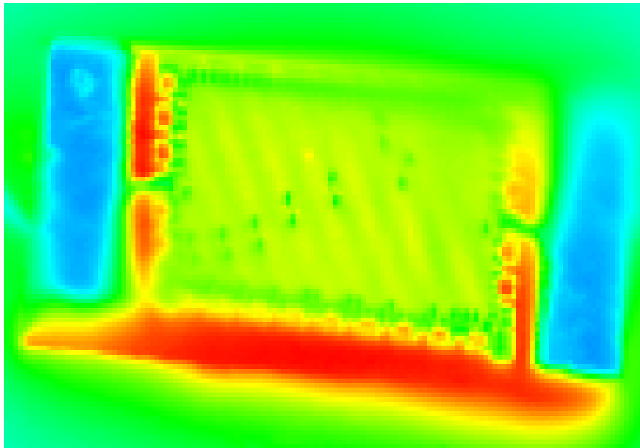
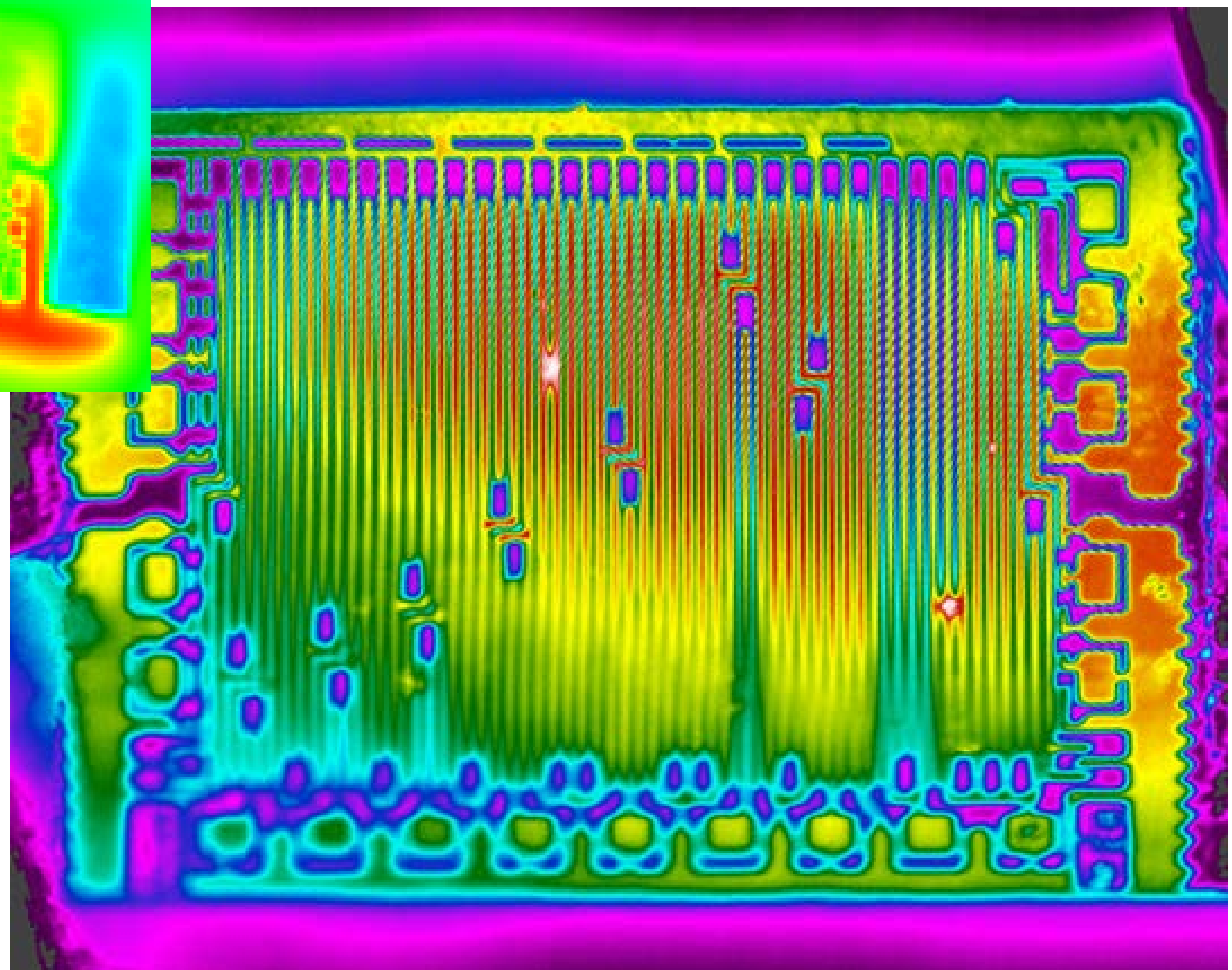
First Light

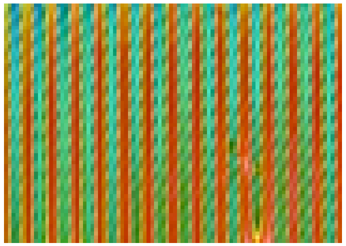
Was



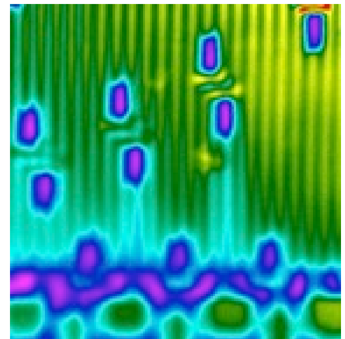
IS



Items of Interest from First Light

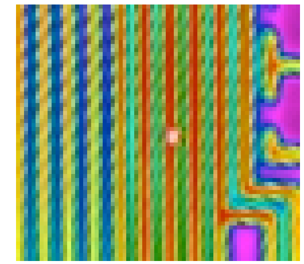


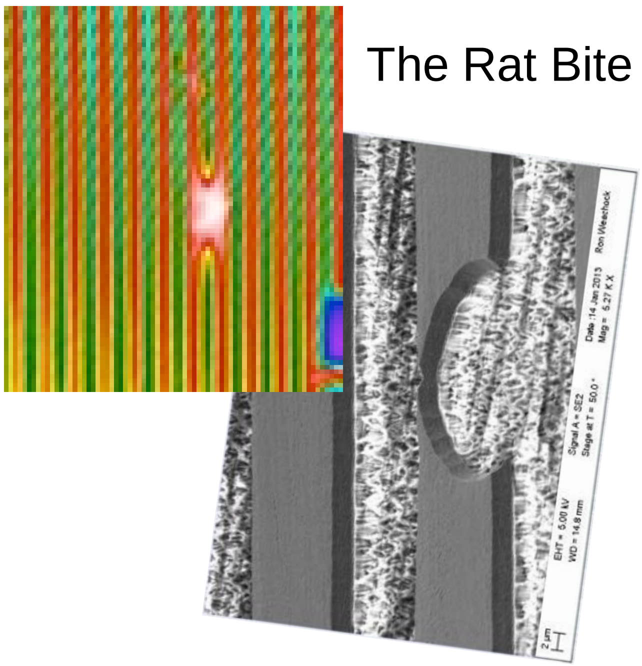
Moiré Patterns



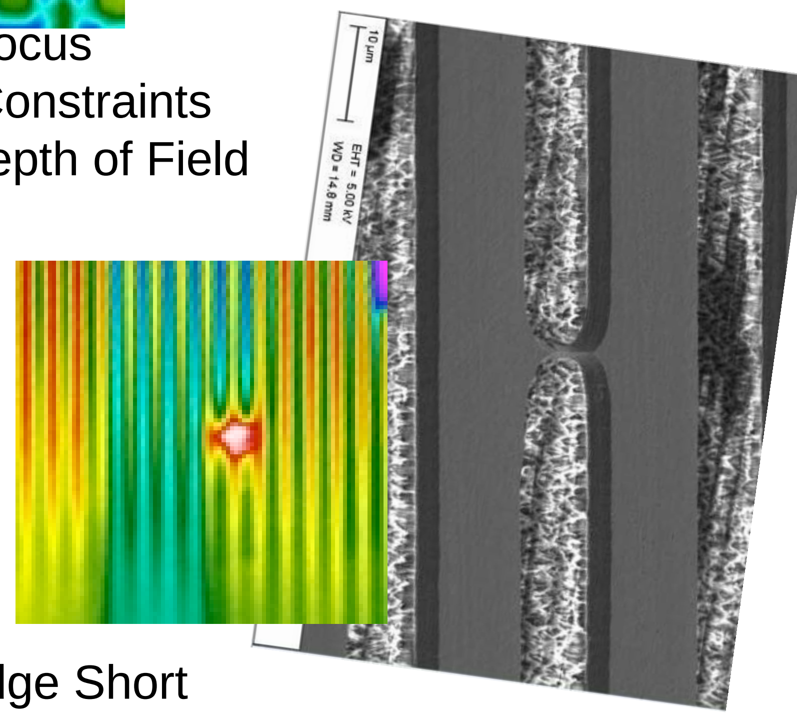
Out of Focus
Due to Time Constraints
Very Shallow Depth of Field

Dust



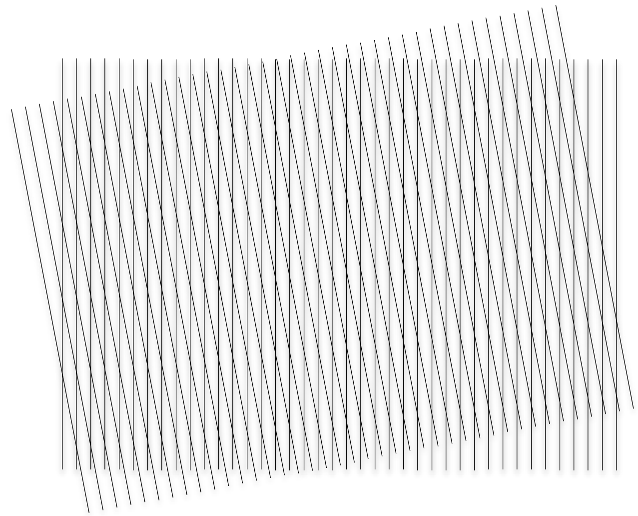


The Rat Bite

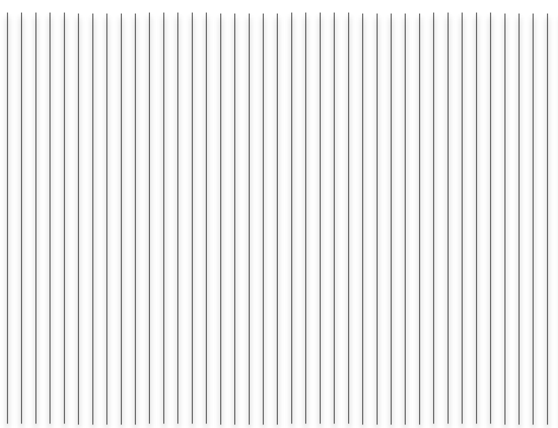


Bridge Short

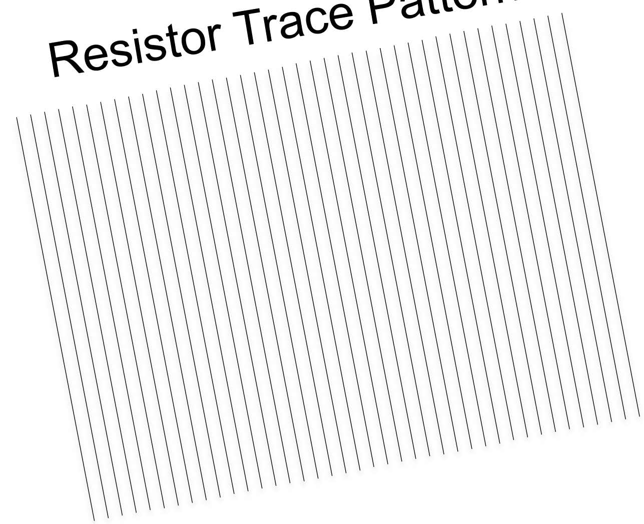
Moiré Pattern (11° Angle Fine Line)



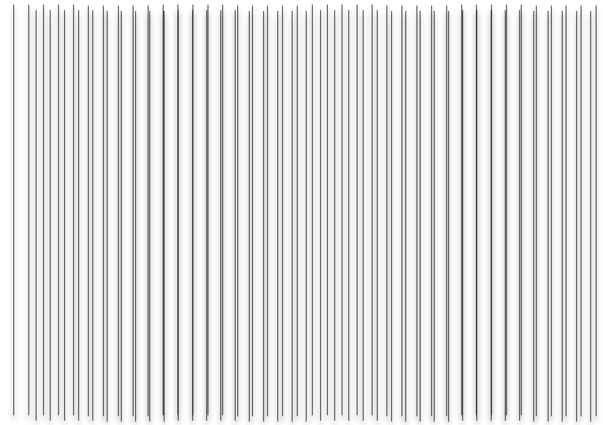
Camera Pixel Pattern



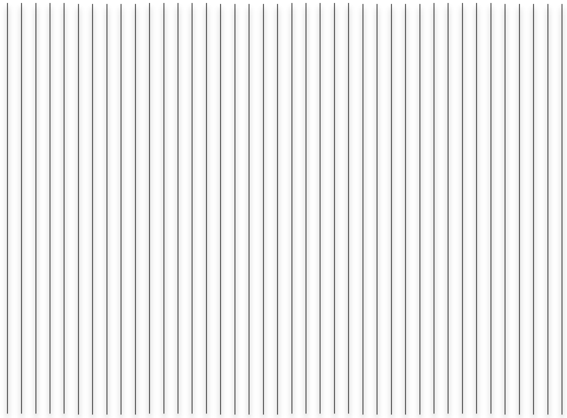
Resistor Trace Pattern



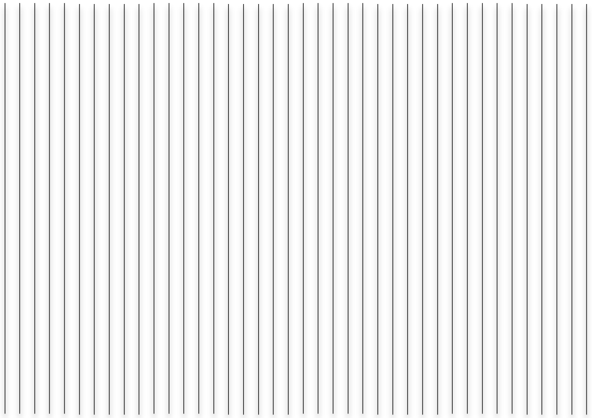
Moiré Pattern (Parallel Fine Line)



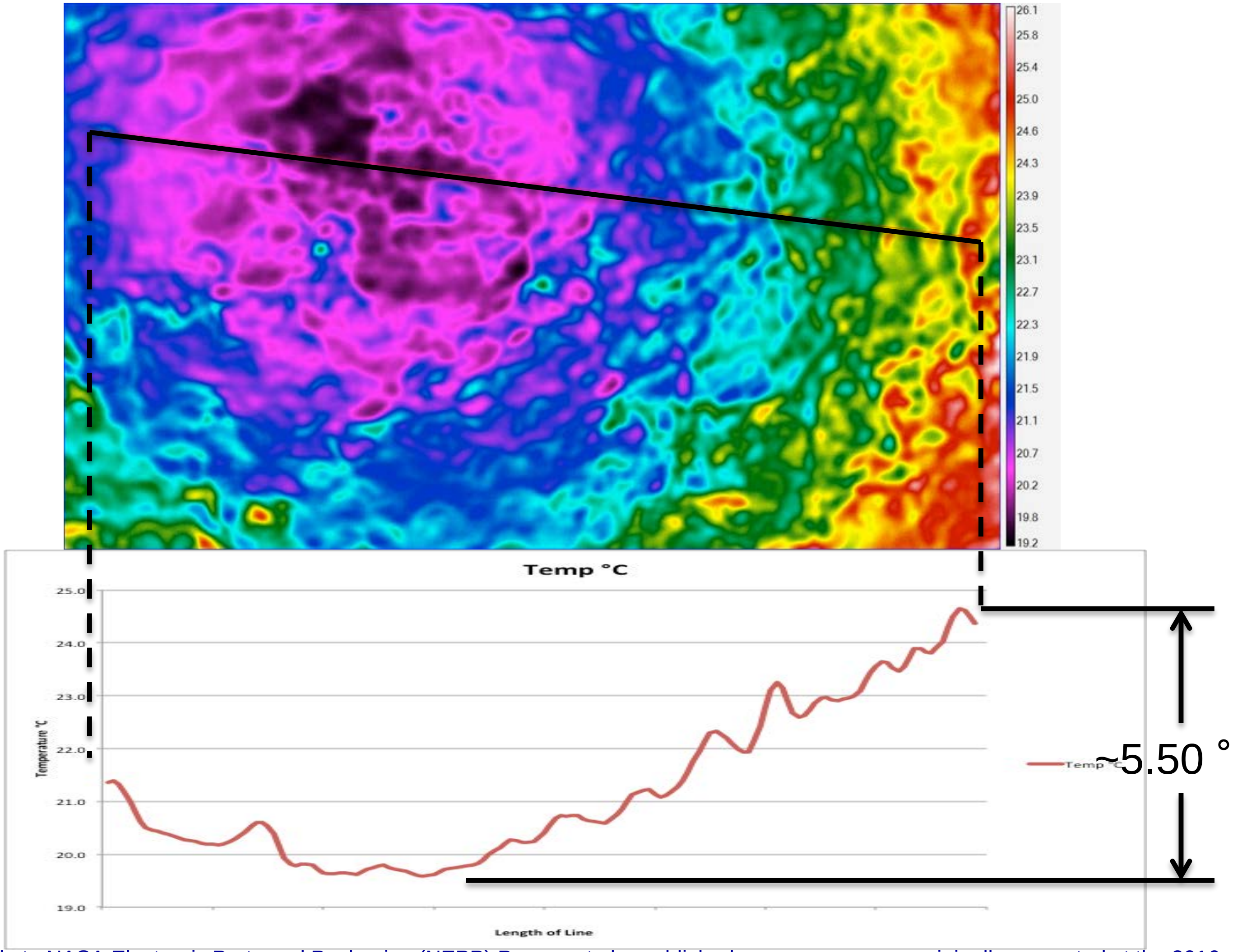
Camera Pixel Pattern



Resistor Trace Pattern



Narcissus Effect on Emissivity Measurement



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Room Temp with One Emissivity

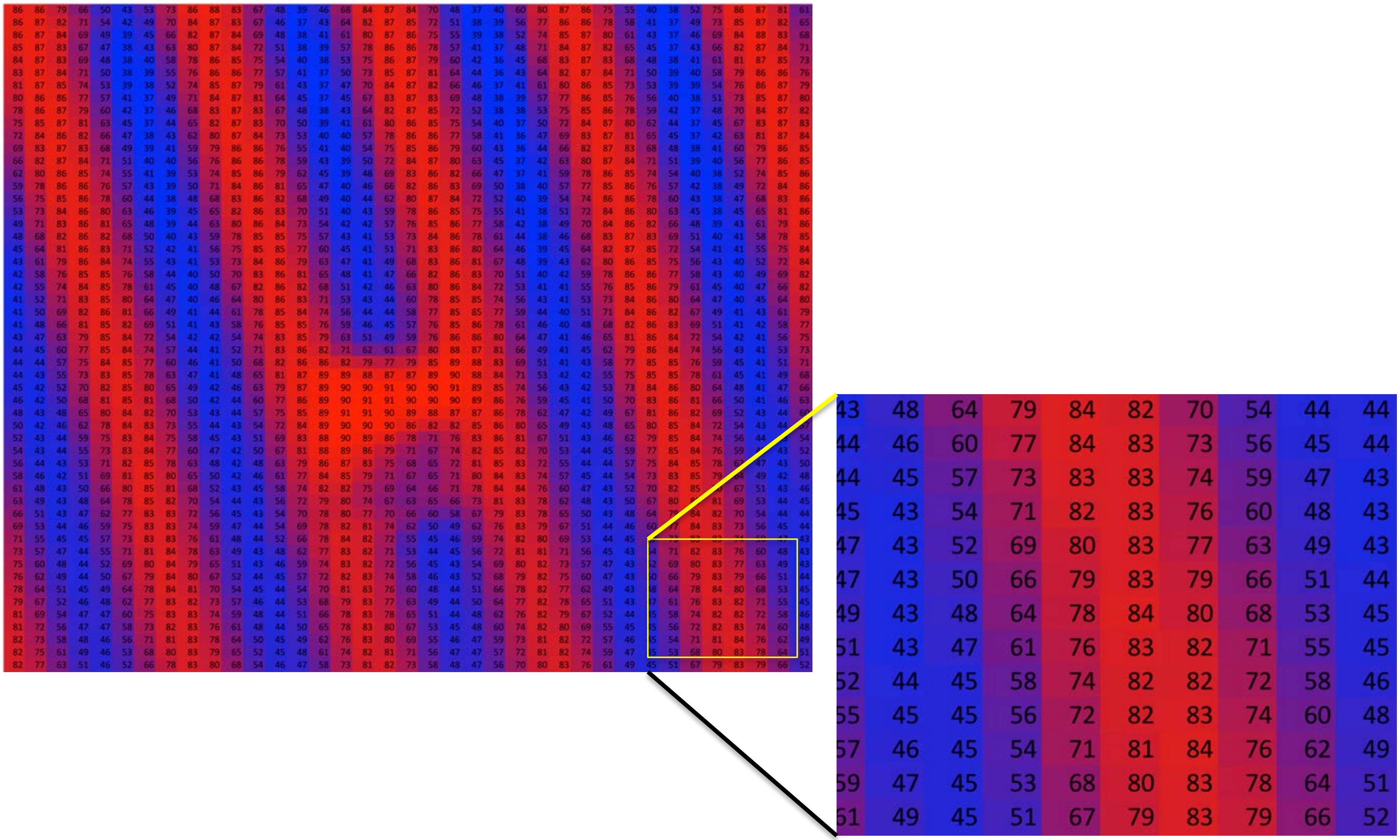
21.4	19.3	14.5	10.8	10.2	14.0	19.0	21.3	21.5	20.1	15.8
21.4	19.7	15.6	11.2	10.0	13.0	18.4	21.1	21.5	[illegible]	[illegible]
21.4	20.1	16.3	11.7	10.0	12.4	17.7	20.9	21.6	[illegible]	[illegible]
21.5	20.4	16.9	12.2	10.2	11.7	16.9	20.6	21.6	[illegible]	[illegible]
21.5	20.7	17.6	12.8	10.4	11.3	16.1	20.1	21.5	[illegible]	[illegible]
21.5	20.9	18.1	13.5	10.4	11.0	15.3	19.7	21.5	21.3	19.1
21.5	21.1	18.8	14.2	11.0	10.6	14.6	19.3	21.2	21.4	19.5
21.3	21.2	19.2	15.0	11.3	10.5	13.7	18.7	21.1	21.4	19.9
21.2	21.3	19.7	15.7	11.7	10.6	13.1	18.1	20.9	21.5	20.4
21.0	21.4	20.0	16.4	12.3	10.5	12.7	17.5	20.7	21.5	20.6
20.8	21.4	20.4	17.1	12.8	10.7	12.2	16.9	20.5	21.5	20.8
20.5	21.4	20.6	17.7	13.3	10.9	11.8	16.2	20.2	21.5	21.1
20.1	21.3	20.9	18.4	13.9	11.2	11.4	15.4	19.8	21.3	21.3
19.8	21.2	21.1	19.0	14.8	11.5	11.2	14.9	19.5	21.3	21.4
19.1	21.2	21.3	19.5	15.5	12.1	11.6	14.8	19.3	21.2	21.4
18.7	21.0	21.3	20.0	16.6	13.4	13.0	15.5	19.5	21.4	21.5
18.2	20.8	21.4	20.6	18.4	16.7	16.3	17.6	20.2	21.7	21.7
17.4	20.4	21.5	21.4	20.8	20.3	20.0	20.2	21.2	22.0	21.9
16.8	20.3	21.6	22.0	22.0	22.0	21.8	21.8	22.0	22.2	21.9

Actual Temp's 23C

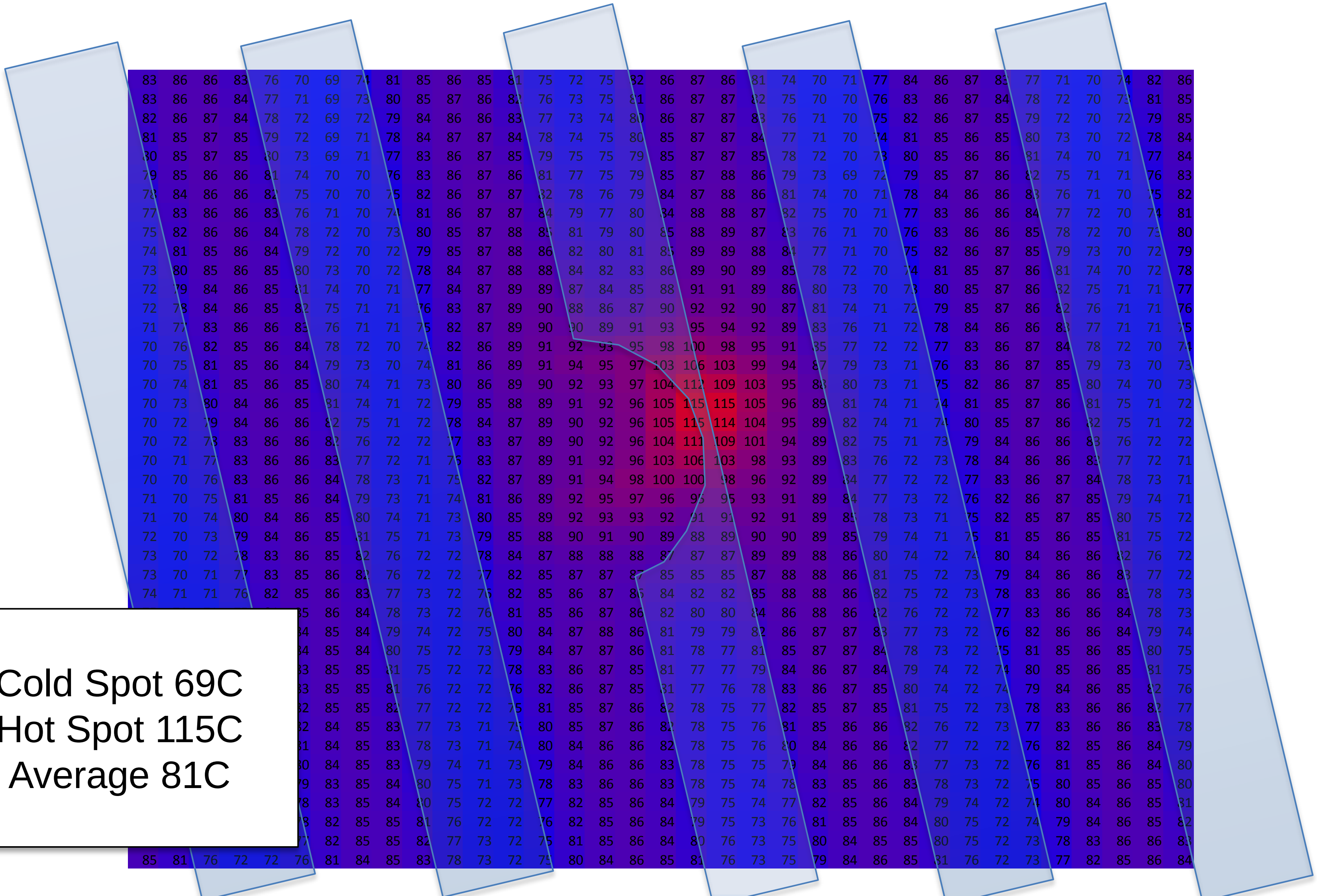
10.5C

21.7C

Emissivity Map

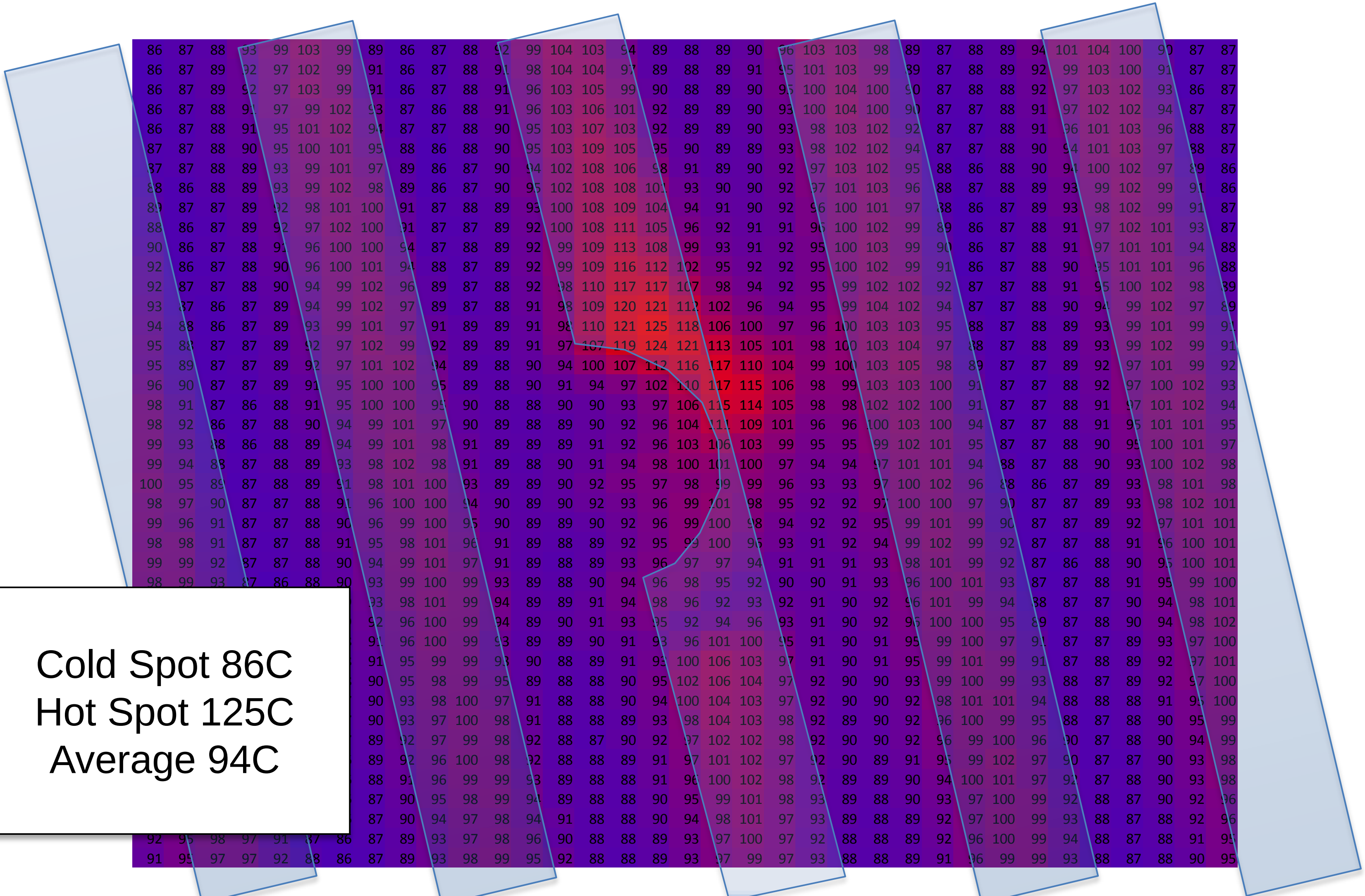


Rat Bite at One Emissivity



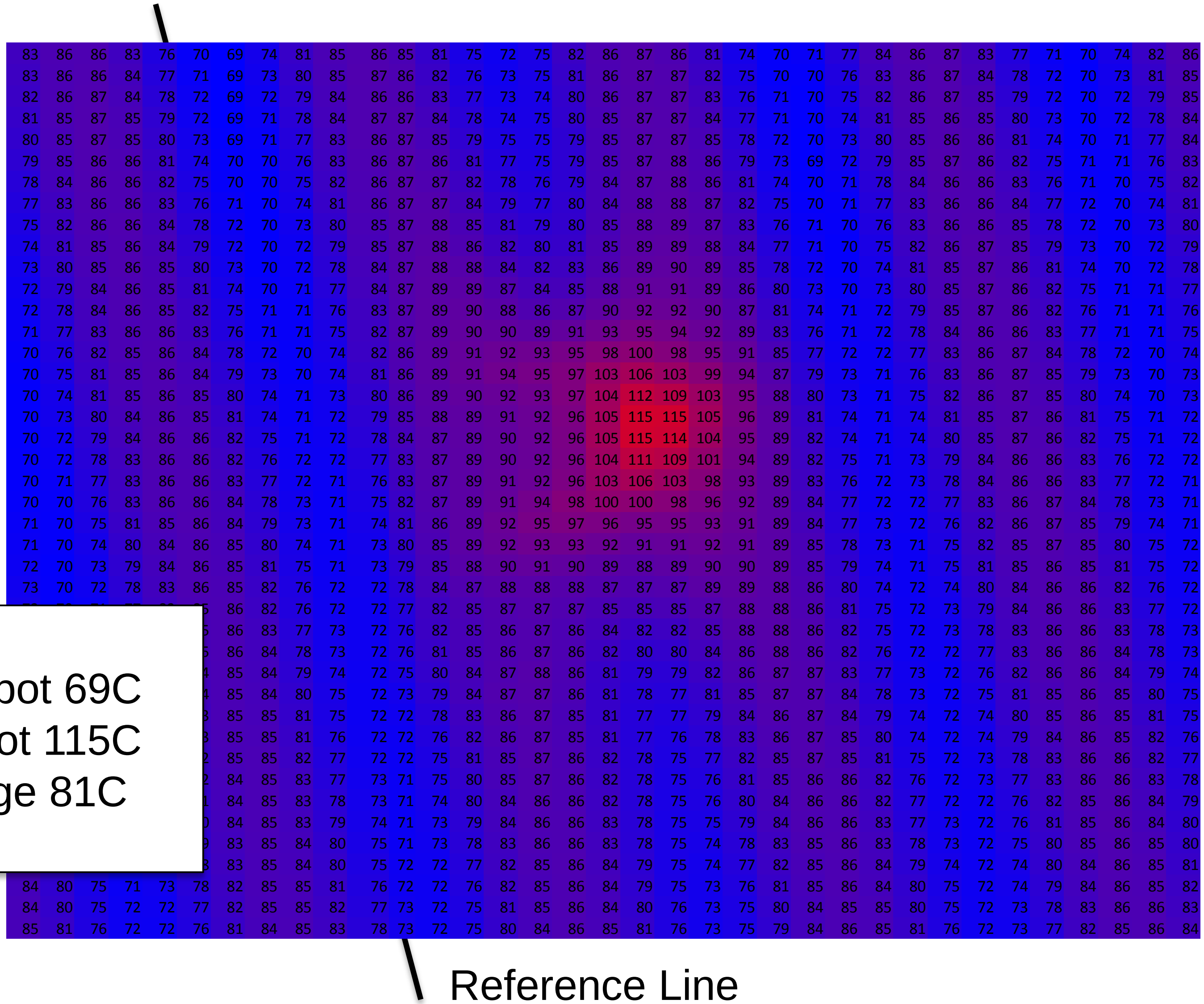
Cold Spot 69C
Hot Spot 115C
Average 81C

Hot Spot Adjusted Emissivity



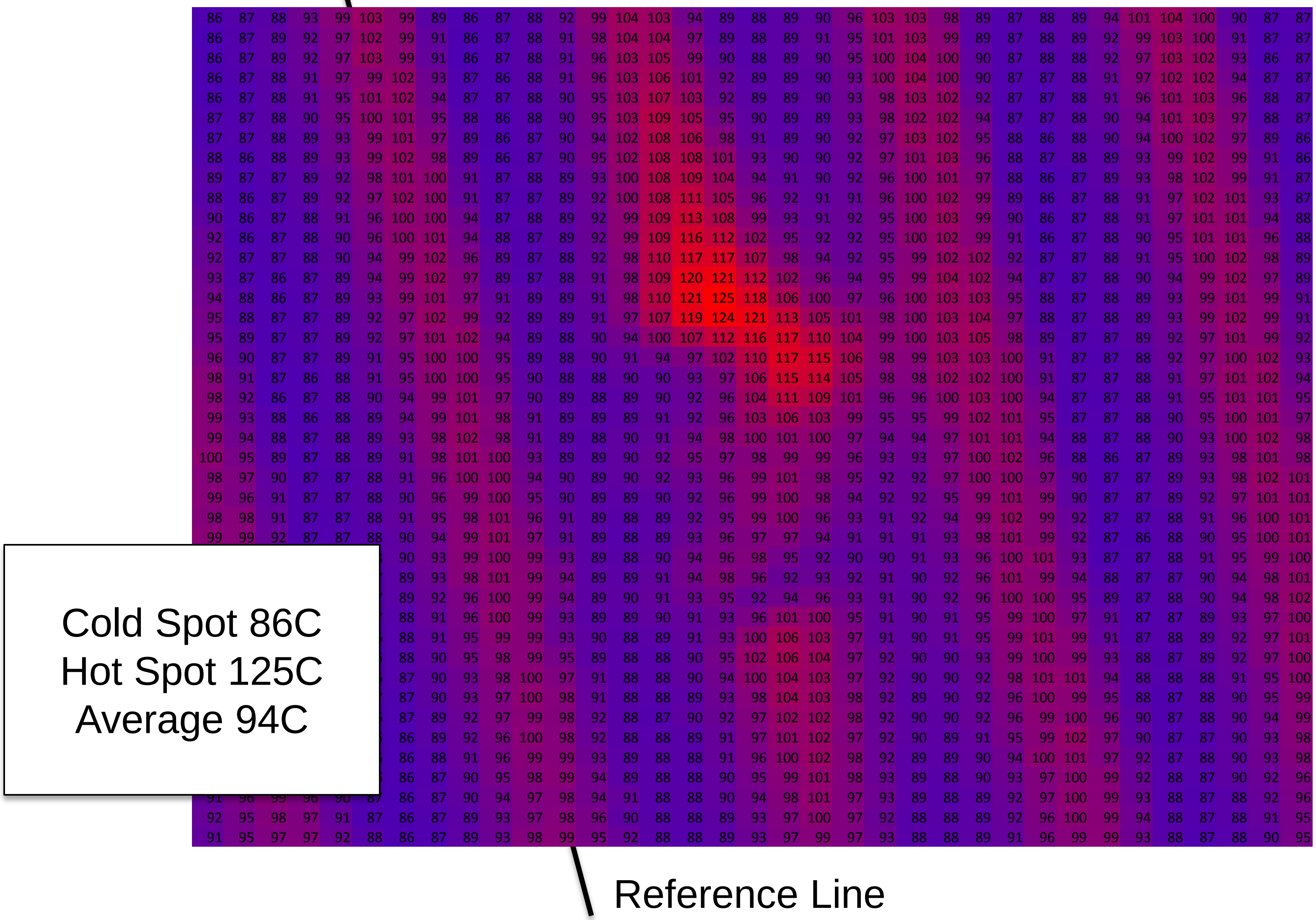
Cold Spot 86C
Hot Spot 125C
Average 94C

Rat Bite at One Emissivity



Cold Spot 69C
Hot Spot 115C
Average 81C

Hot Spot Adjusted Emissivity

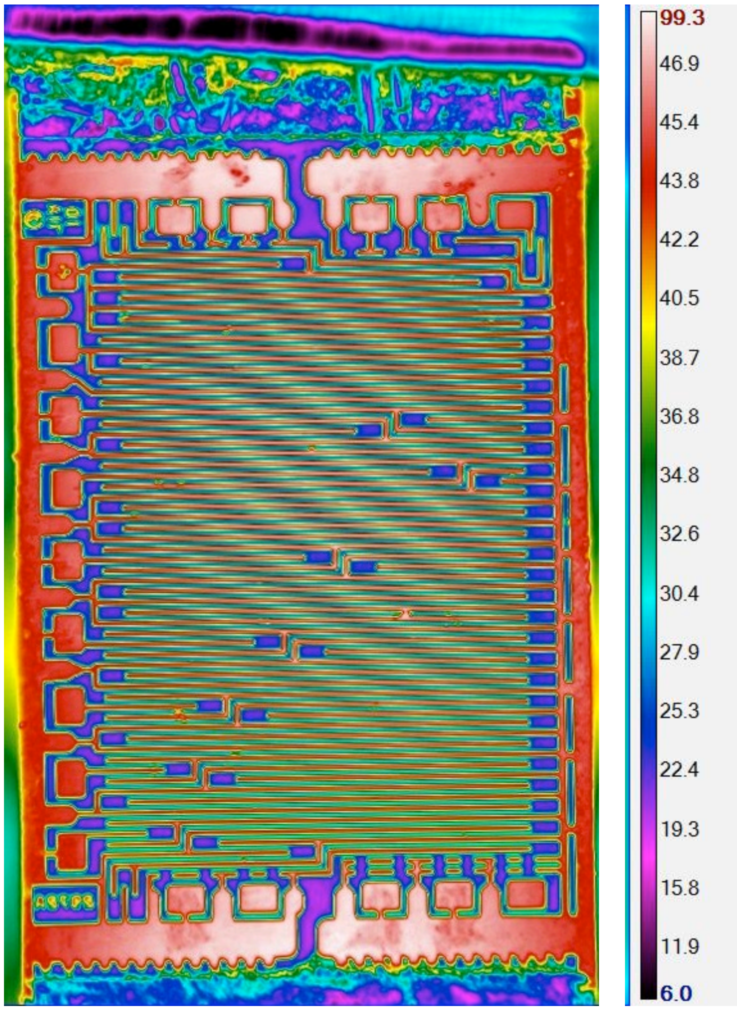


Lesson Learned

Because of the very small size of the part the trace internal to the resistor heats up quickly and cools off quickly.

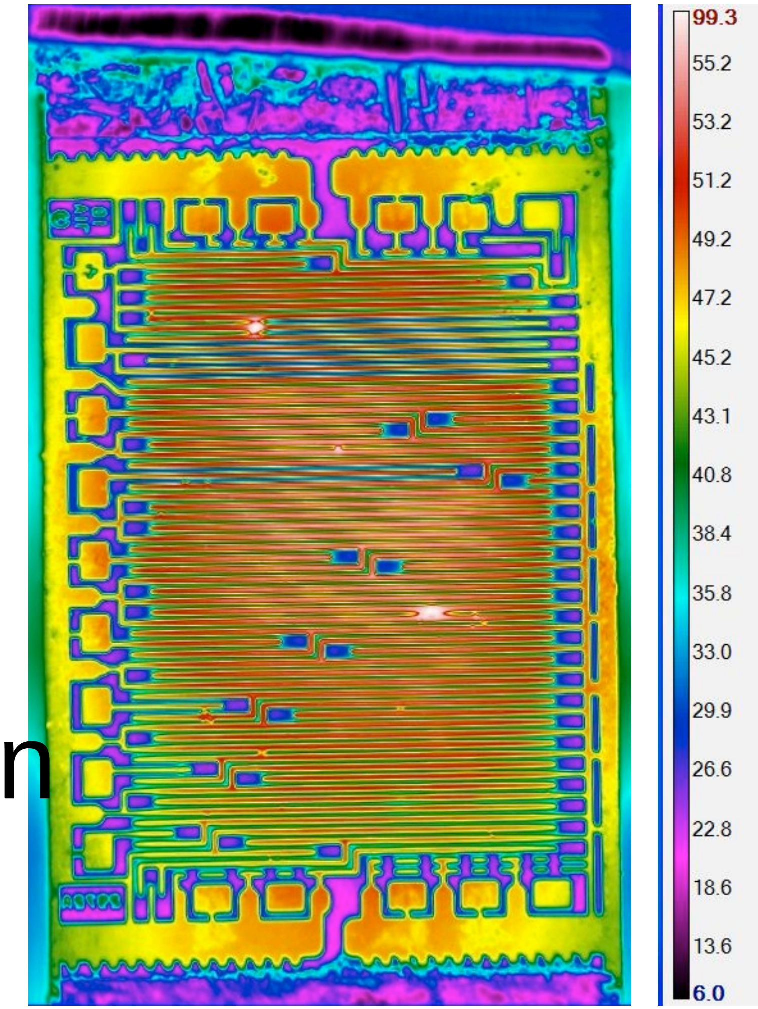
Thermal cycling is quick, and testing with many cycles is beneficial

Pulse Test

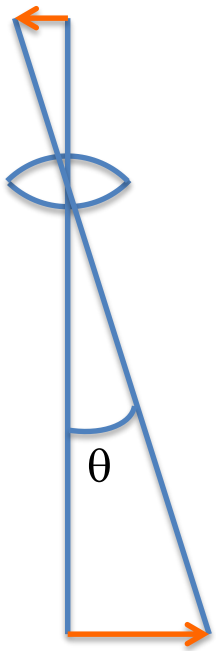


Off

On

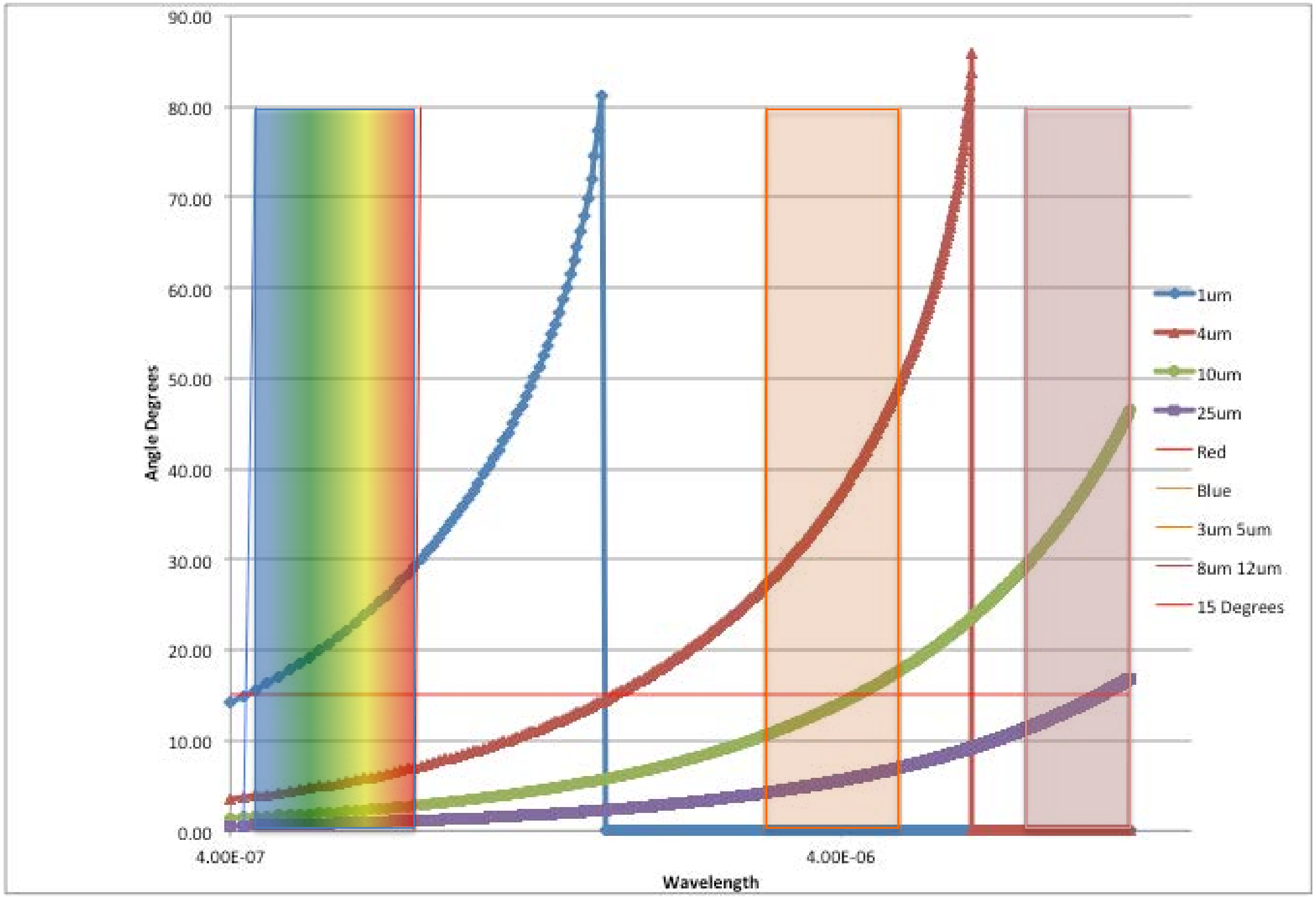


Resolution (r)

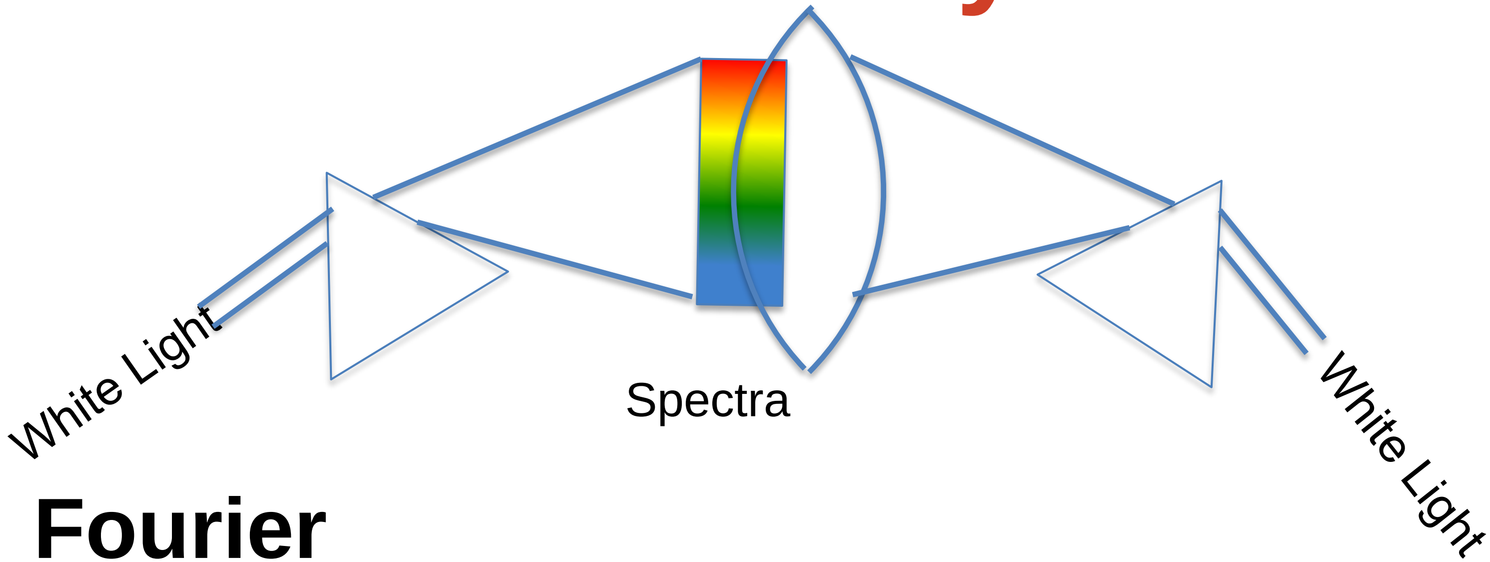


$$r = \frac{1.22\lambda}{2n \sin\theta}$$

Wavelength vs Angle

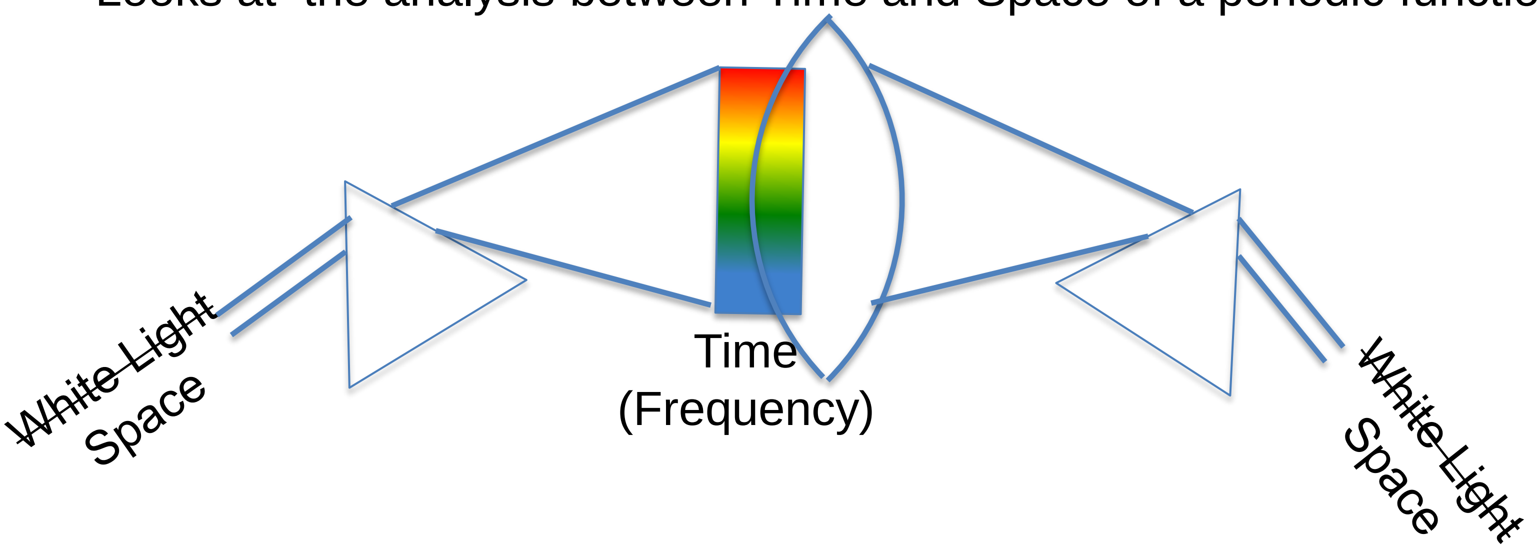


Newtonian Physics

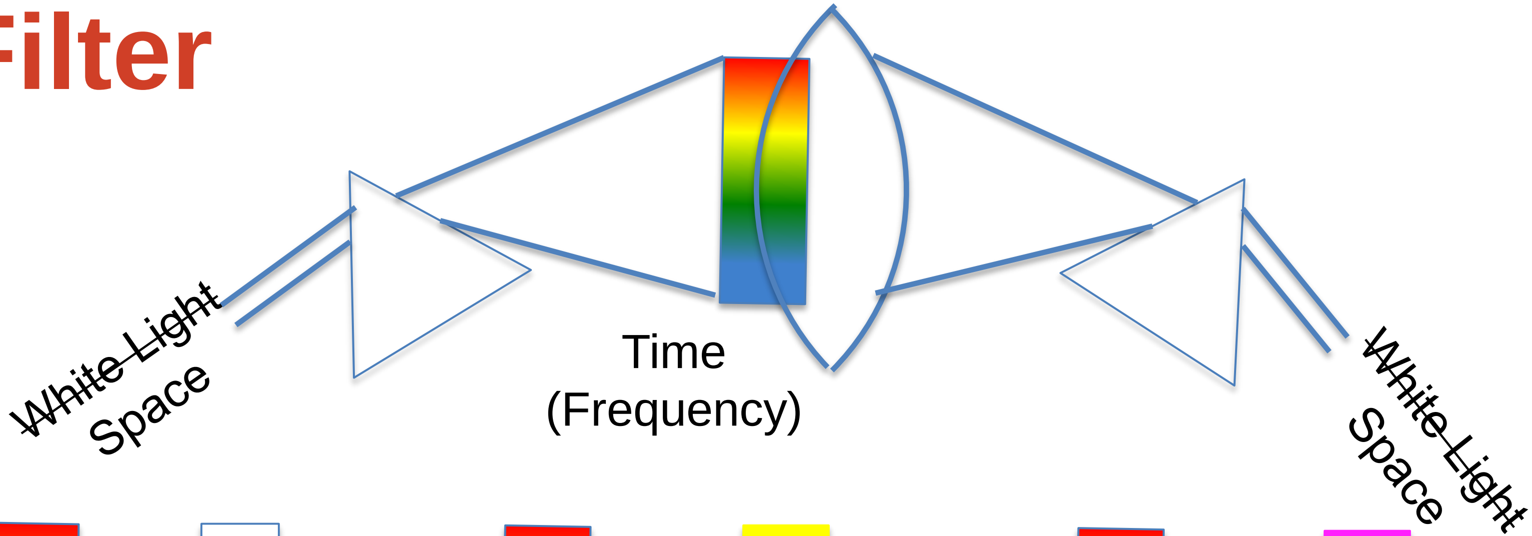


Fourier

Looks at the analysis between Time and Space of a periodic function



Use of Fourier Transform as a Filter



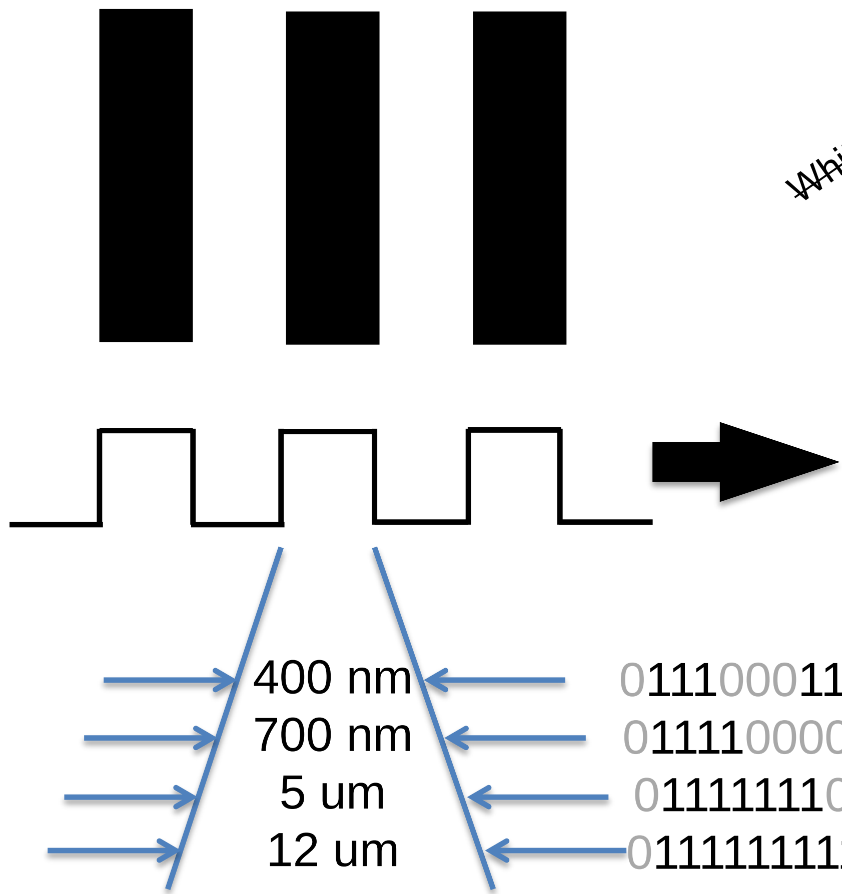
Spectra No Blocking
White

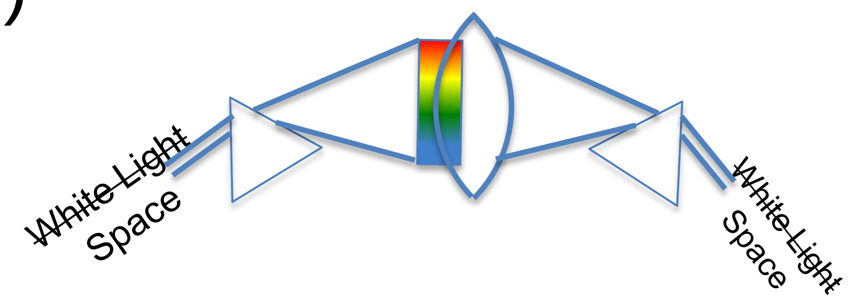
Spectra Blocking Blue
Yellow

Spectra Blocking Green
Magenta

Resolution of Periodic Signal (Lines)

Line Width (space)





0111111000000111111000001

0111000111000111000111 0

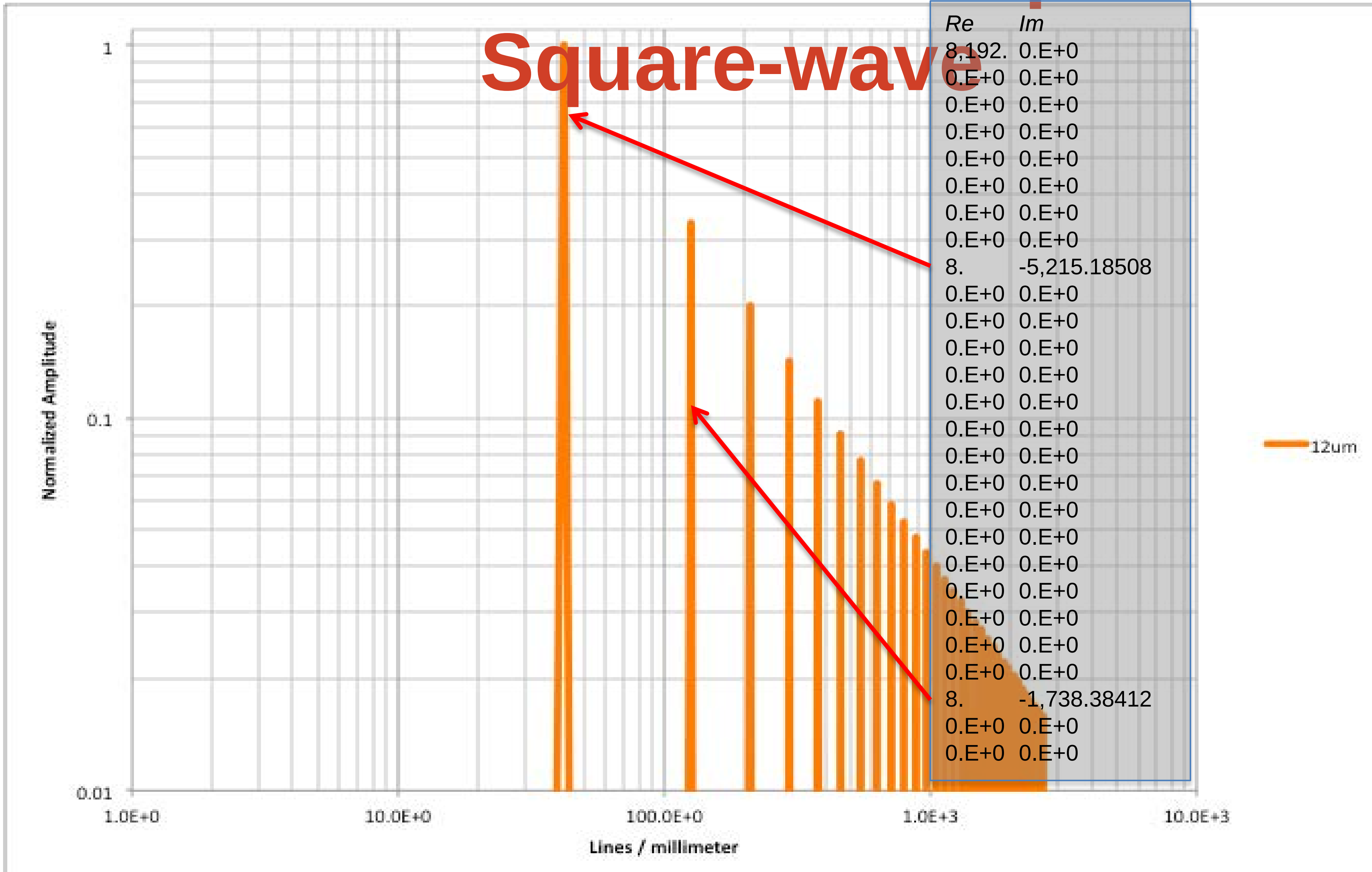
01111000011110000111100

0111111100000001111111 0

0111111111100000000011

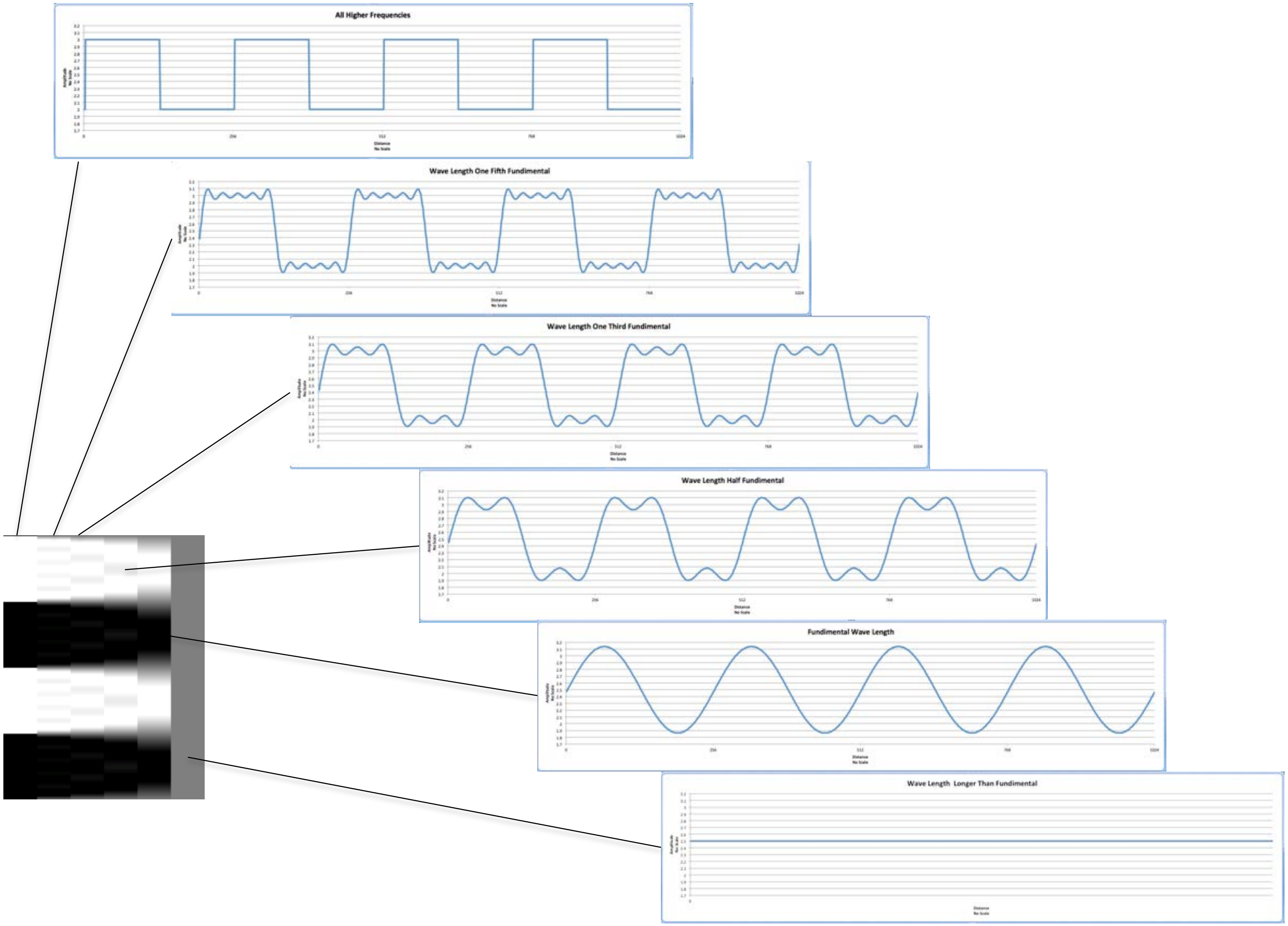
Not to scale

Fourier Transform of 12µm Square-wave

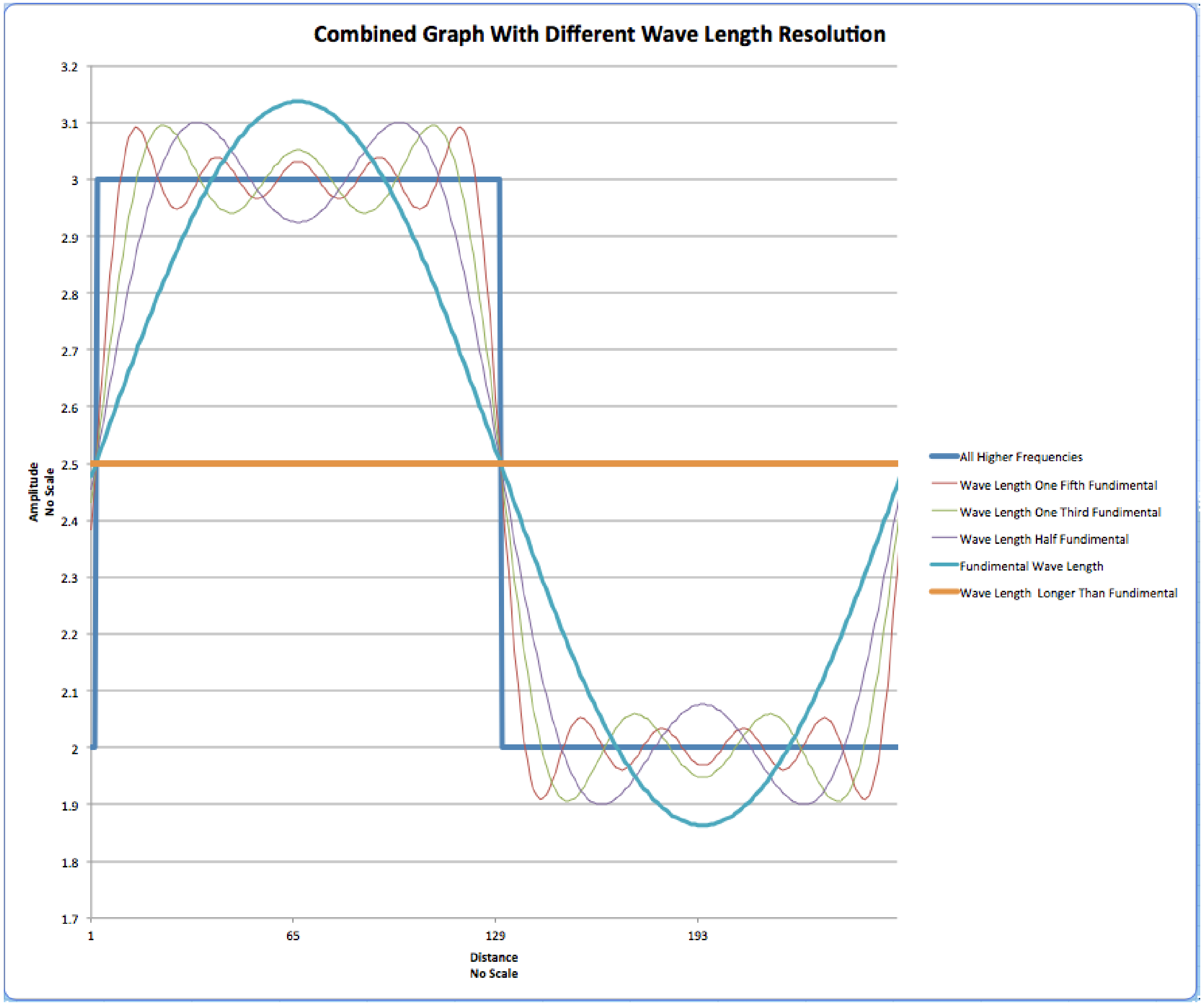


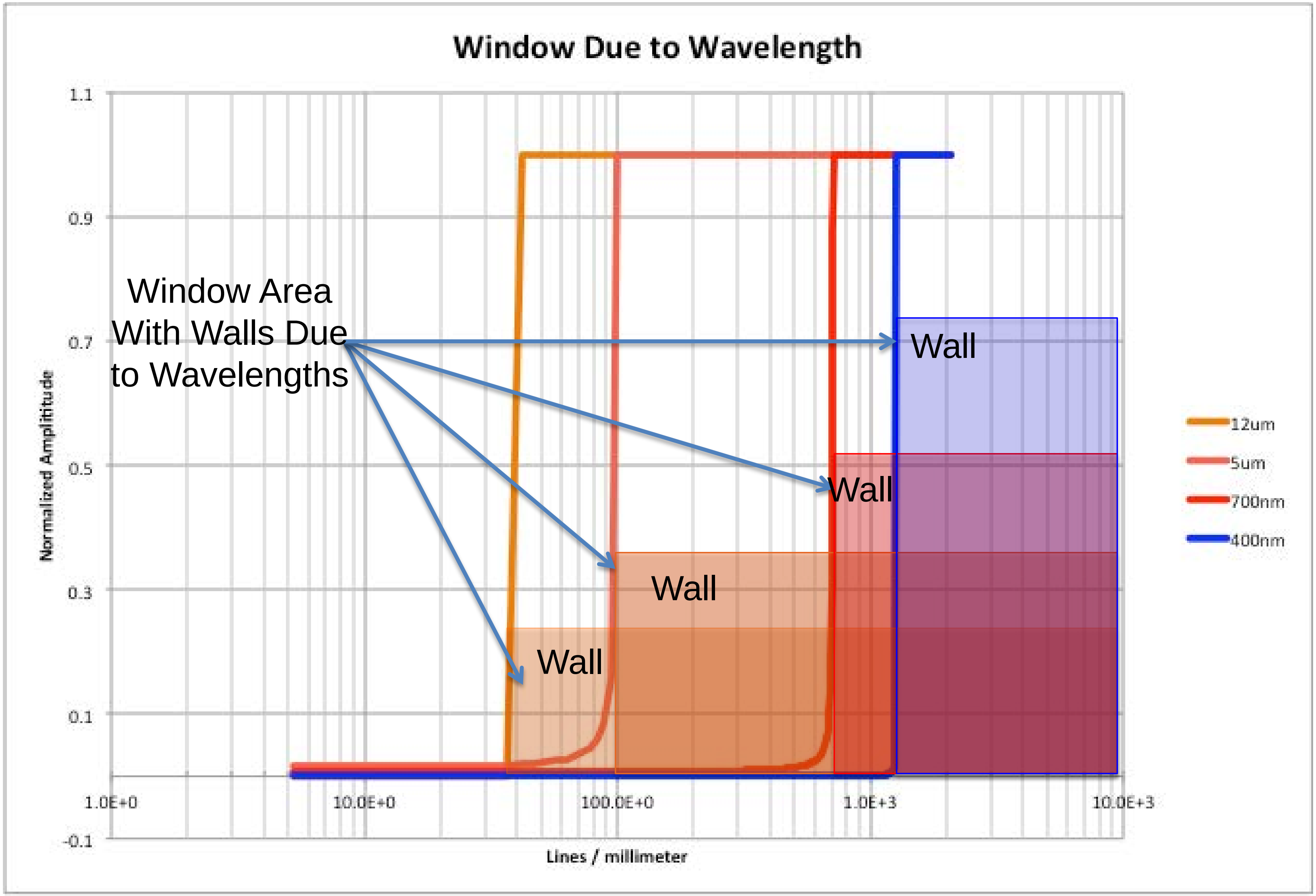
Re	*Im*
8,192.	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
8.	-5,215.18508
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
8.	-1,738.38412
0.E+0	0.E+0
0.E+0	0.E+0

Fourier Remove of Frequencies

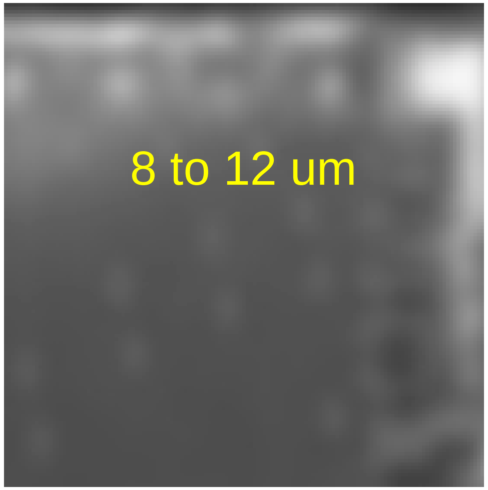


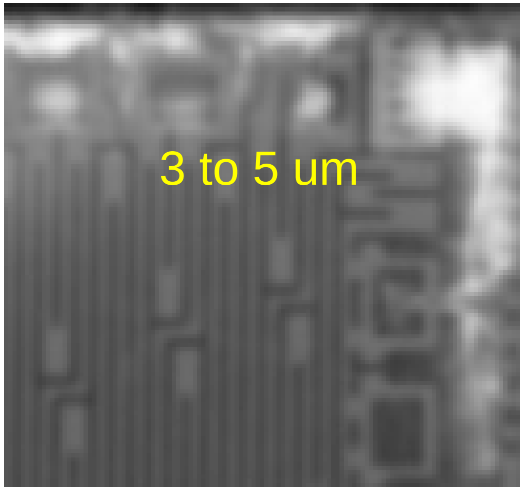
Fourier Remove of Frequencies

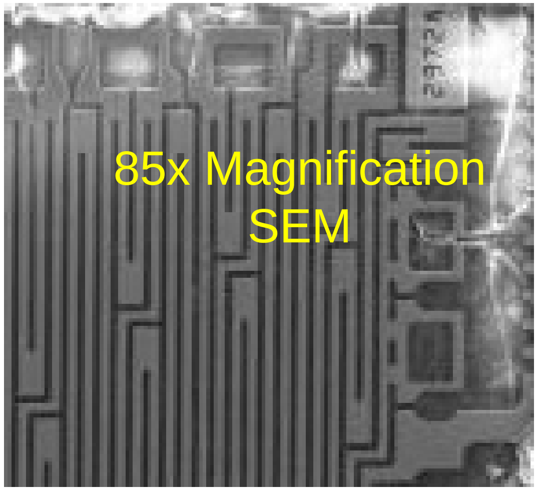


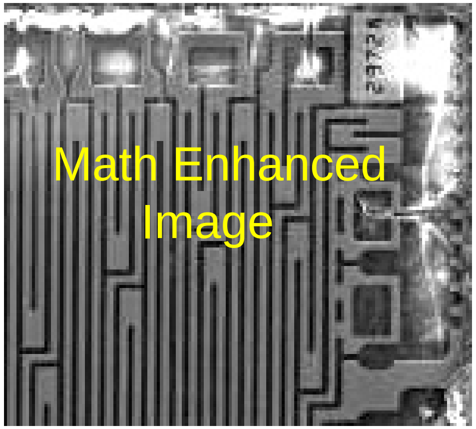

Window Due to Wavelength
1.1
0.9
0.7
0.5
0.3
0.1
-0.1
Normalized Amplititude
1.0E+0
10.0E+0
100.0E+0
1.0E+3
10.0E+3
Lines / millimeter
Window Area
With Walls Due
to Wavelengths
Wall
Wall
Wall
Wall
12um
5um
700nm
400nm

Simulation of Resolution of different Wavelengths









Conclusions

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- There are test setup issues with using a Thermal Microscope.
  – Moiré Patterns

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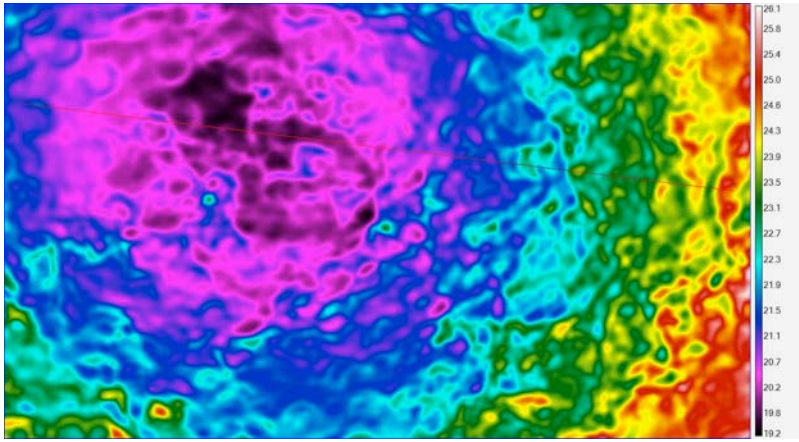

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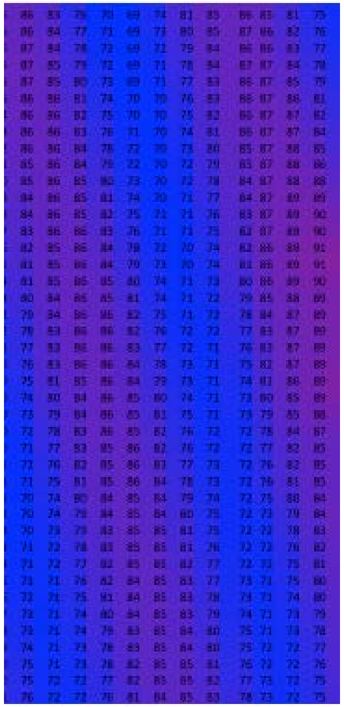
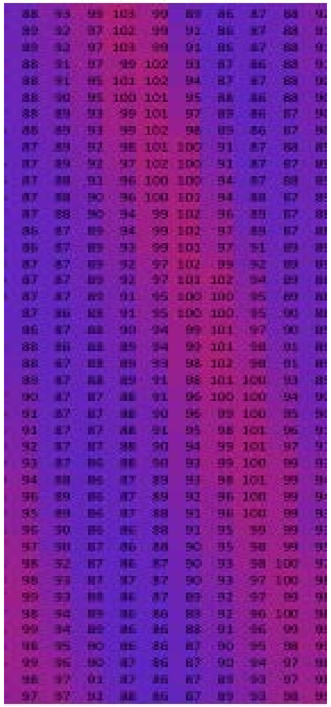
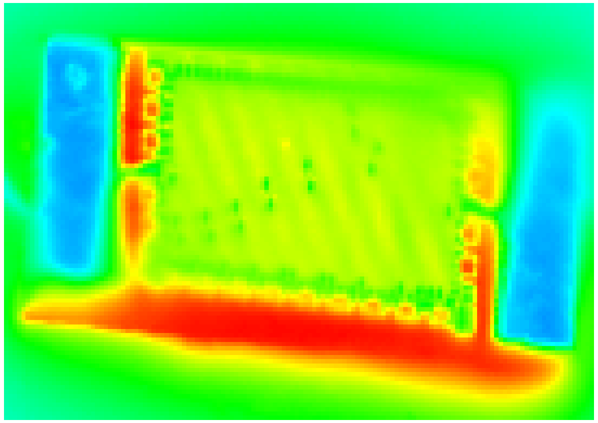
  - – Emissivity





Conclusions

- Defects do cause hot spots
- There are test setup issues with using a Thermal Microscope.
  - Moiré Patterns
  - Narcissus effects
  - Emissivity
  - Limits on Resolution in the IR




Thank You