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The Future of Thermal Imaging

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Submicron Device Level Thermal Characterization for Photonics and Power MMICs

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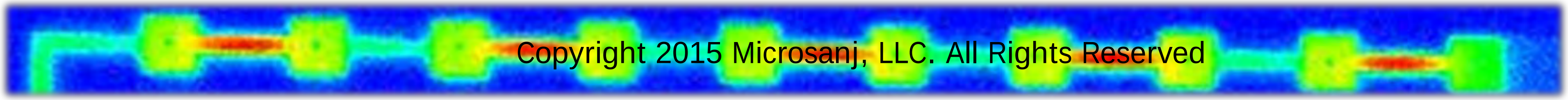
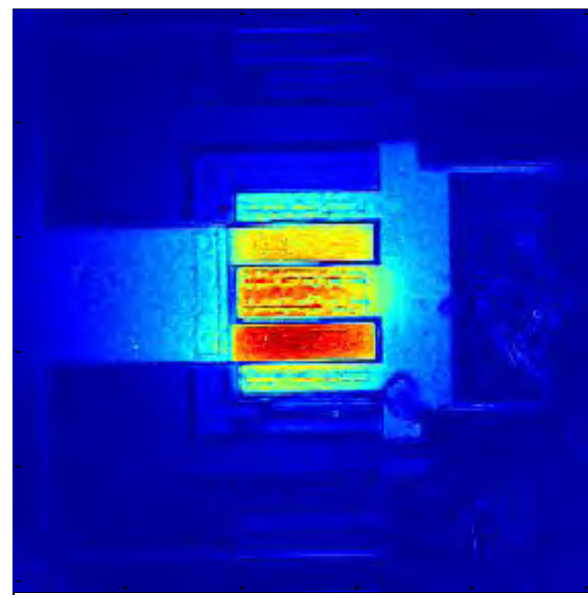
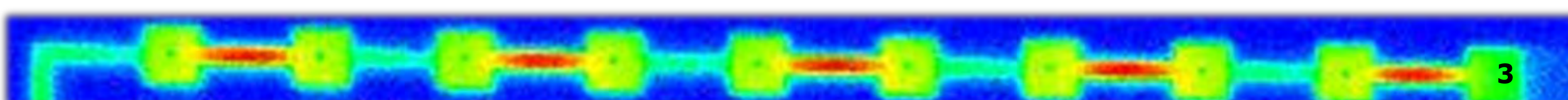


Key Features

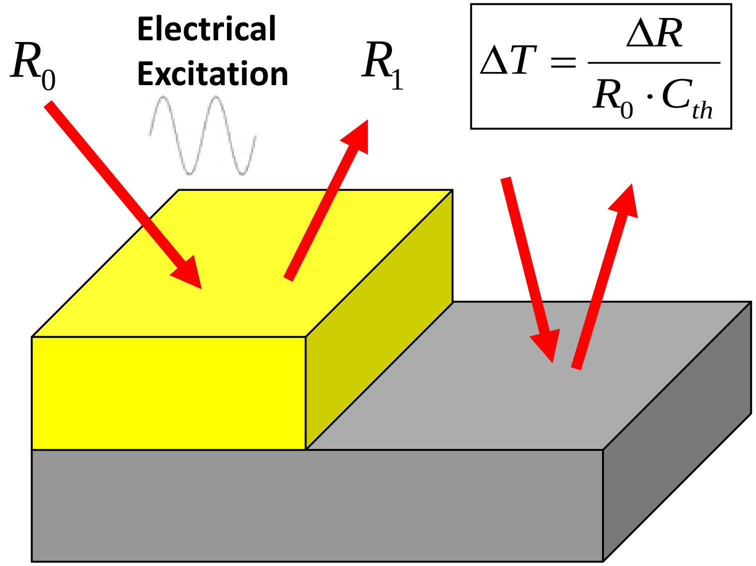
- ✓ Superior submicron spatial resolution for more accurate peak temperature measurements **(250nm)**
- ✓ High temperature resolution **(<0.1 ºC)** with lock-in
- ✓ High speed transient imaging **(800ps/50ns options)**
- ✓ Through-the-Substrate imaging
- ✓ Low cost with high performance



- [ ] Basic Principles of Thermoreflectance Imaging
- [ ] Measurement for HEMT Transistor
- [ ] Transient measurements
- [ ] GaN High Power Amplifiers
- [ ] ESD protection devices
- [ ] Failure Analysis (FA) HotSpot detection
- [ ] Vias and Interconnects
- [ ] Optoelectronics (Photodiodes, Solar Cells, LEDs, and Lasers)
- [ ] Power amplifiers
- [ ] Sub-diffraction thermoreflectance thermal imaging
- [ ] Summary



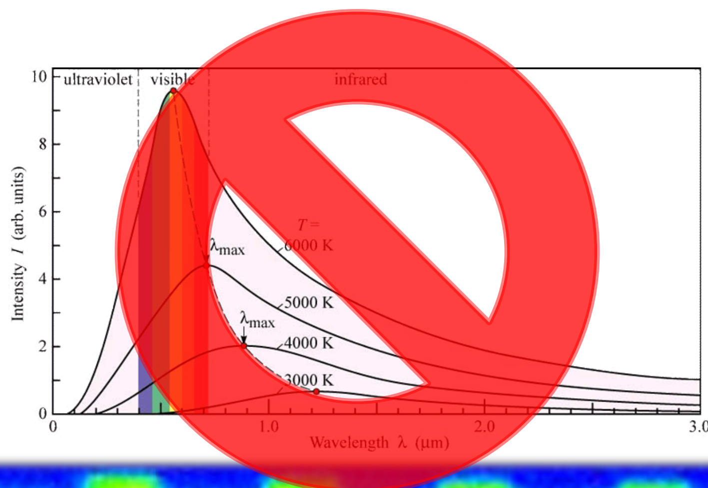
Thermoreflectance



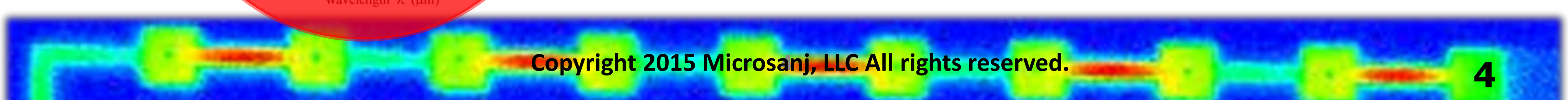
$$\Delta T = \frac{\Delta R}{R_0 \cdot C_{th}}$$

- Thermoreflectance is the <u>change in reflected light due to a change in temperature</u>.

- 250nm Spatial Resolution
- 800ps Time Resolution
- <0.1C Temperature Resolution



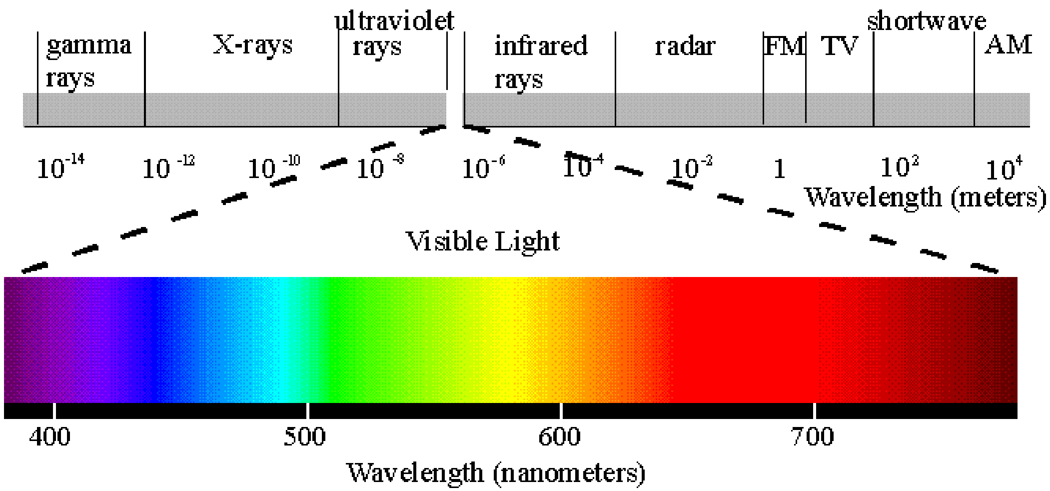
<u>Thermoreflectance is not based on black-body radiation</u>



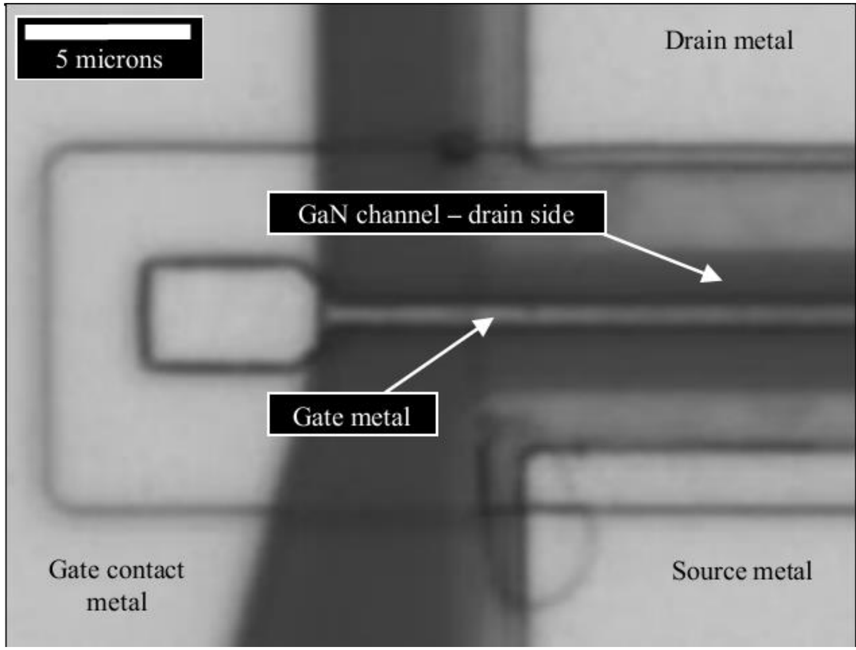
Diffraction Limited Spatial Resolution

$$R \approx \frac{\lambda}{2\,NA}$$

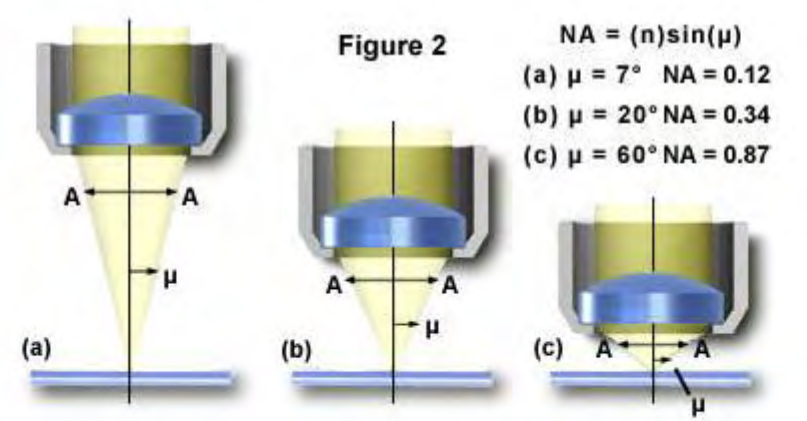
~260 nm for 470 nm light & 0.9 NA

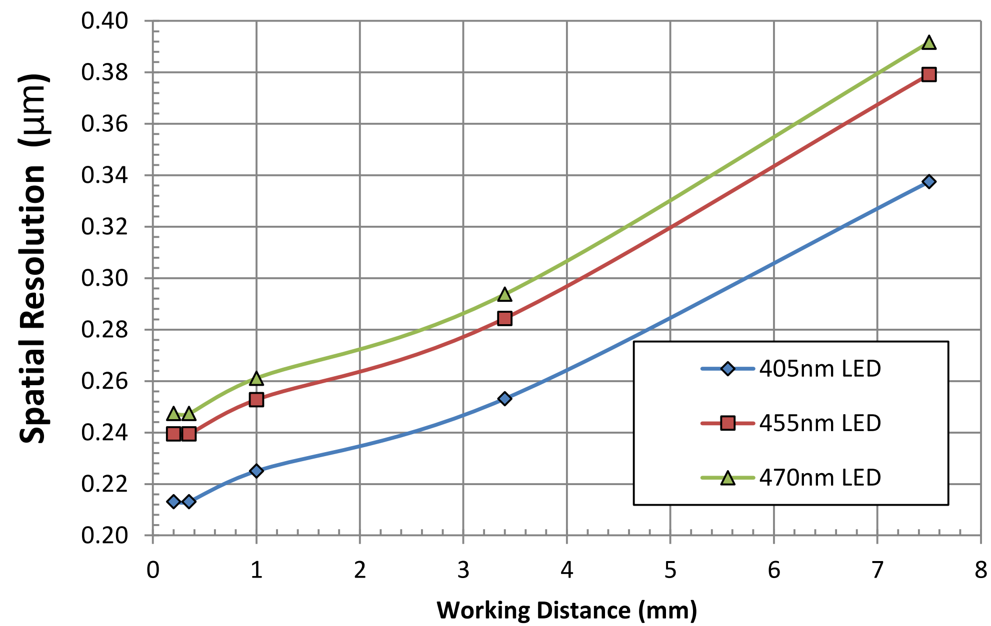


0.5µm GaN Gate

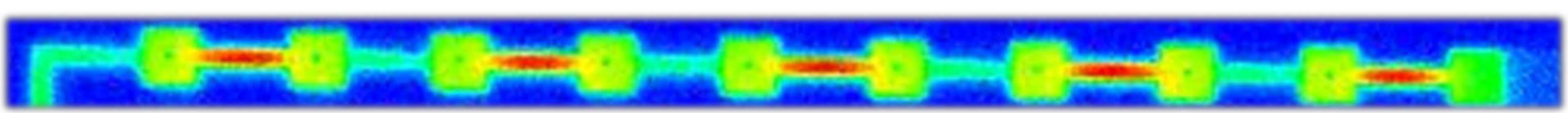


Spatial Resolution and Working Distance

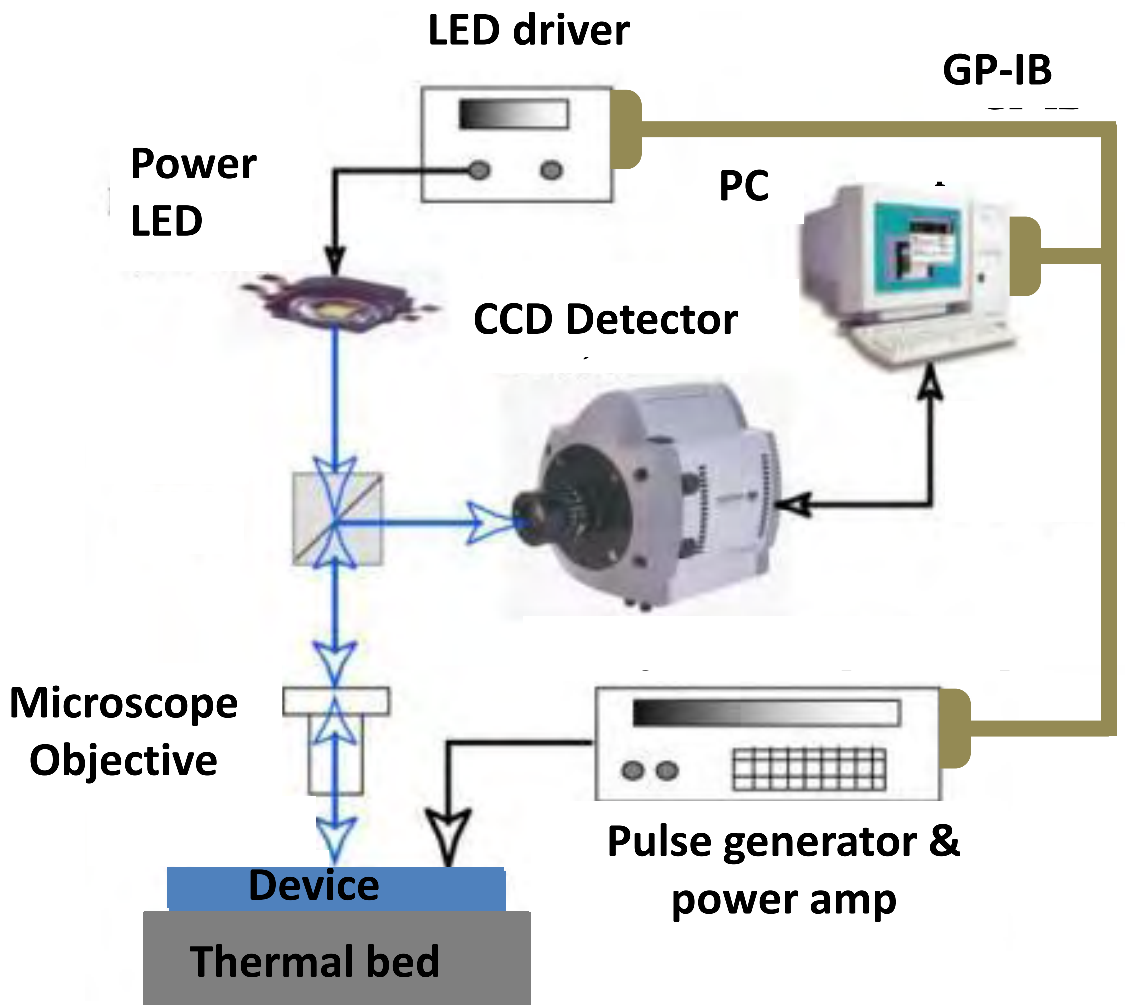




			Abbe Optical Resolution (μm)		
	N.A.	Working Distance (mm)	405nm LED	455nm LED	470nm LED
SLMPLN 100x	0.6	**7.5**	0.34	**0.38**	0.39
LMPLFLN 100x	0.8	**3.4**	0.25	**0.28**	0.29
MPLFLN 100x	0.9	**1.0**	0.23	**0.25**	0.26
MPLAPON 100x	0.95	**0.35**	0.21	0.24	0.25
UMPlan Fl 100x	0.95	0.2	0.21	0.24	0.25

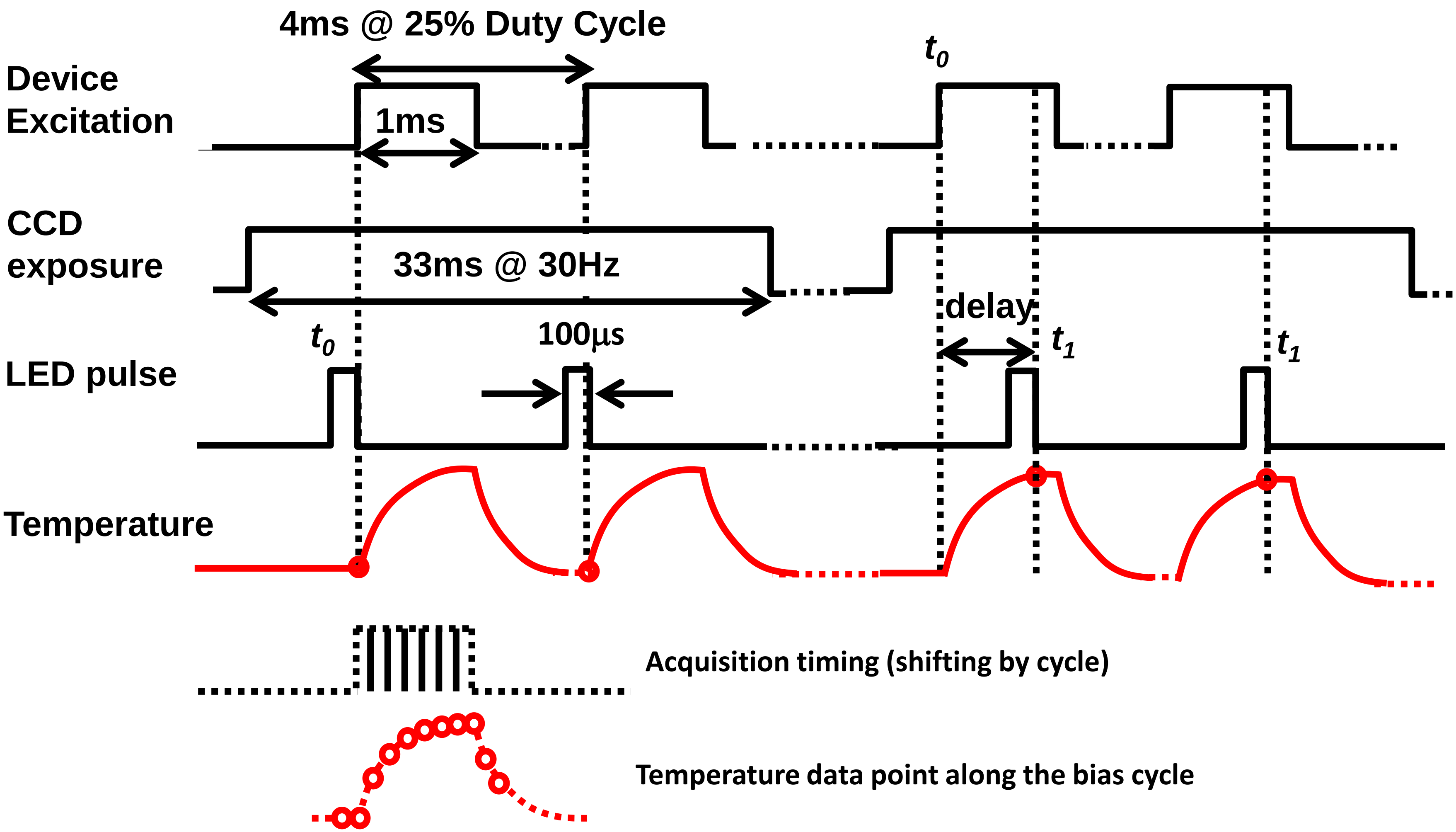


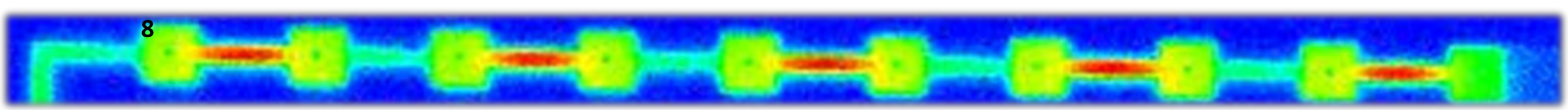
How it works -Thermoreflectance



System diagram

Phase-Locked Timing Signals



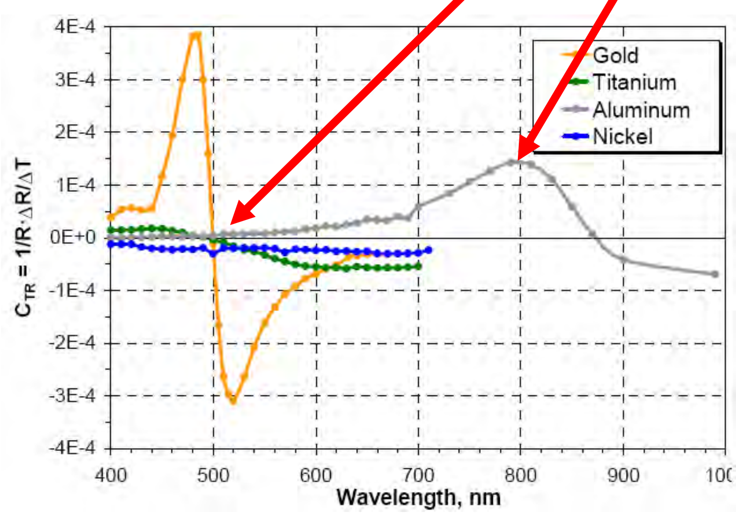


Dependencies of the Thermoreflectance Coefficient

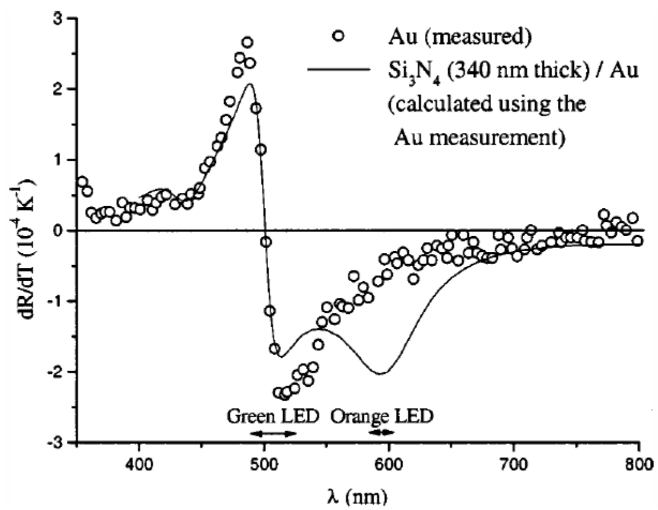
- Illumination Wavelength Dependent
- Material Dependent
- Temperature sensitivity is increased dramatically by optimizing the wavelength of light for a specific material.

$$C_{th} = \frac{1}{R_0}\frac{dR}{dT} \approx 10^{-4}$$

-e.g. choosing an LED of 500 nm produces almost no thermoreflectance signal for Al, but an LED of 800 nm increases the thermoreflectance signal by several orders of magnitude



(Komarov, et al, Thermoreflectance Thermography System…)

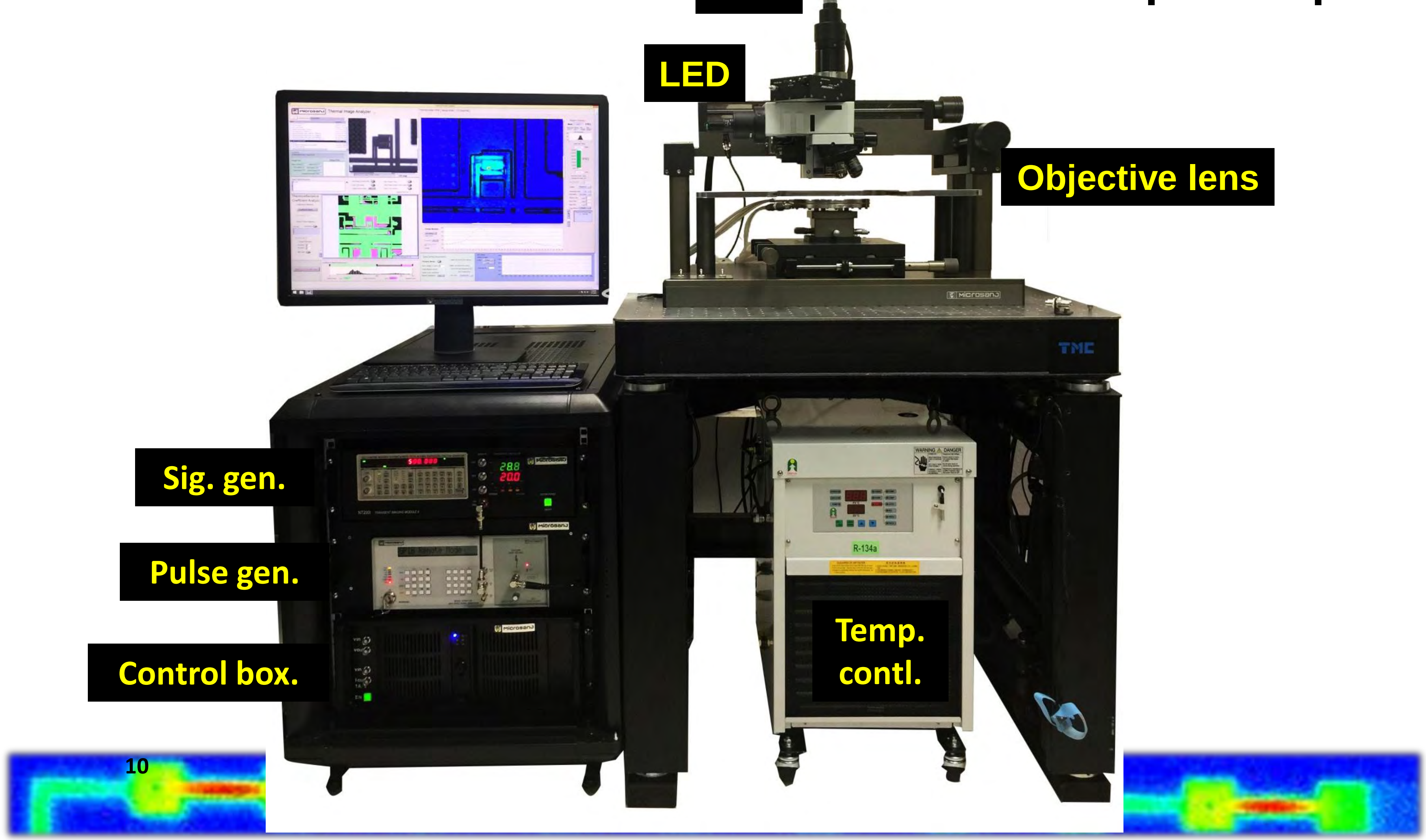


(Tessier, et al, Quantitative thermal imaging by synchronous…)

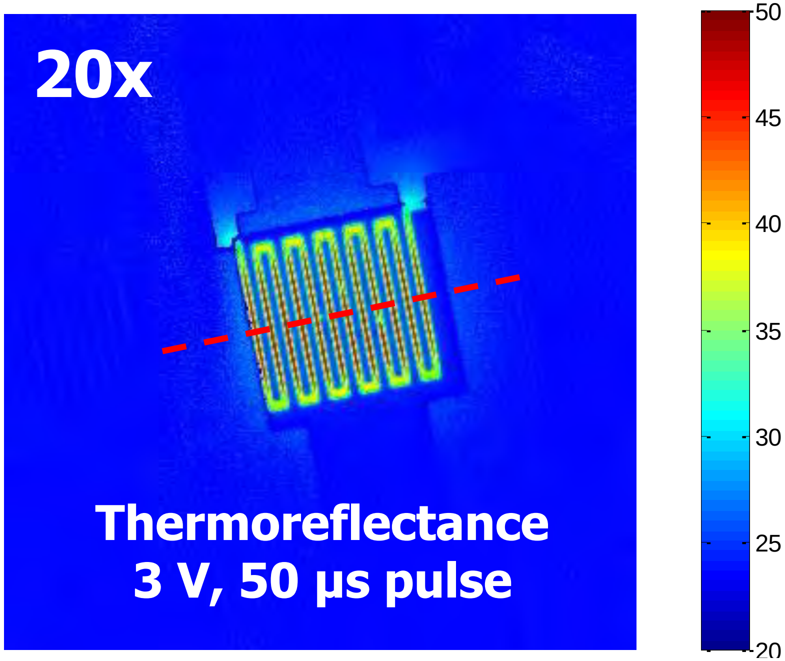
Thermoreflectance imaging setup

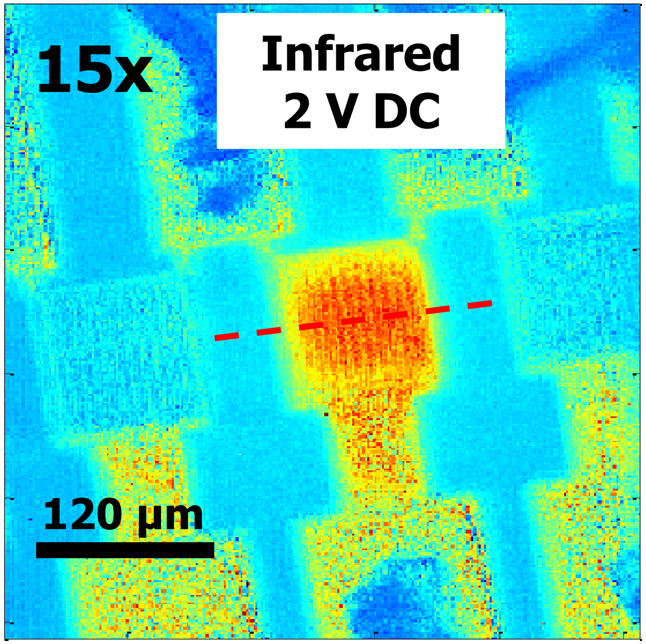
NT220 Rack

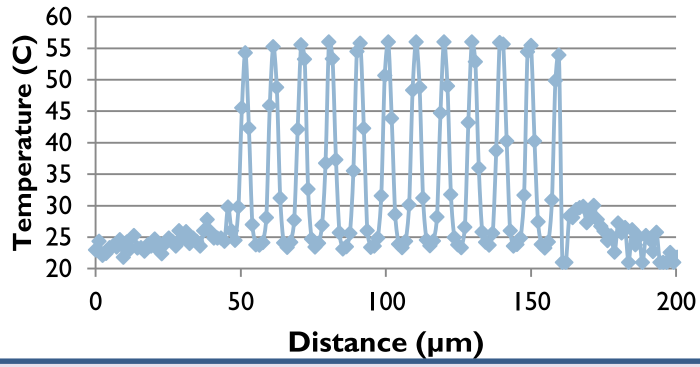
Microscope setup

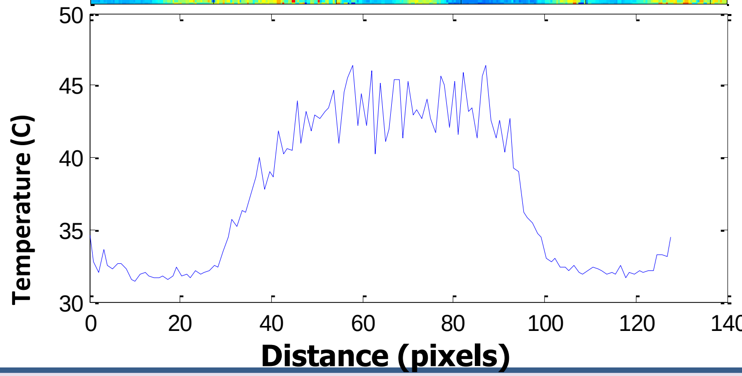


High Magnification Comparison

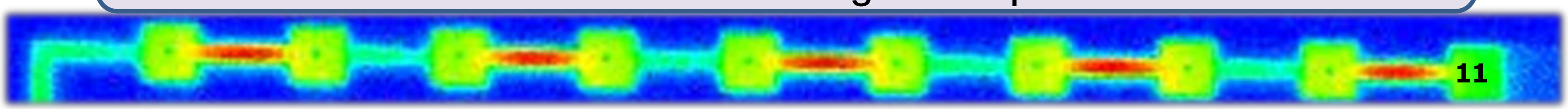








- With AC measurement & pulsing DUT, localized peak temperatures are found in thermoreflectance image on 4 µm wide heater lines.



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- ❑ **Measurement for HEMT Transistor**
- ❑ Transient measurements
- ❑ GaN High Power Amplifiers
- ❑ ESD protection devices
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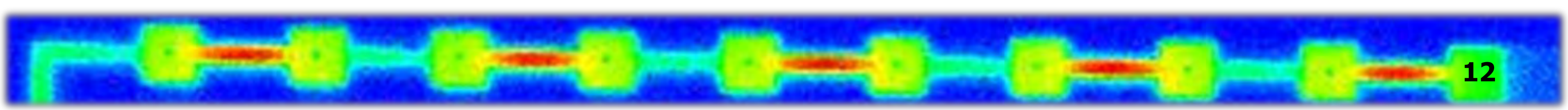
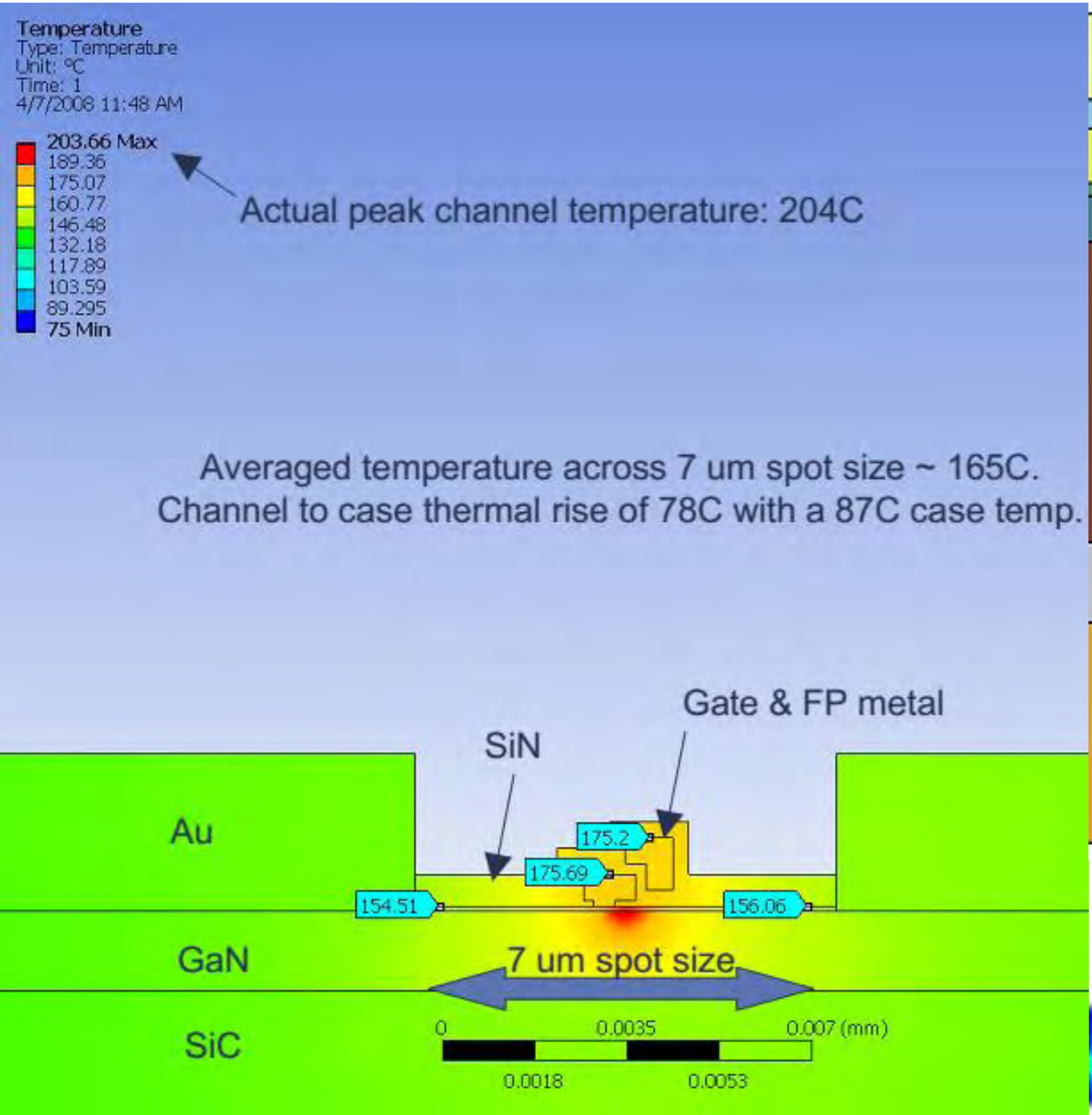
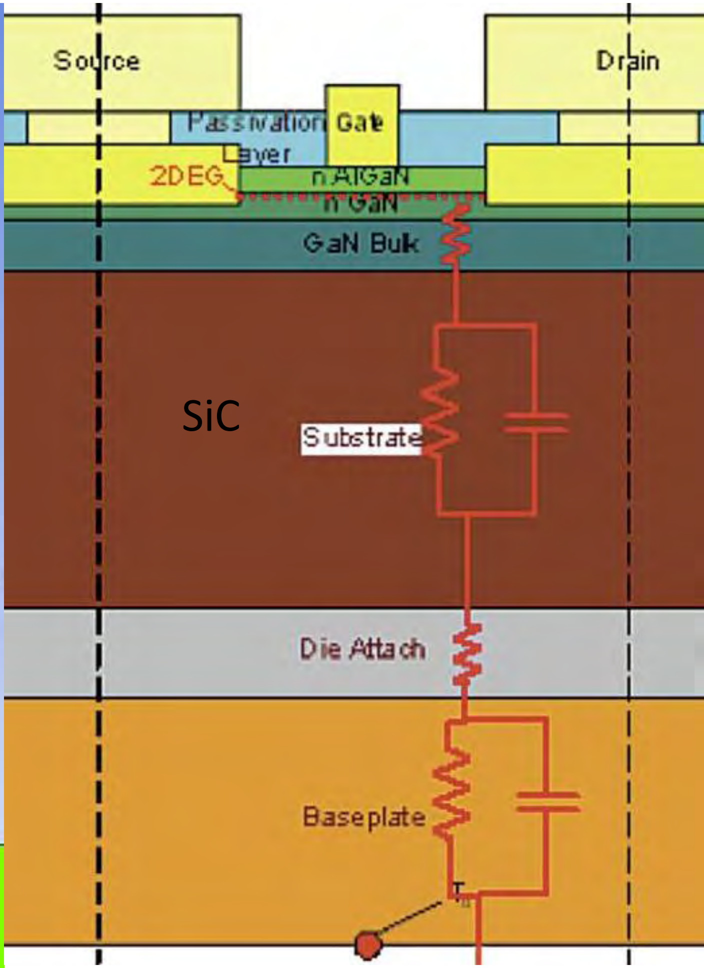
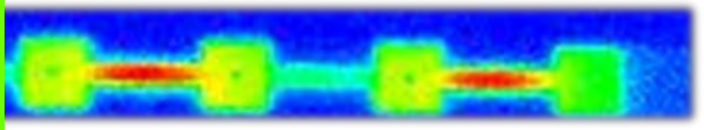


Typical GaN HEMT Structure

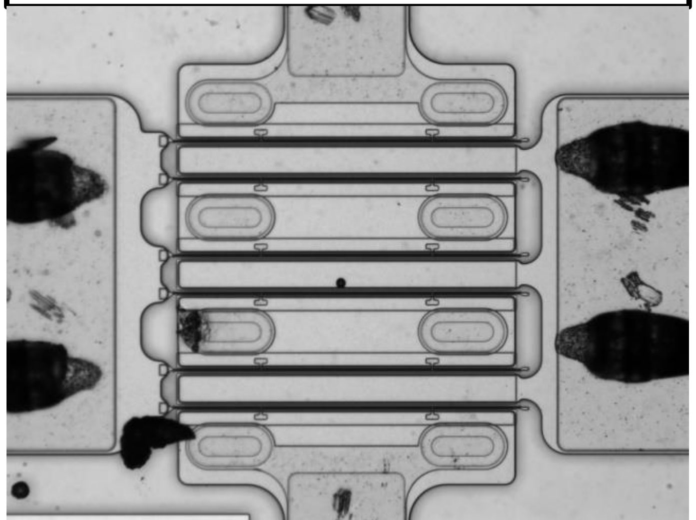




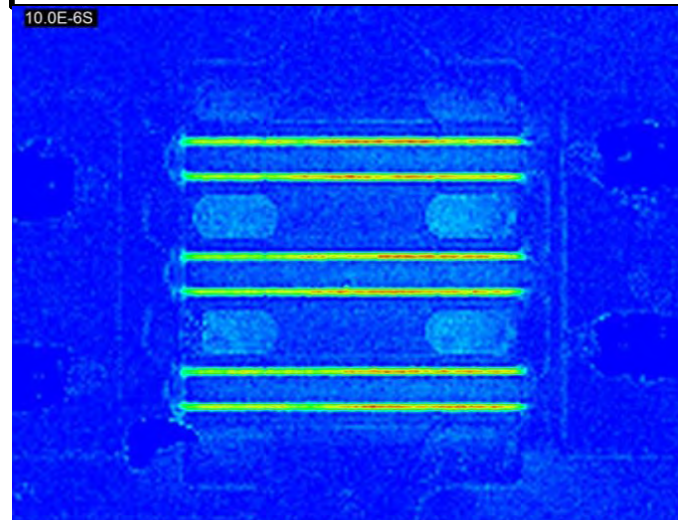


10x Transient Thermal Images(40006p)

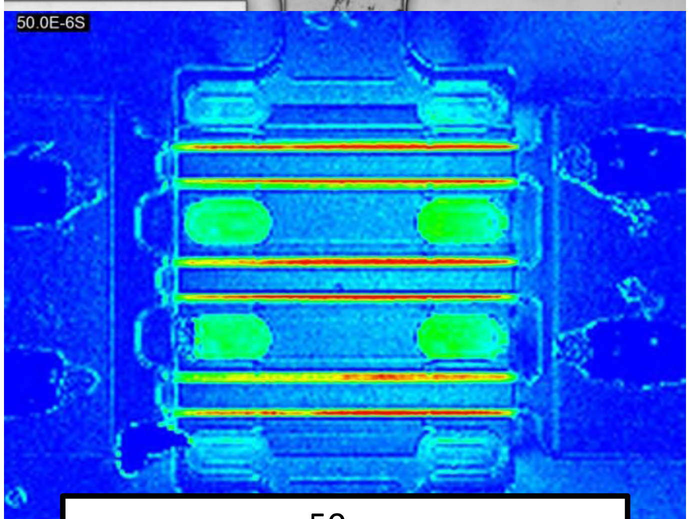
CCD Image



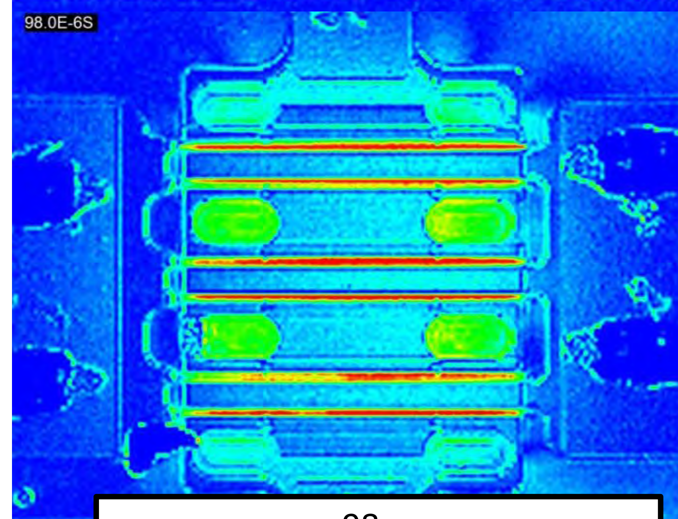
10µs



$28V_{ds}$,
480mA,
13.44W,
470nm LED,
10% duty cycle



50µs

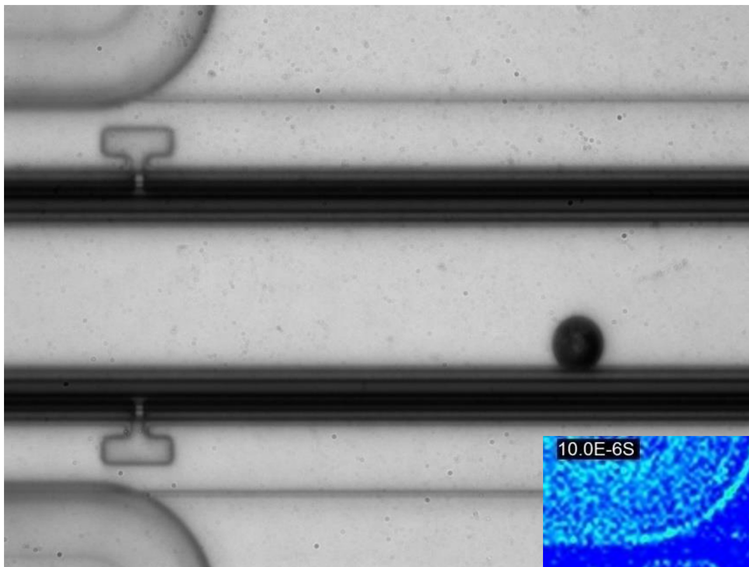


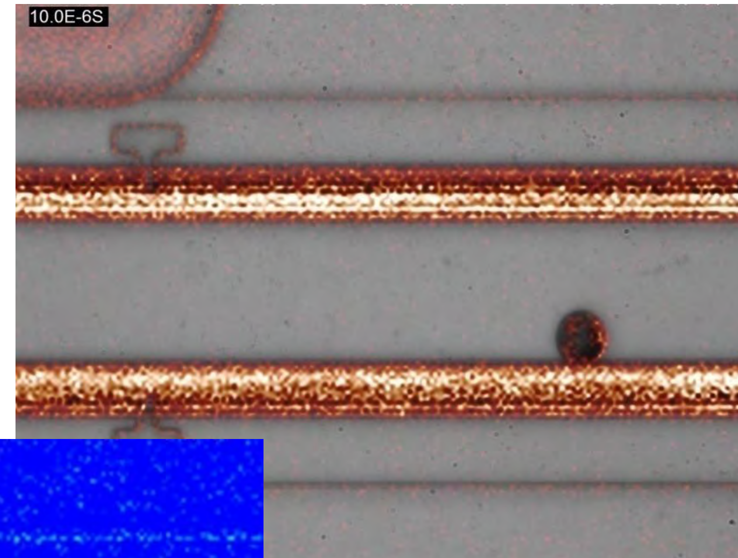
98µs

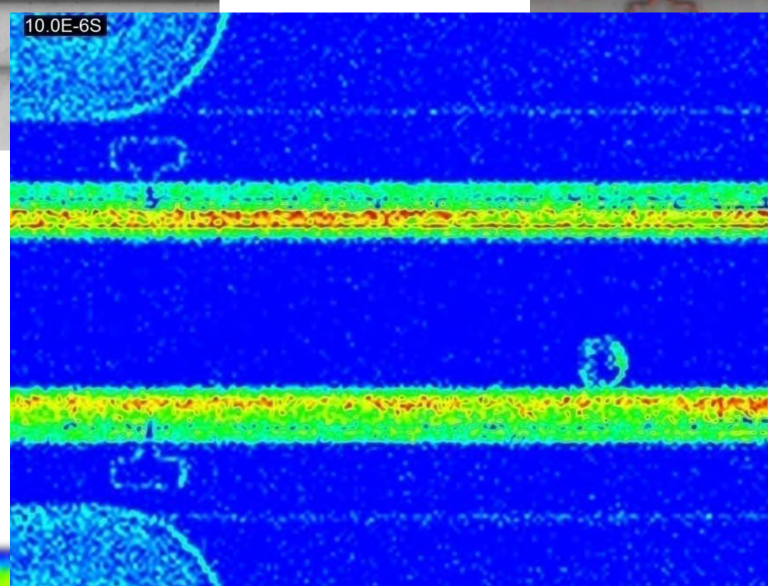
Here we can see how heat spreads throughout the DUT in response to a 10µs pulse.

50x Thermal Image(40006p)

CCD Image	Thermal Image

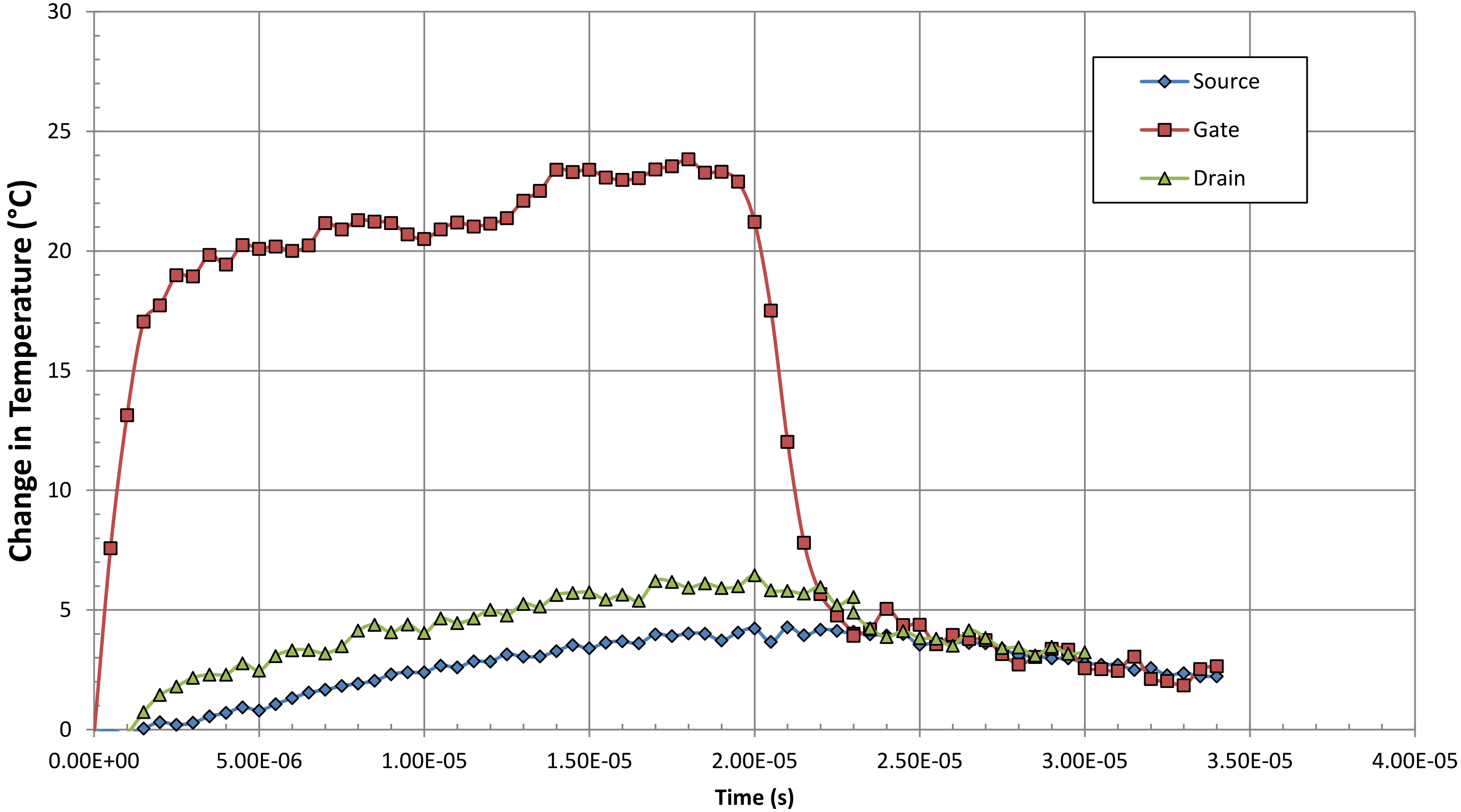




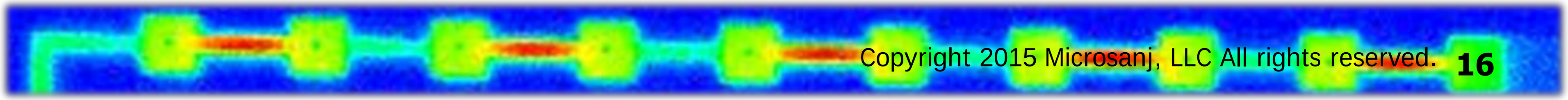


28V_{ds}, 480mA, 13.44W,
470nm LED, 10us,
10% duty cycle

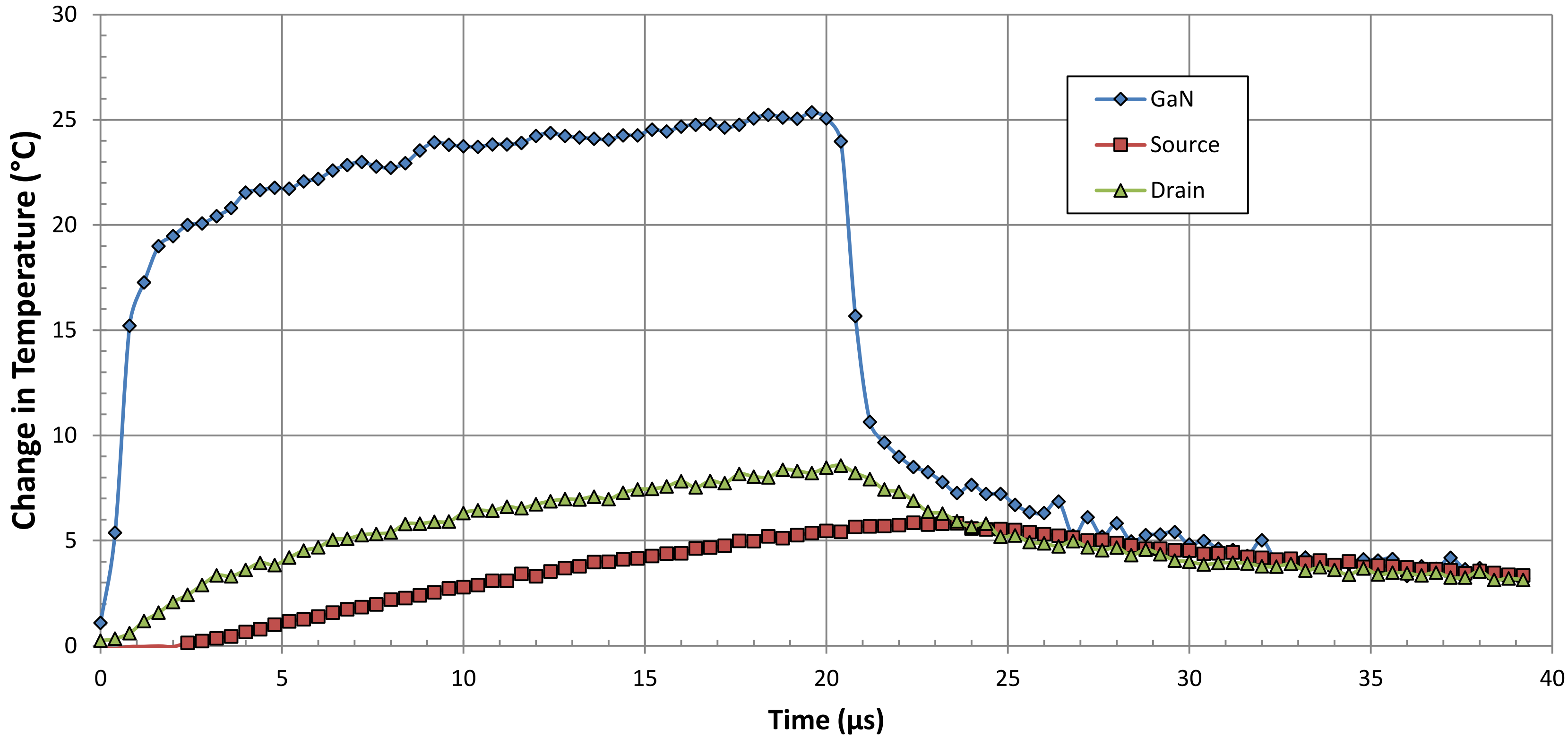
20µs, Cold White LED Gate Measurements



- This data shows an 19.6C ΔT between the source and gate region.
- Sample 40010, 9.1W



20µs, 470nm LED Gate Measurements



- This data shows an <u>19.5C</u> ΔT between the source and gate region.
- Sample 40006p

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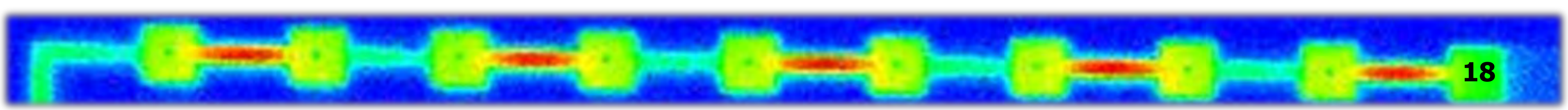


Heating Curve

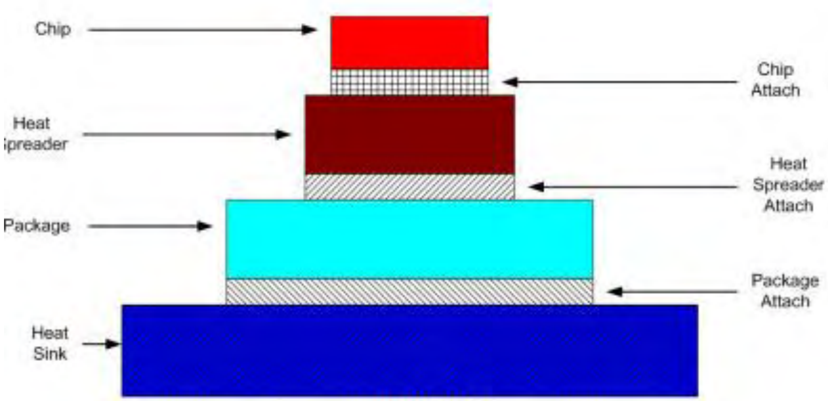
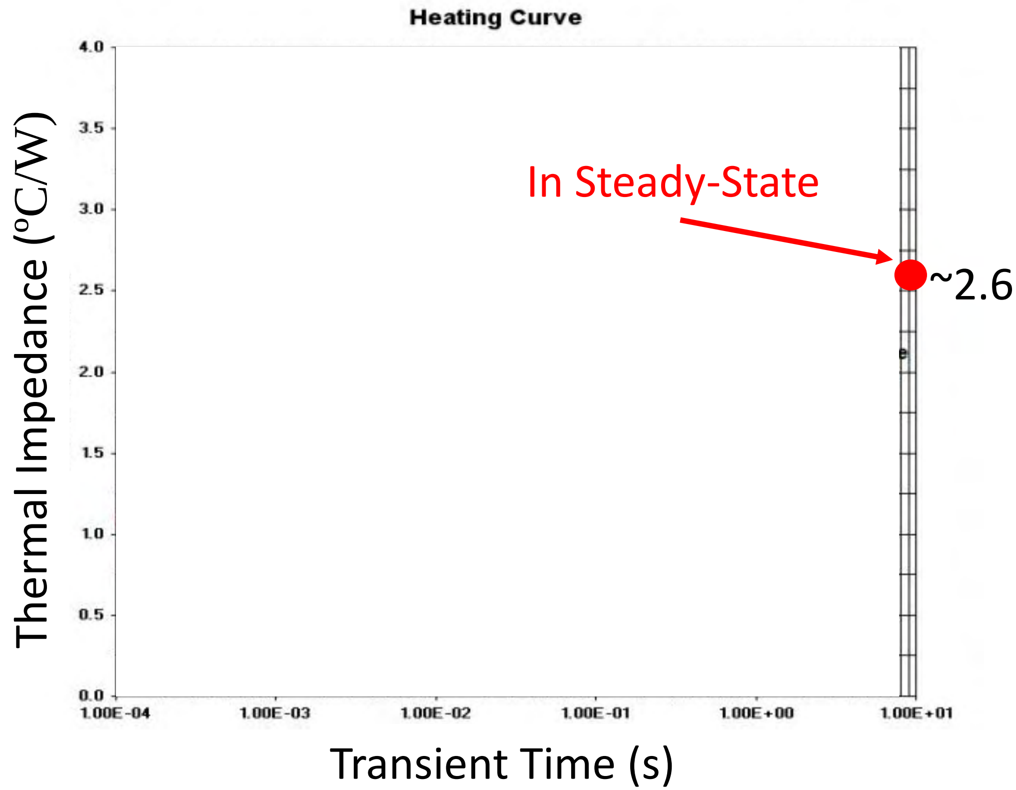
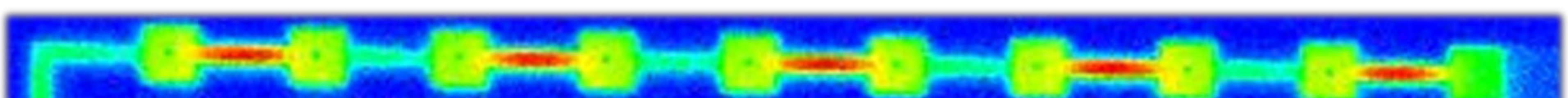


Figure 1





Heating Curve

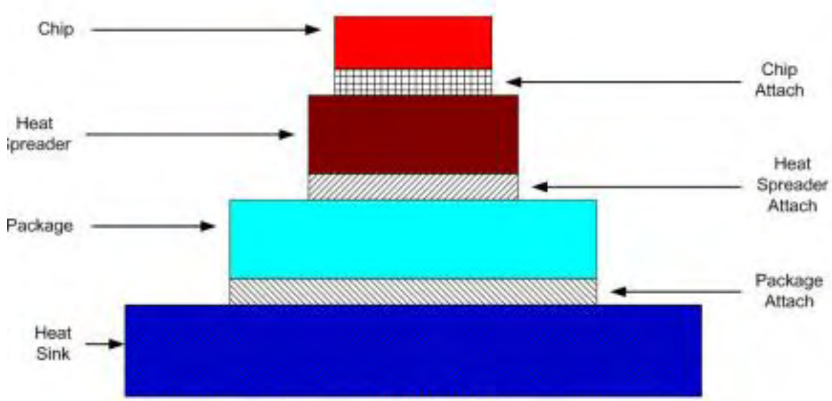
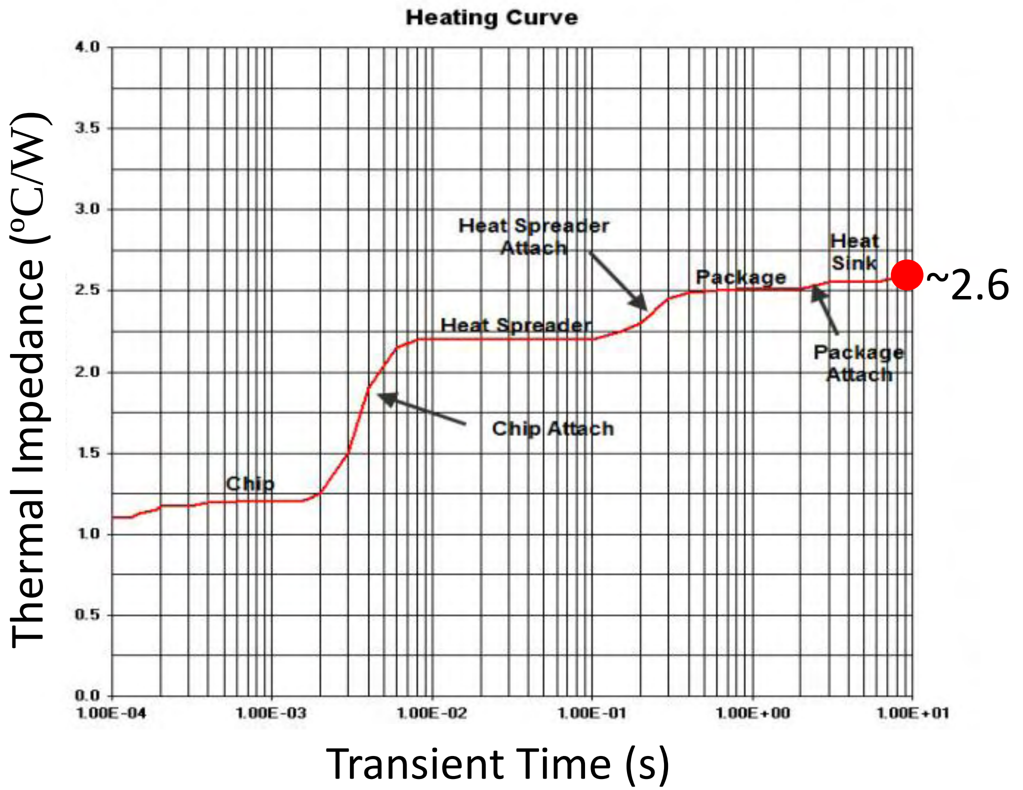
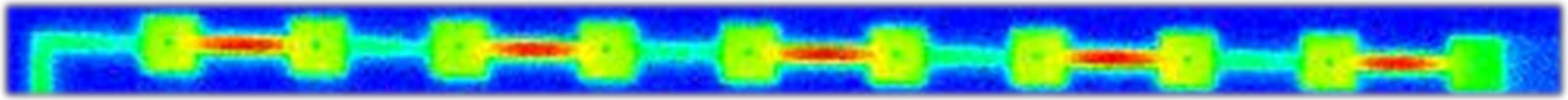
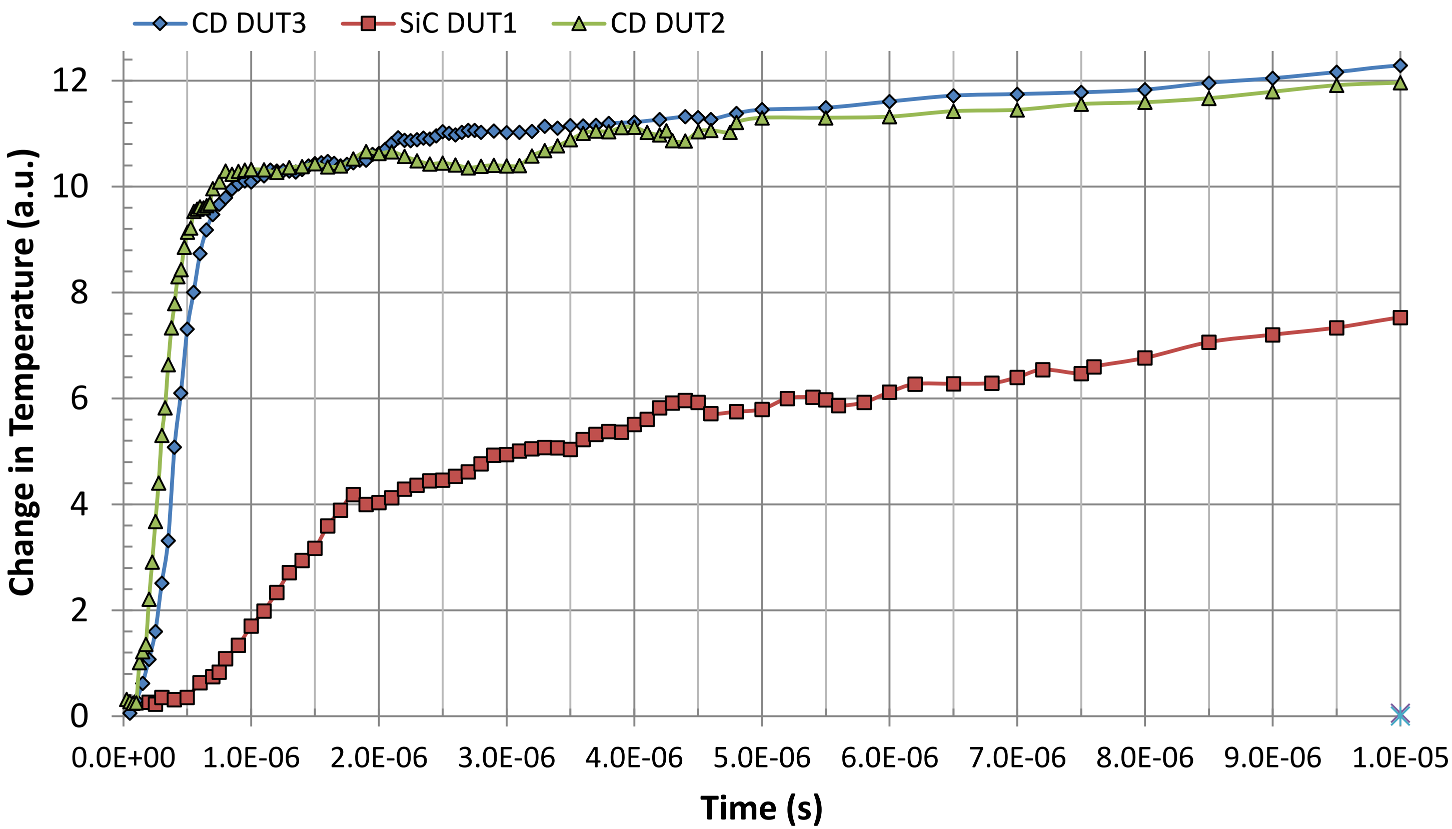


Figure 1

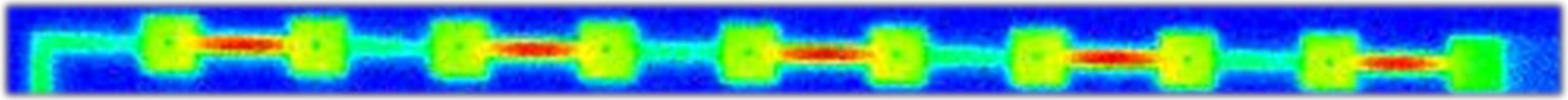




Diamond vs SiC TBR Comparison



- This data shows that even with diamond having ~3x higher thermal conductivity the poor thermal interface between GaN and Diamond can cause higher heating closer to the junction.



Diffusion length estimations

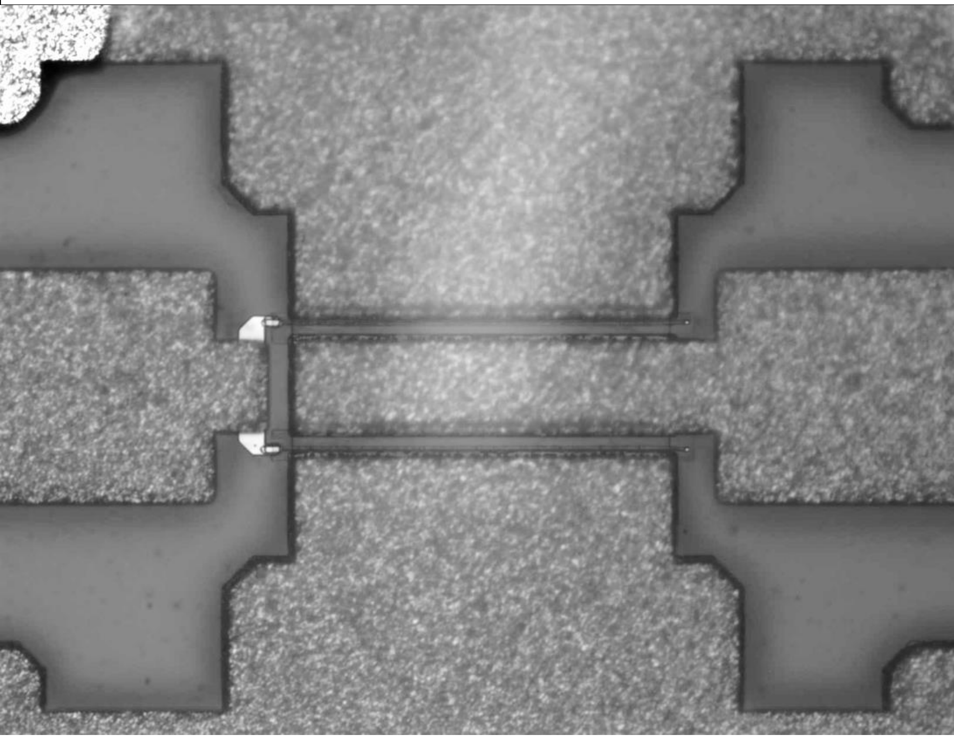
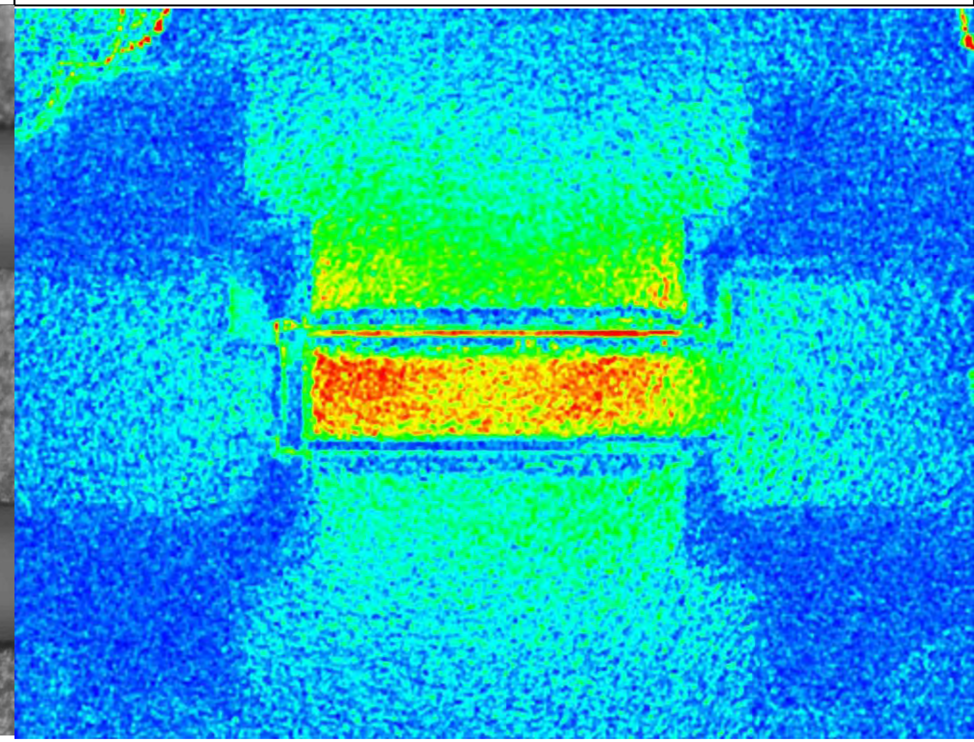
$\mu_t = 2\sqrt{\alpha t}$ Effective thermal diffusion length (in the time domain, for pulsed heating)

$\mu = \sqrt{\frac{2\alpha}{\omega}}$ Thermal diffusion length (in frequency domain, for periodical heating)

$$t = \frac{\mu^2}{4\alpha} \approx 3125\mu^2 \text{ (for Si)}$$

				6-20W/cmK	3-11 cm2/s						
Diffusion time estimations	SiO2	Si	Cu	Diamond	DiamondUp	Al	Ag	Au	3C-SiC	4H-SiC	6H-SiC
Thermal diffusivity: α (m^2/s)	8.30E-07	8.80E-05	1.11E-04	3.00E-04	1.10E-03	8.42E-05	1.55E-04	1.27E-04	1.60E-04	1.70E-04	2.20E-04
thickness (µm)	diffusion time (µs)										
1	0.301	0.003	0.002	0.001	0.000	0.003	0.002	0.002	0.002	0.001	
5	7.530	0.071	0.056	0.021	0.006	0.074	0.040	0.049	0.039	0.037	
10	30.120	0.284	0.225	0.083	0.023	0.297	0.162	0.197	0.156	0.147	
25	188.253	1.776	1.408	0.521	0.142	1.856	1.011	1.230	0.977	0.919	
50	753.01	7.10	5.63	2.08	0.57	7.42	4.05	4.92	3.91	3.68	
100	3012.05	28.41	22.52	8.33	2.27	29.69	16.18	19.69	**15.63**	**14.71**	
280	23614	223	177	65	18	233	127	154	123	115	
500	75301	710	563	208	57	742	405	492	391	368	
700	147590	1392	1104	408	111	1455	793	965	766	721	
1000	301205	2841	2252	833	227	2969	1618	1969	1563	1471	
1500	677711	6392	5068	1875	511	6681	3641	4429	3516	3309	
2000	1204819	11364	9009	3333	909	11876	6472	7874	6250	5882	

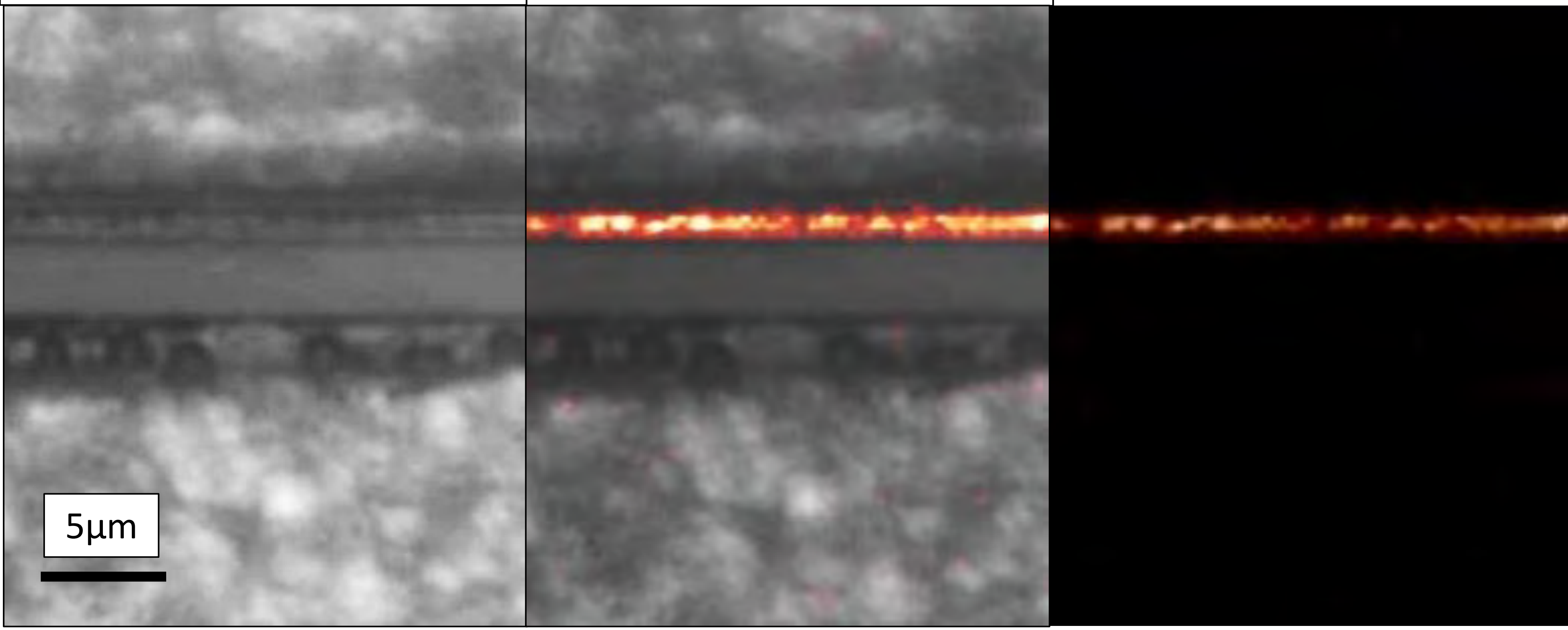
GaN Thermal Image

20X CCD Image, 530nm LED	Thermal Image
	

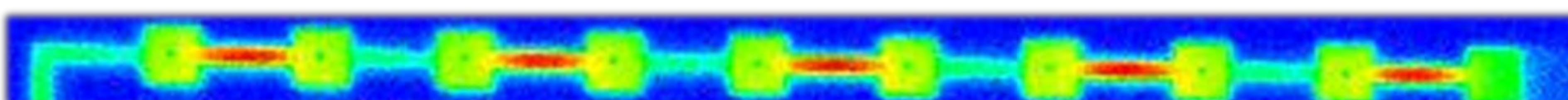
- ❑ Single HEMT finger
- ❑ 8V, 70mA
- ❑ 530nm LED
- ❑ -1.85E-4 Cth for Passivated Gold

Overlay Images

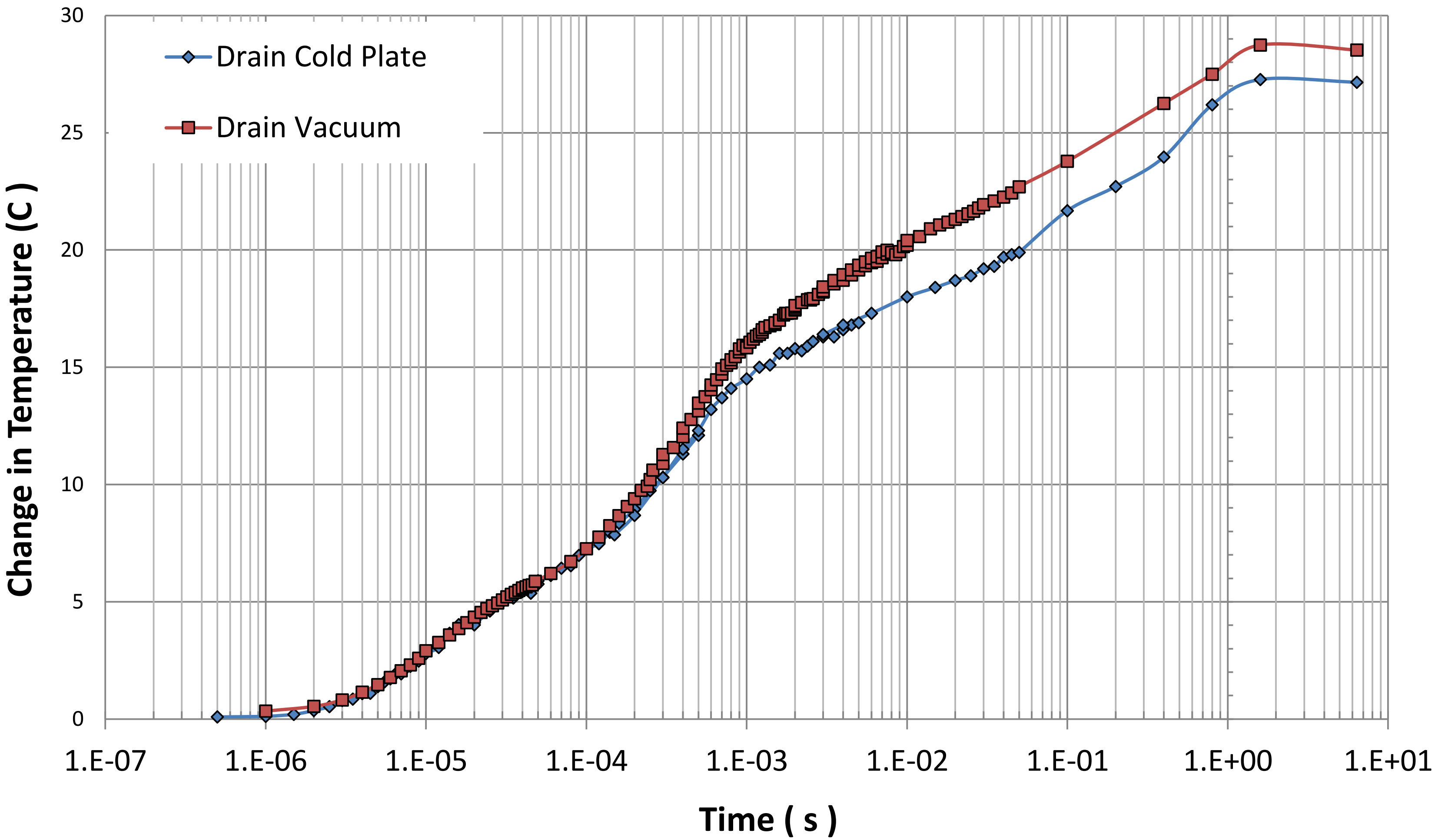
CCD Image	Overlay of Thermal and CCD	Gate Thermal Image



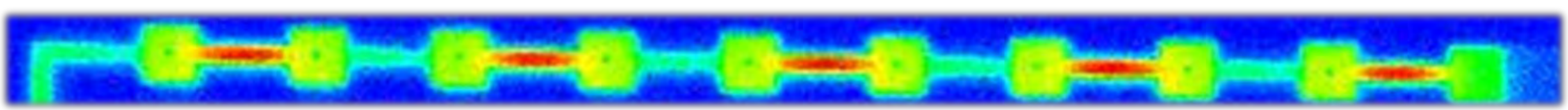
- These images show the precise location of the thermal signal coming from the top gate metal
- The Gate length is 0.3um



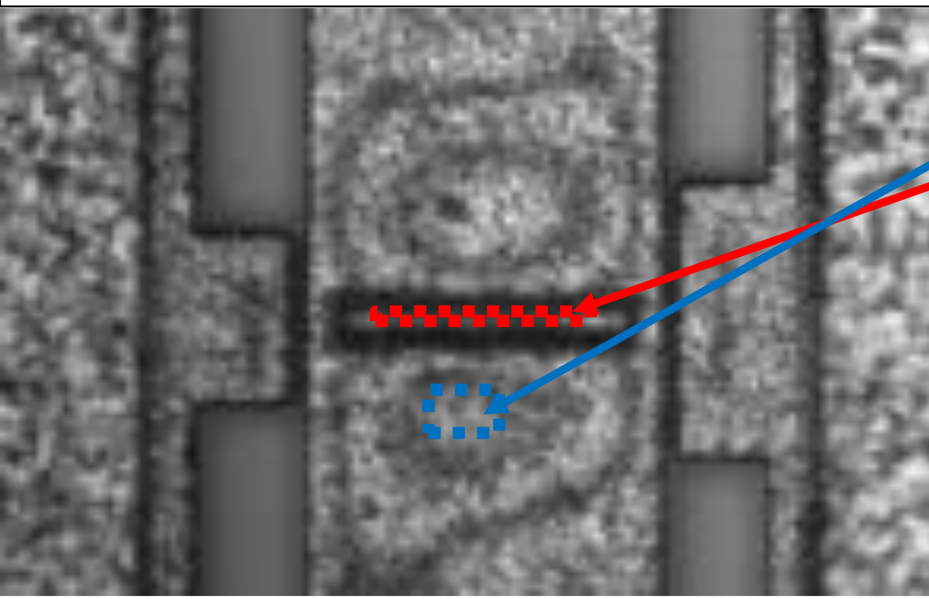
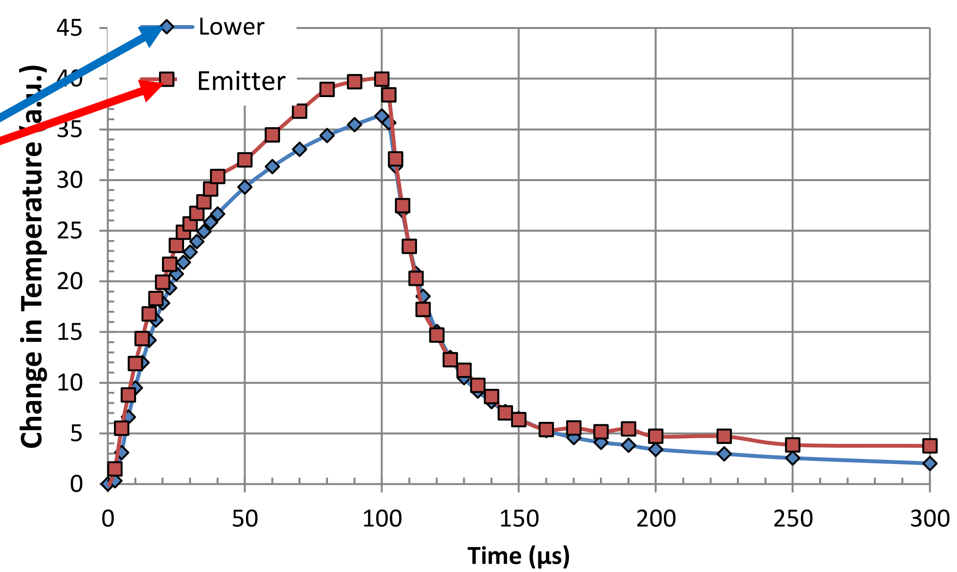
Heating Curves



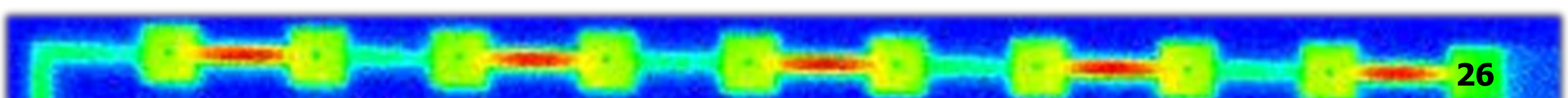
- ❑ 0.1µs to 10s



HBT 100µs Transient Response

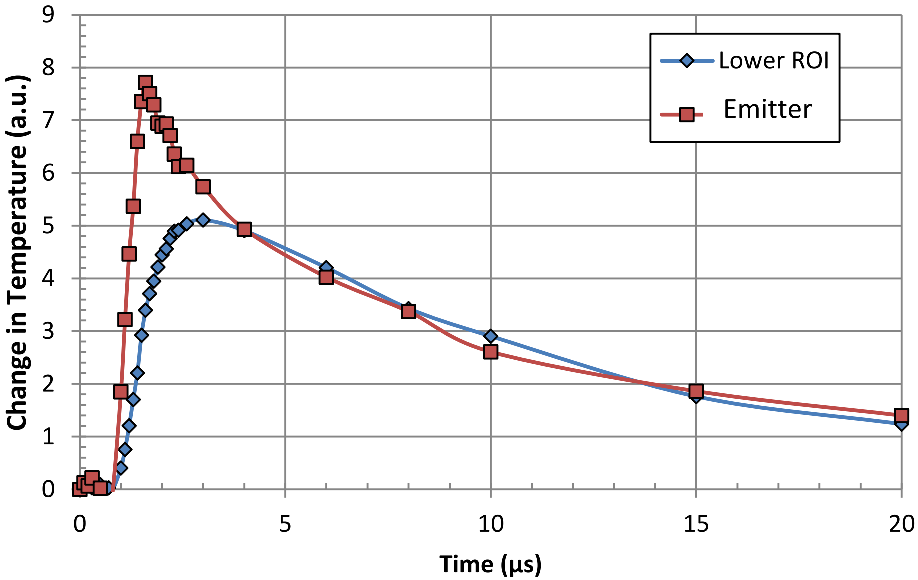
20x CCD Image, 530nm	100µs Thermal Transient
	

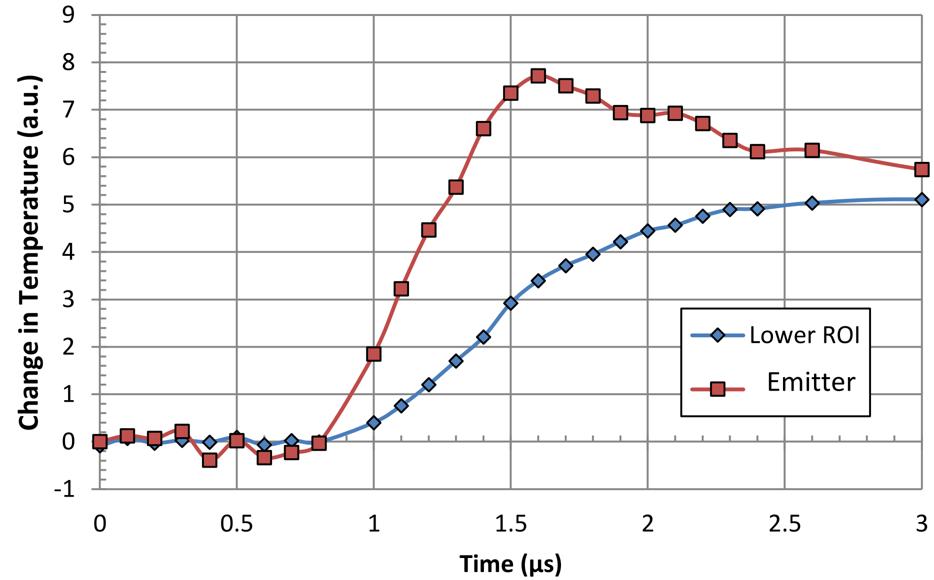
- 20X, 100us, 10% duty cycle
- 3V, 20mA
- 530nm LED



1µs AMCAD Pulse Thermal Transients

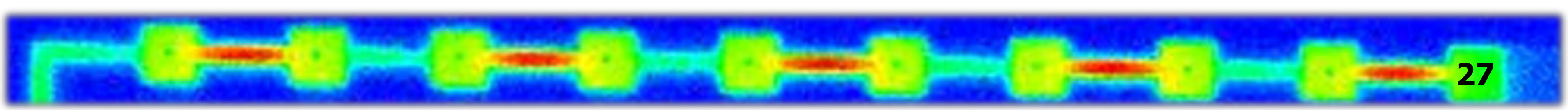
1us Transient Thermal Response	Signal Delay





- ❑ 20X, 1us, 5% duty cycle
- ❑ 3V, 80mA, 530nm LED
- ❑ The data shows the fast thermal rise time and slow thermal decay of the device

- ❑ A ~700ns delay in the power signal was seen on the IVCAD software. This data clearly shows the resulting delay in the thermal signal.



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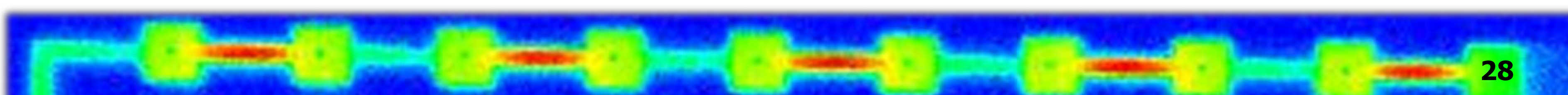
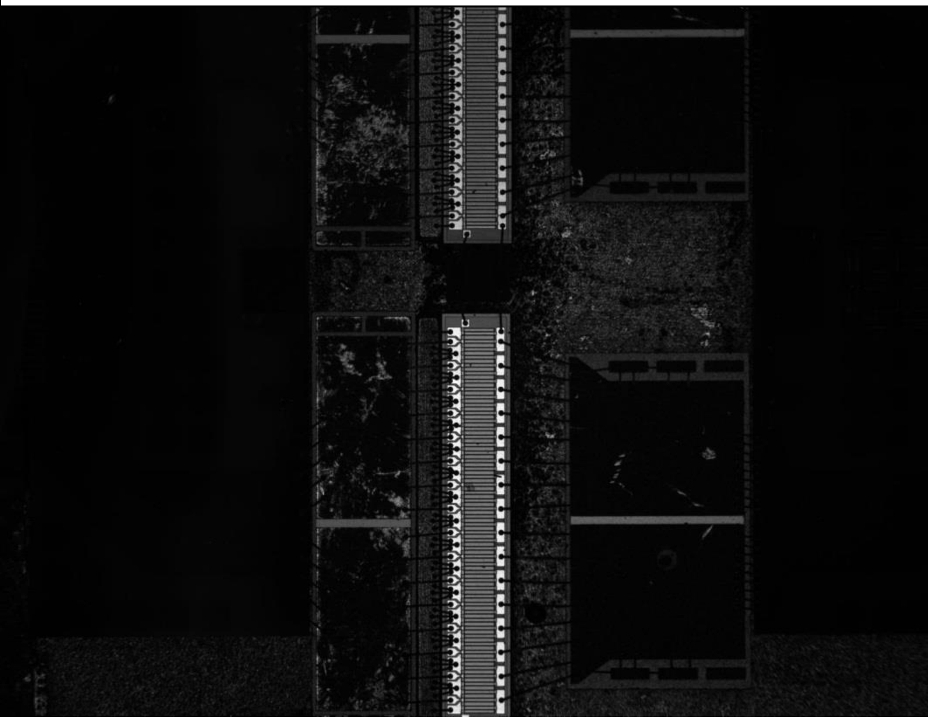
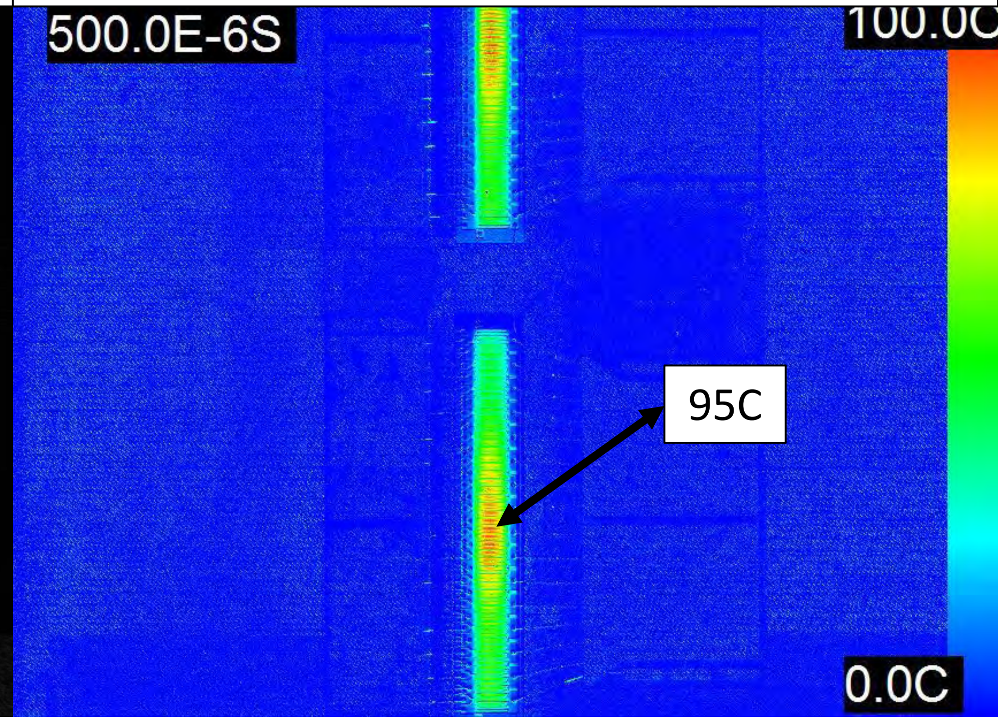
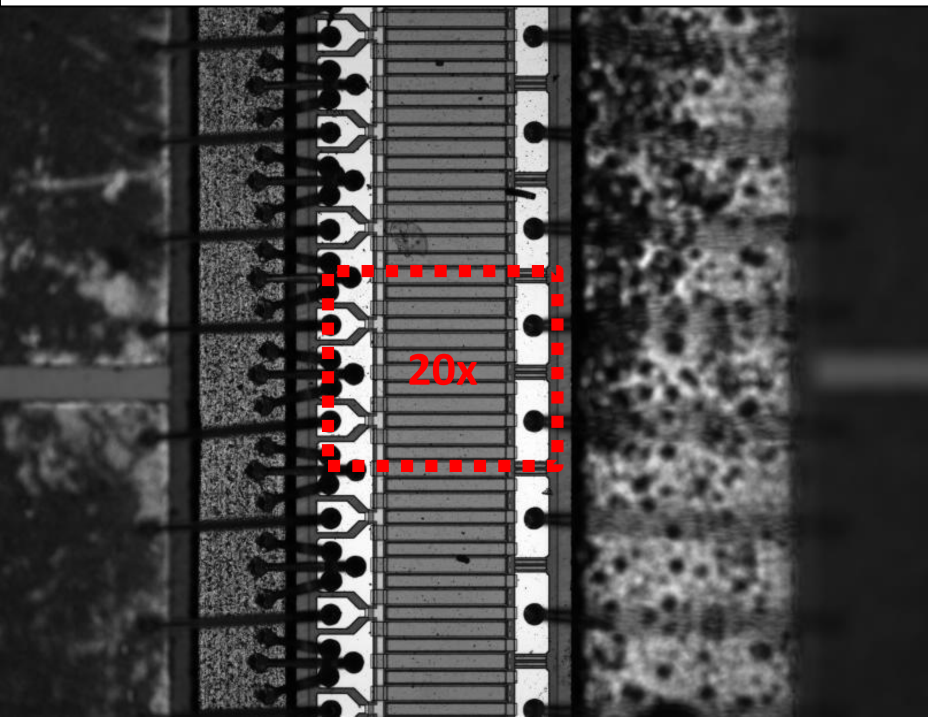
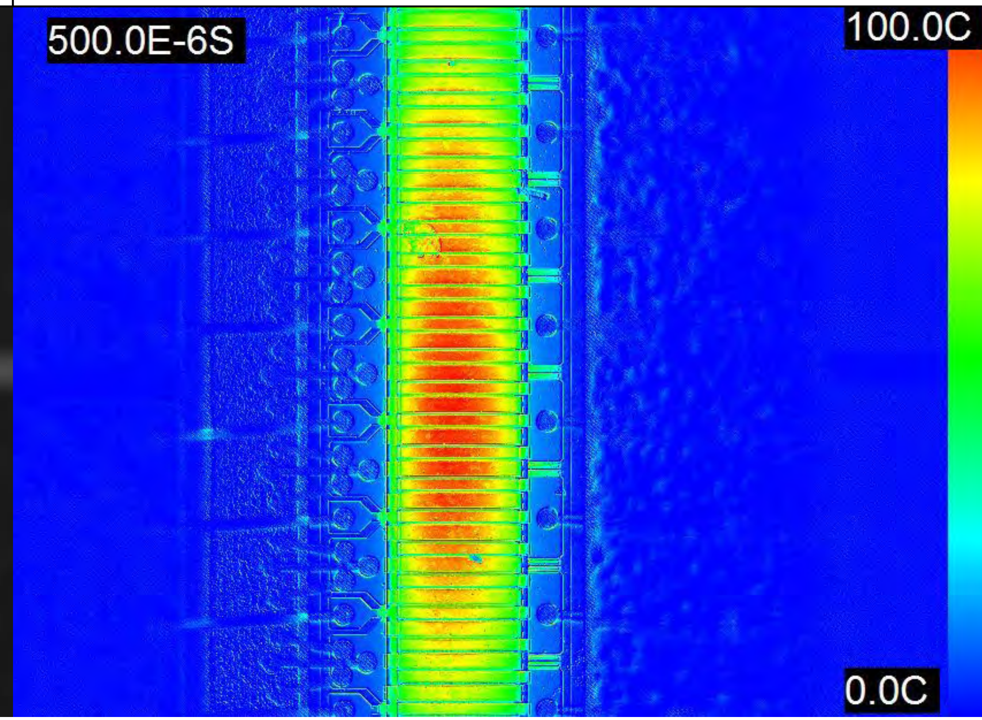


1.25X Thermoreflectance Image

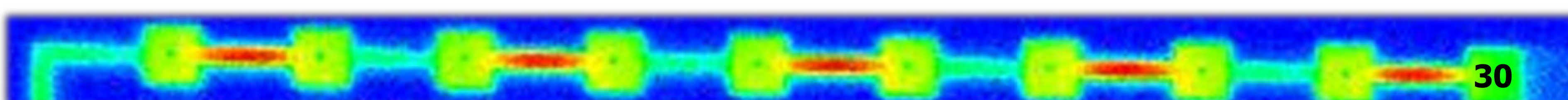
1.25x CCD Image, 530nm	Thermal Image
	

- 1.25X, 500us, 20% duty cycle, **<u>30C Case Temperature</u>**
- Vg -2.5V, 150W RF
- 530nm LED, -3.74E-4/C for the thermoreflectance coefficient for passivated Au

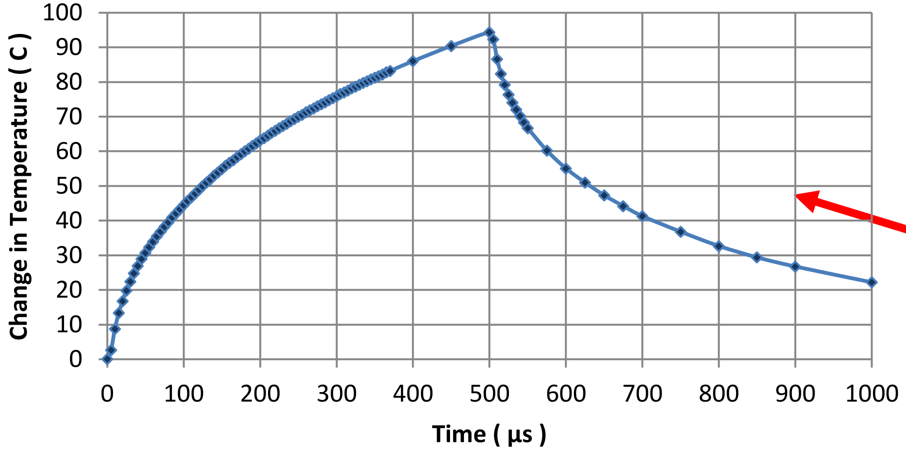
5X

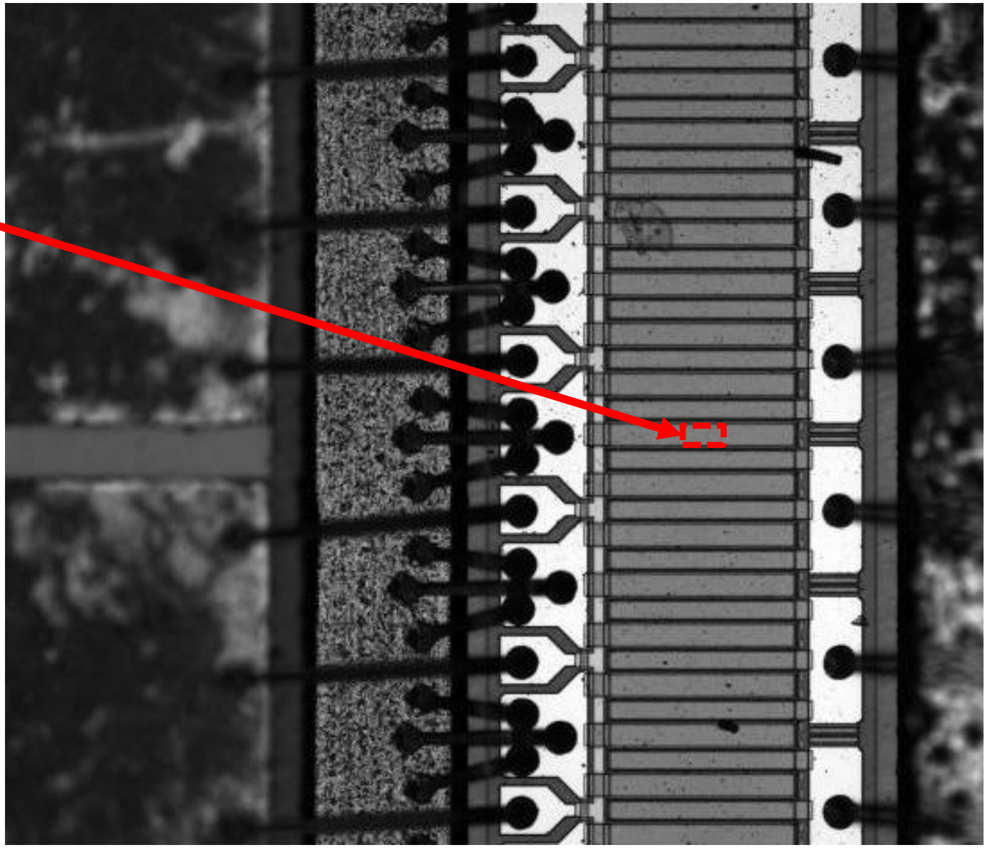
5x CCD Image, 530nm	Thermal Image
	

- 5X, 500us, 20% duty cycle, **38C Case Temperature**
- Vg -2.5V, 150W RF
- 530nm LED, -3.74E-4/C for the thermoreflectance coefficient for passivated Au



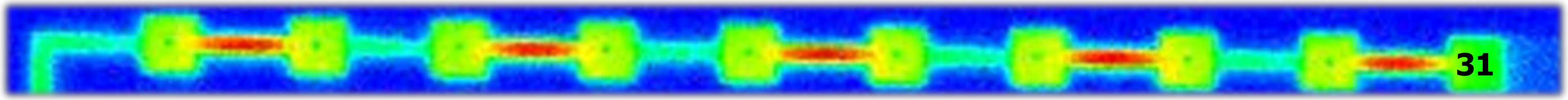
500µs Transient Data



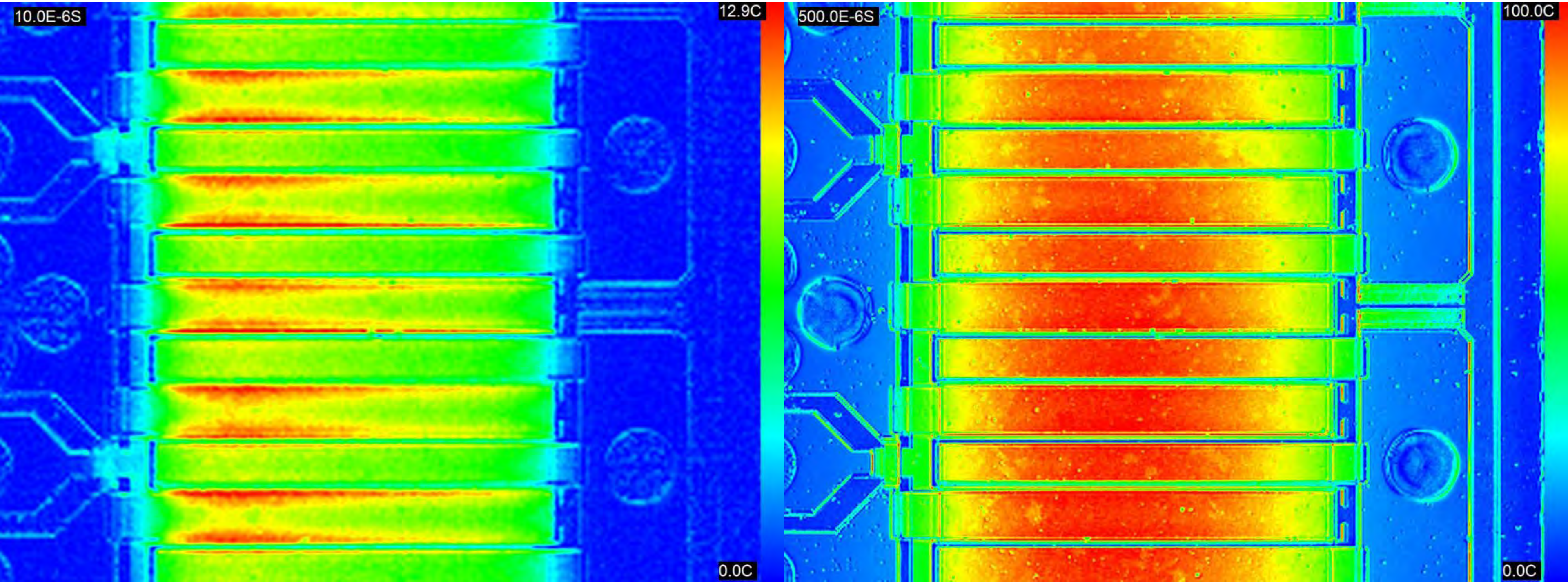


Above is the transient response of the center drain contact due to a 500µs pulse.

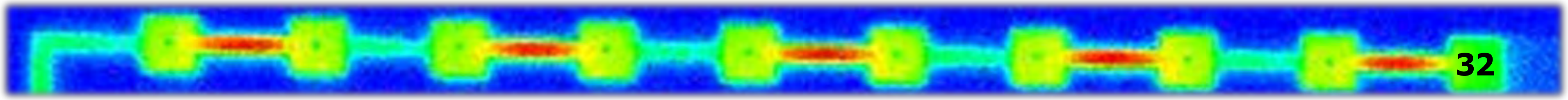
- 50X, 500µs, 20% duty cycle, 39C Case Temperature
- Vg -2.5V, 150W RF
- 530nm LED, -3.46E-4/C for the thermoreflectance coefficient for passivated Au 50x



10µs and 500µs Thermal Images



- This data shows the change in temperature distribution between 10us and 500us. 10us is much more asymmetrical



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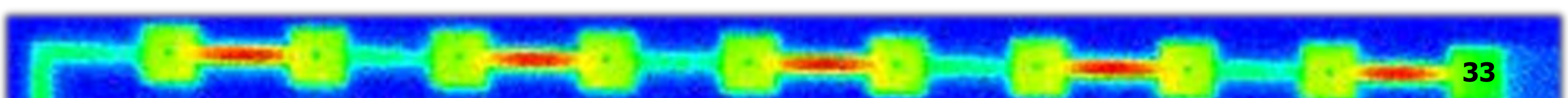
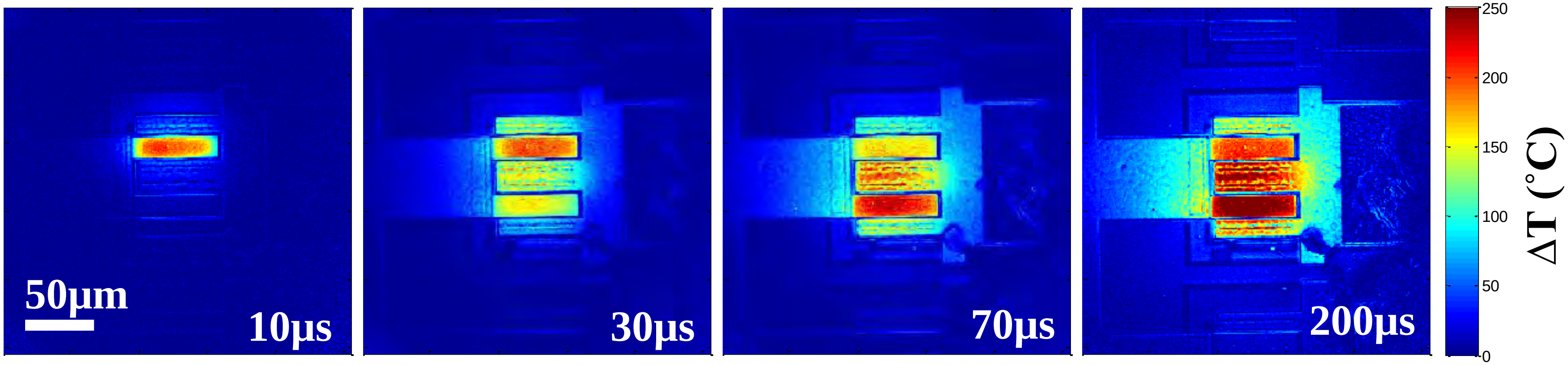
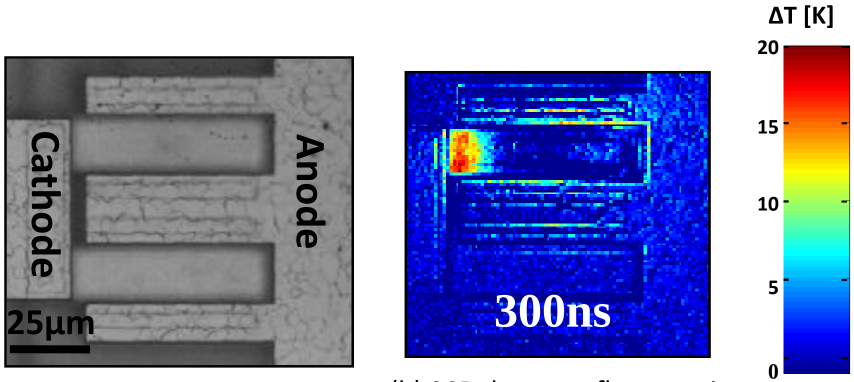


100 ns temporal resolution of ESD-type event



- Characterization during operation to improve efficiency or identify undesired behavior.
- Non-uniform device turn on in a symmetrical Silicon Controlled Rectifier (SCR) in response to a 2.5 ms pulse



(a) SCR optical image

(b) SCR thermoreflectance in snapback after 300ns at 1.28A

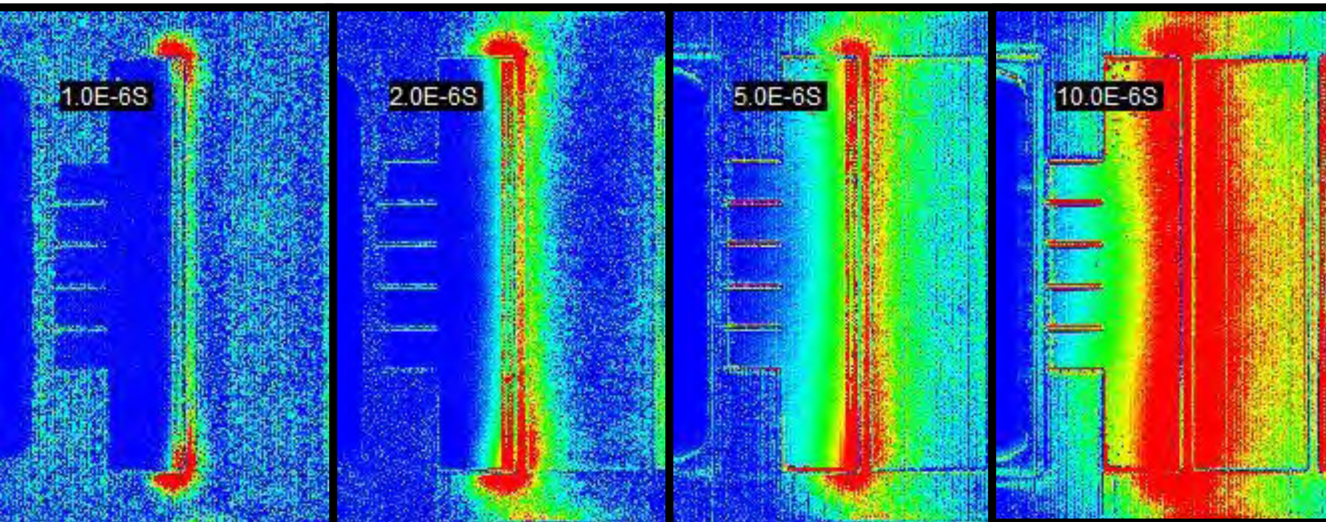
Initial response to the 300 ns 120V pulse shows highly localized heating.

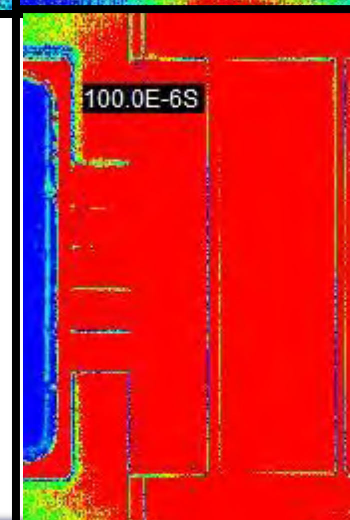
K. Maize, V. Vashchenko et al, *IRPS*, 2011.

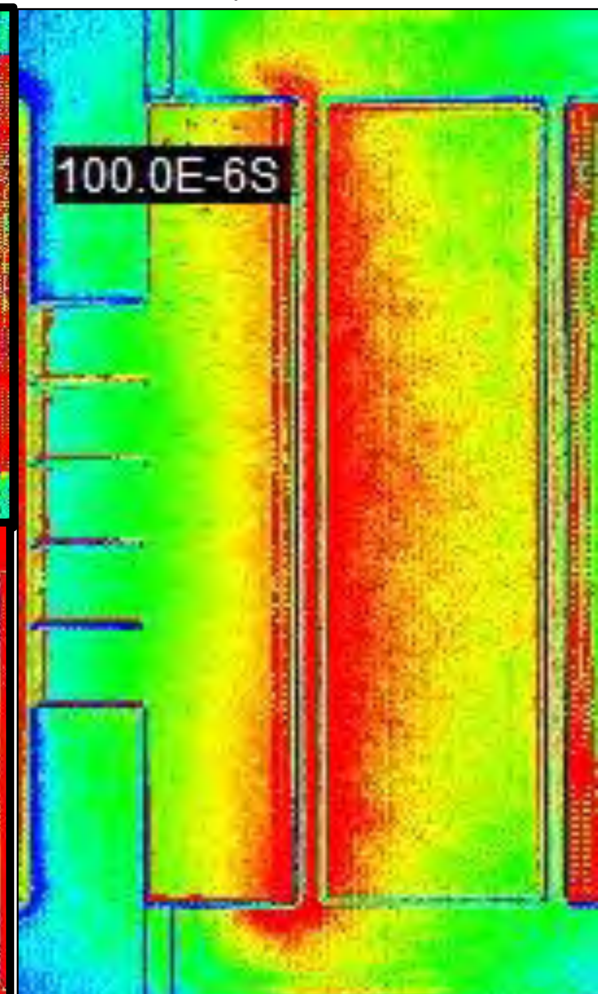
Transient SCR response

10V was applied to the device. The current and precise voltage across the device was not measured for this series

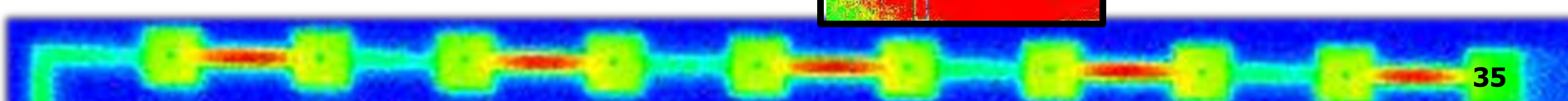
Scaled 100µs image to Show temperature distribution





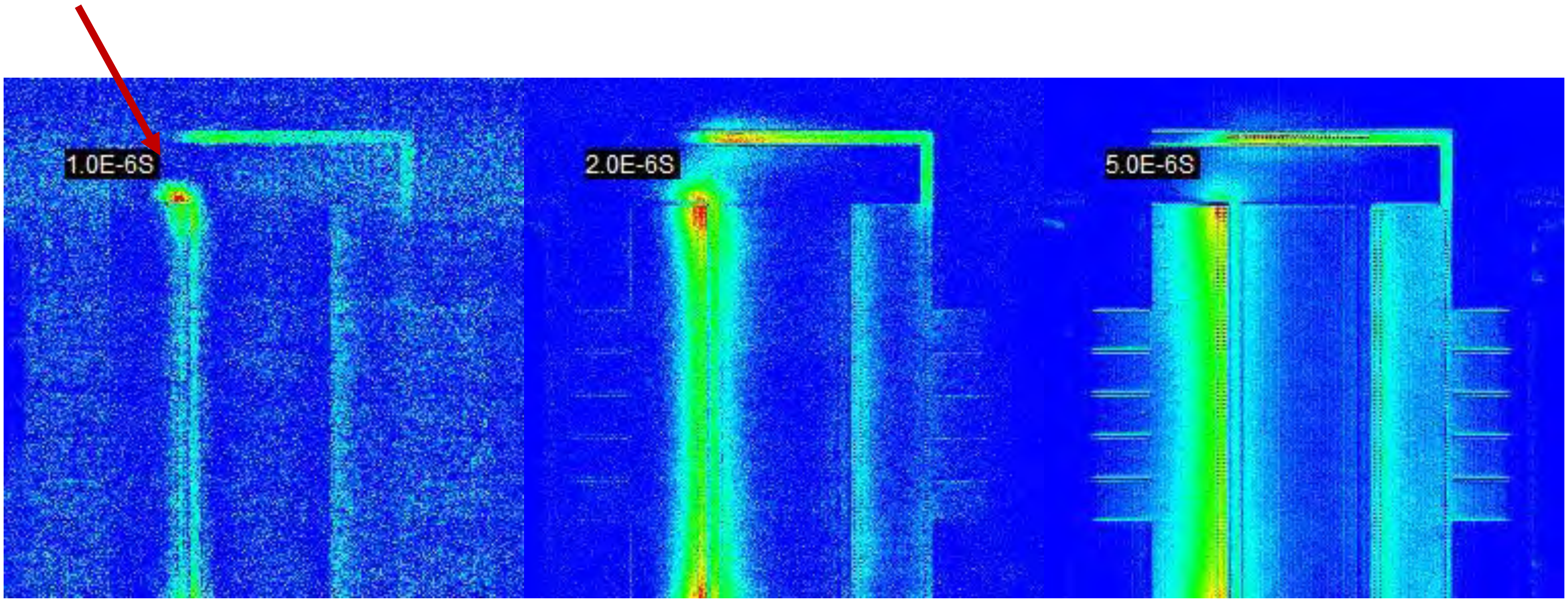


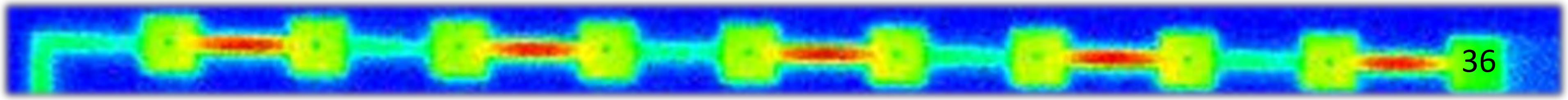
- These thermal images show the transient thermal response of the SCR.
- The SCR starts to conduct at the corners of the Anode (due to high electric field)
- Images are all on the same temperature scale
- These devices are fabricated to be tested and operated at nanosecond time scale



Transient SCR response

High Electric Field at sharp corners





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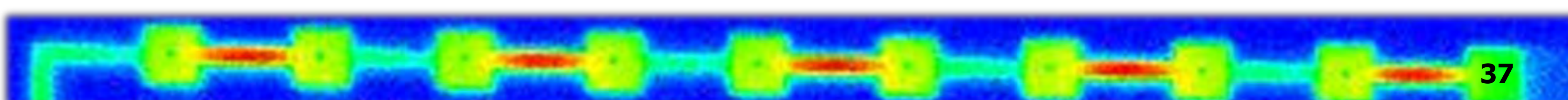
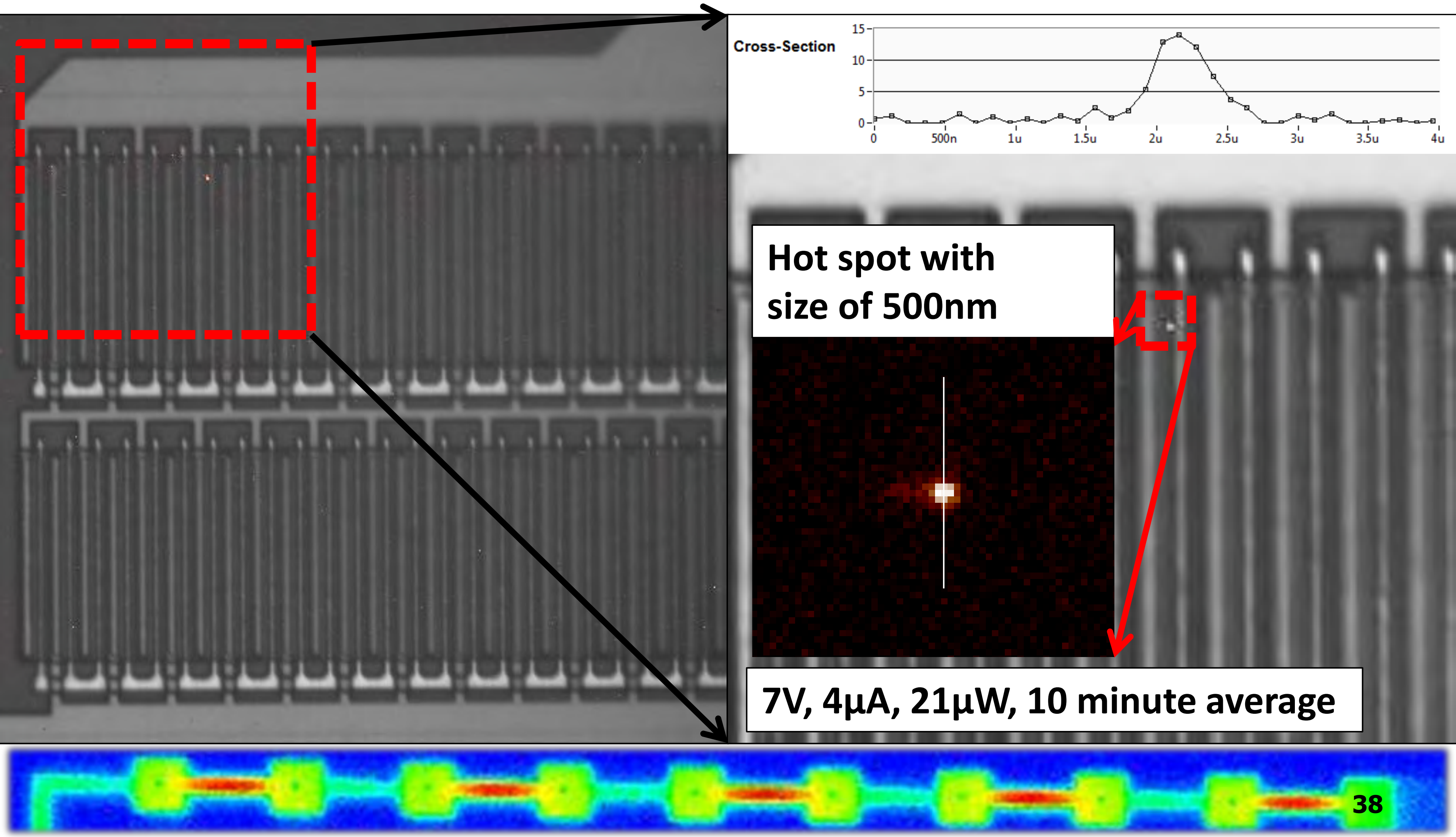
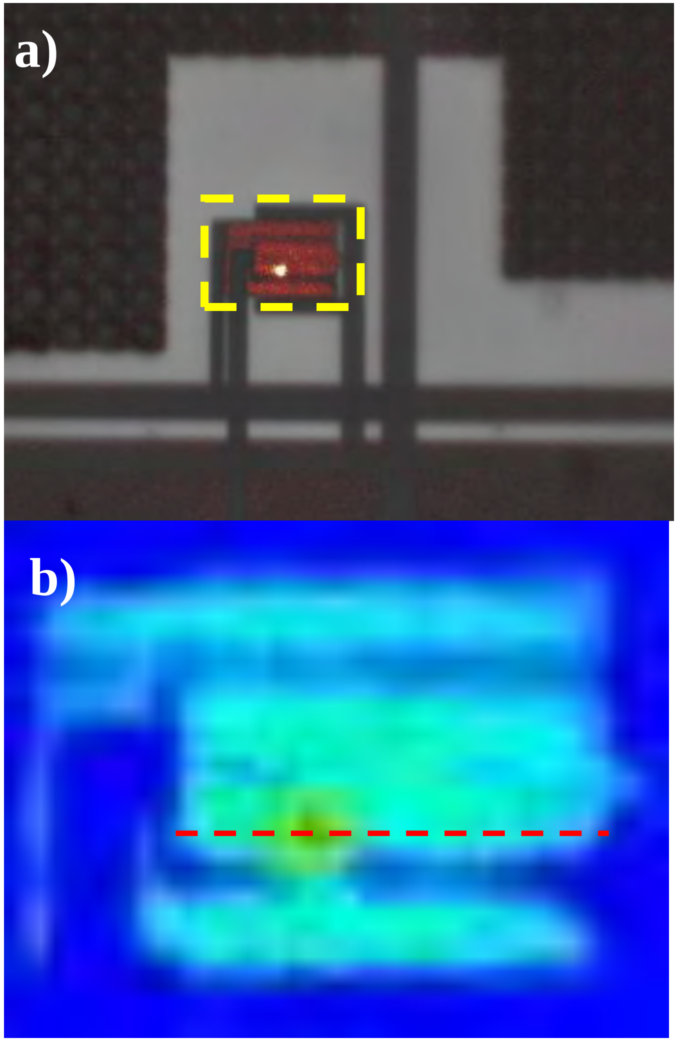
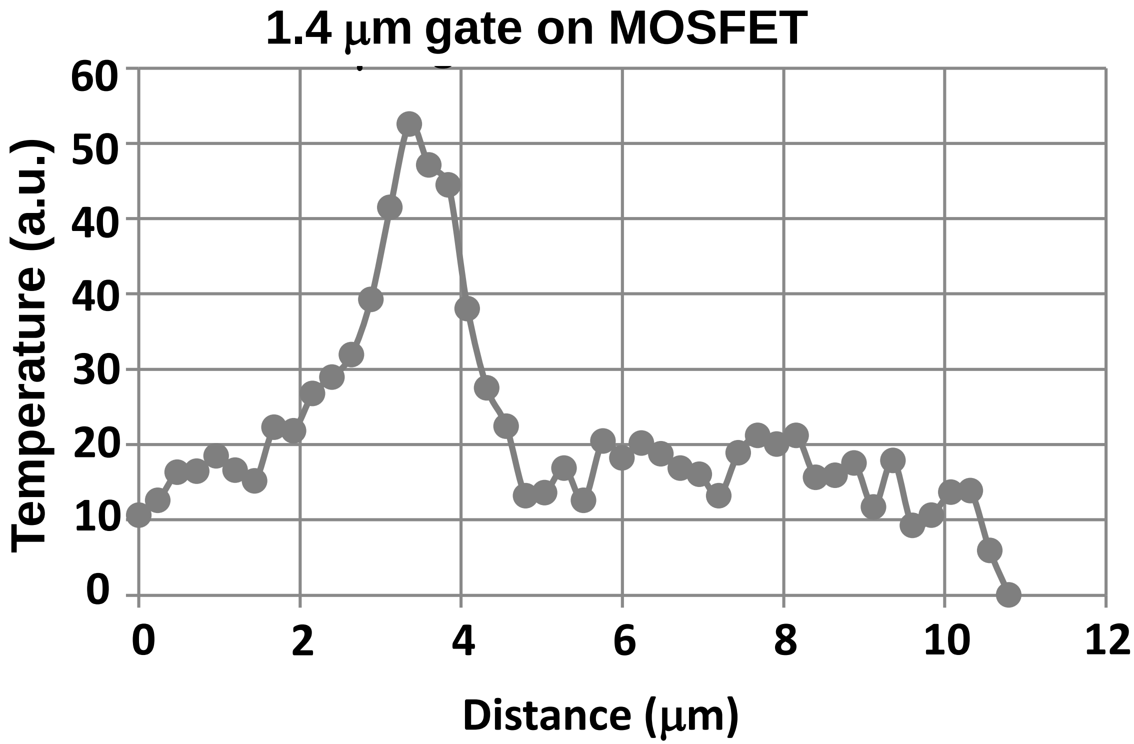


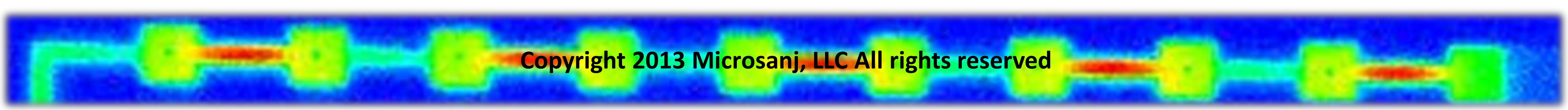
Thermal Image of <500nm Defect



Small hotspot

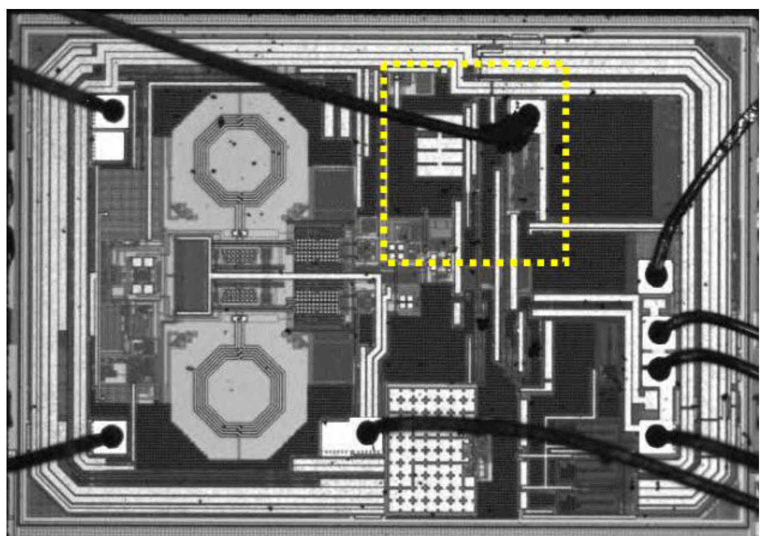




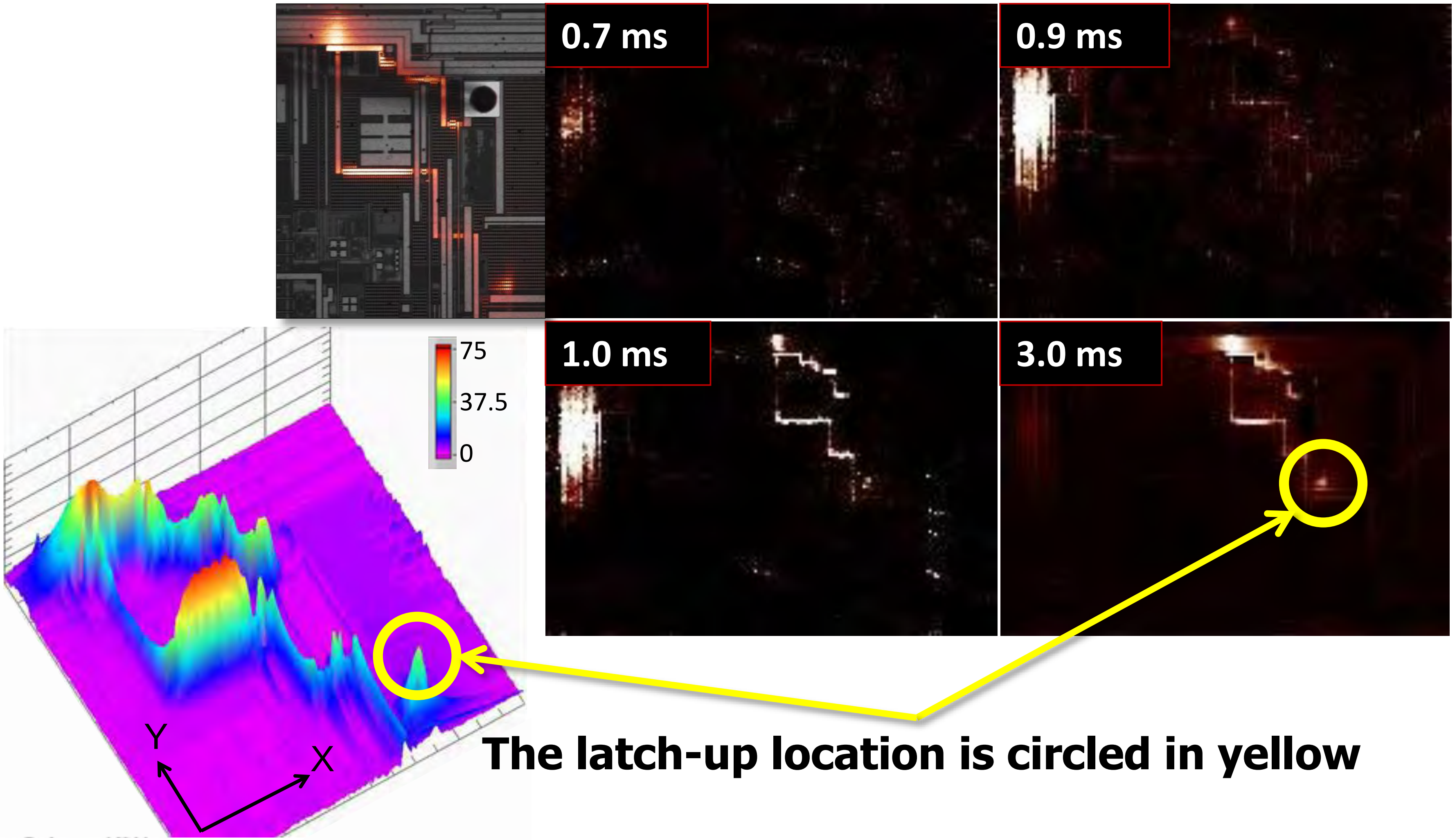


Transient Measurement of Latchup in an IC

- By synchronizing with the startup sequence of the IC, transient temperature maps can show different stages and locations of the power cycle
- For devices with higher power dissipations and poor heat sinking, low duty cycles can be used to limit overall heating. This can prevent damage done to the device that could occur at DC bias



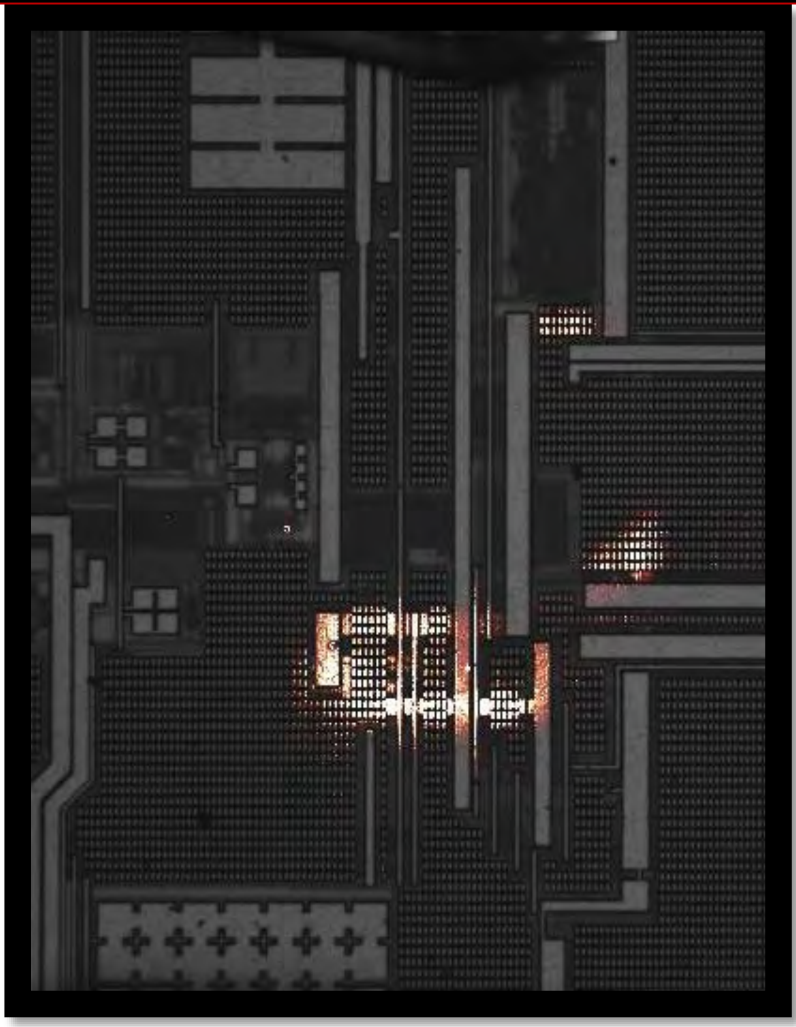
Transient Behavior of IC Latch-Up



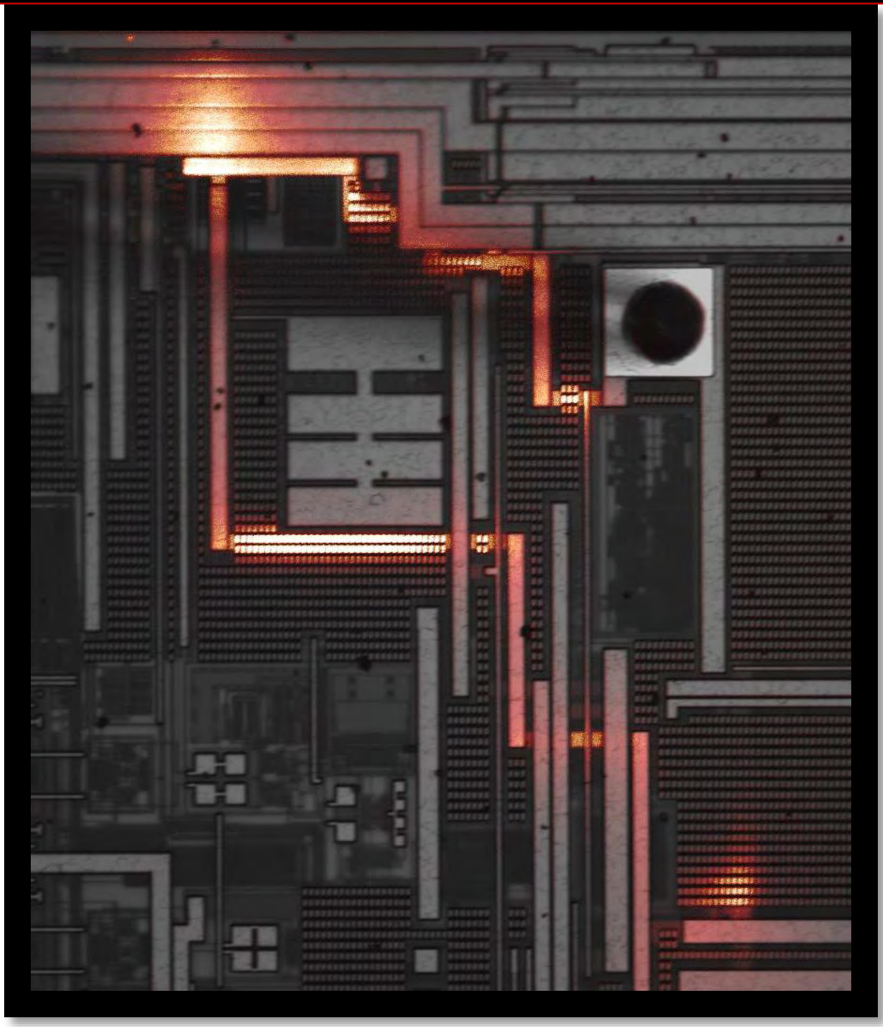
The latch-up location is circled in yellow

Current paths for DUT1 and DUT2

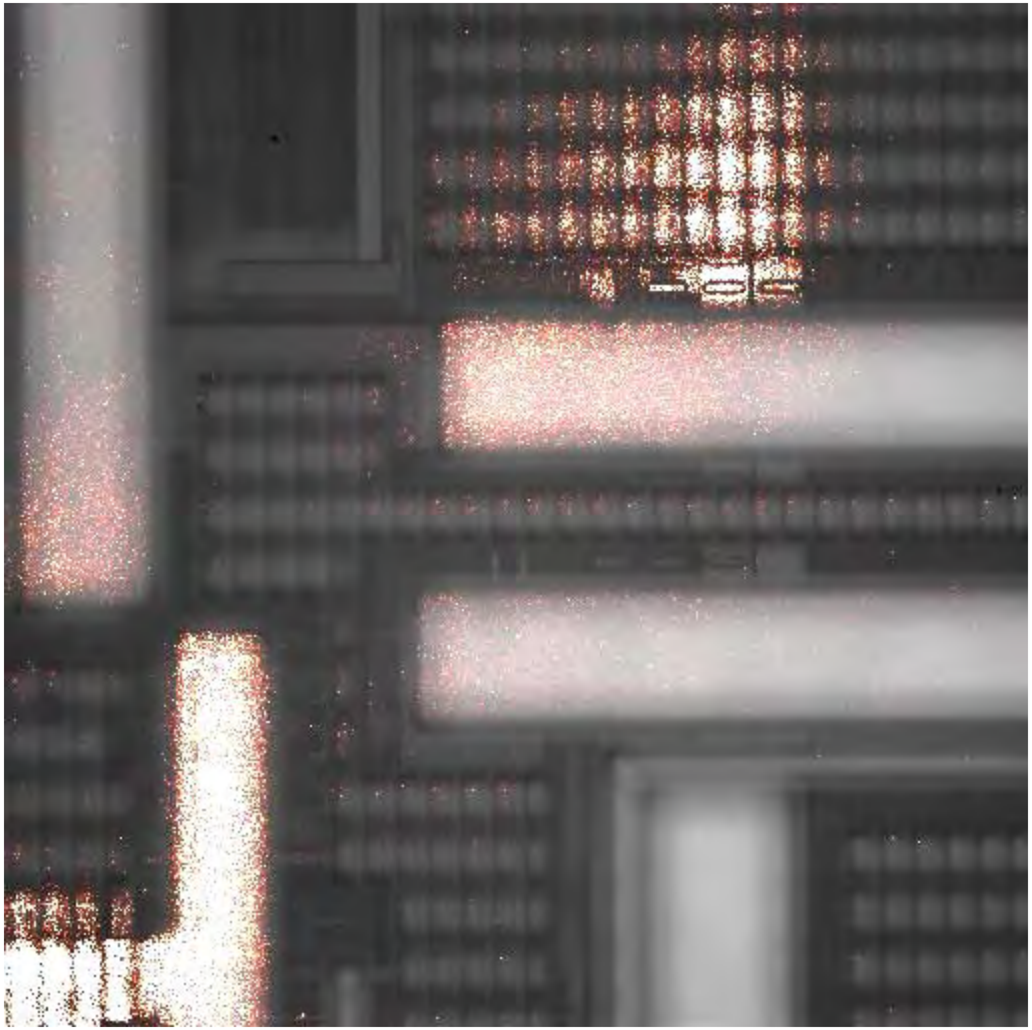
DUT1



DUT2

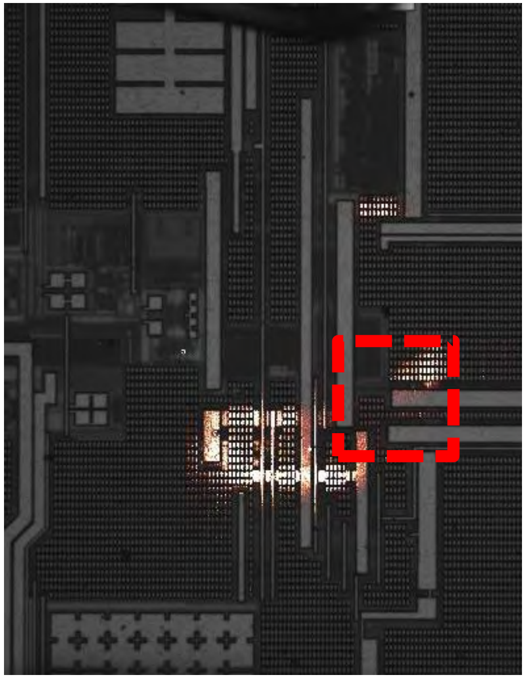


100x Thermoreflectance image overlay



This is an overlay of the optical and thermal image at 100x magnification

At 100x the depth of focus is 870nm, so this thermal image is focused on the top metal surface.



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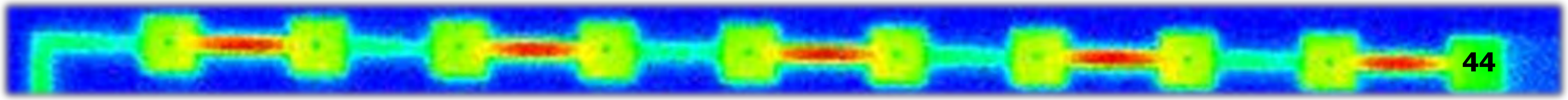
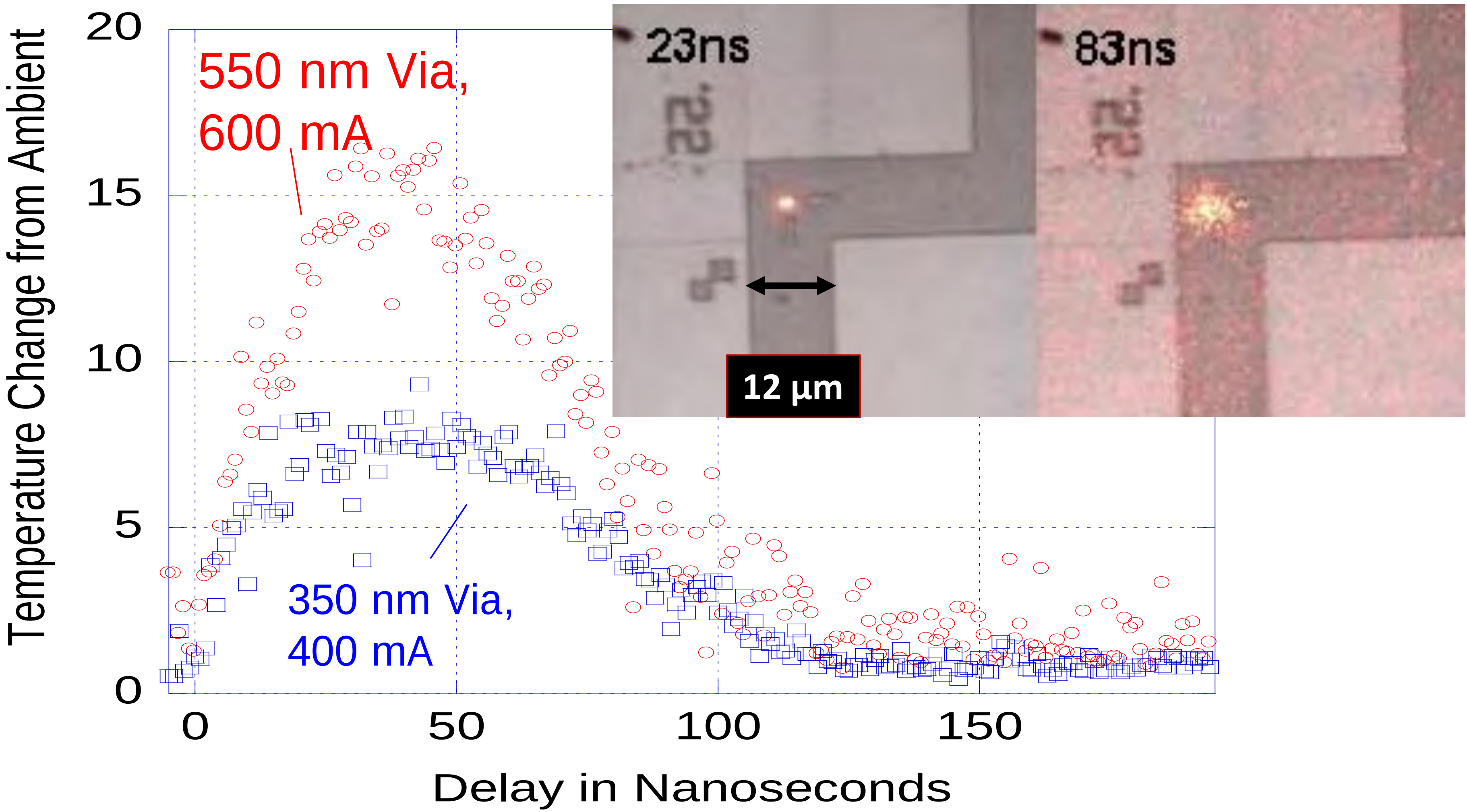
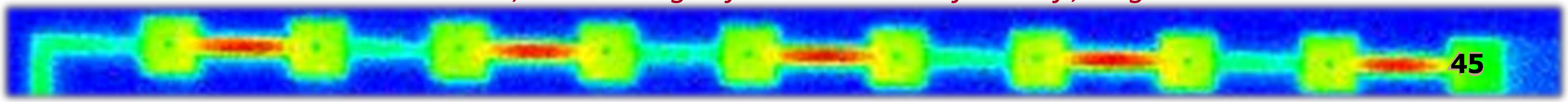


High Speed Thermal Imaging **(800 ps)**

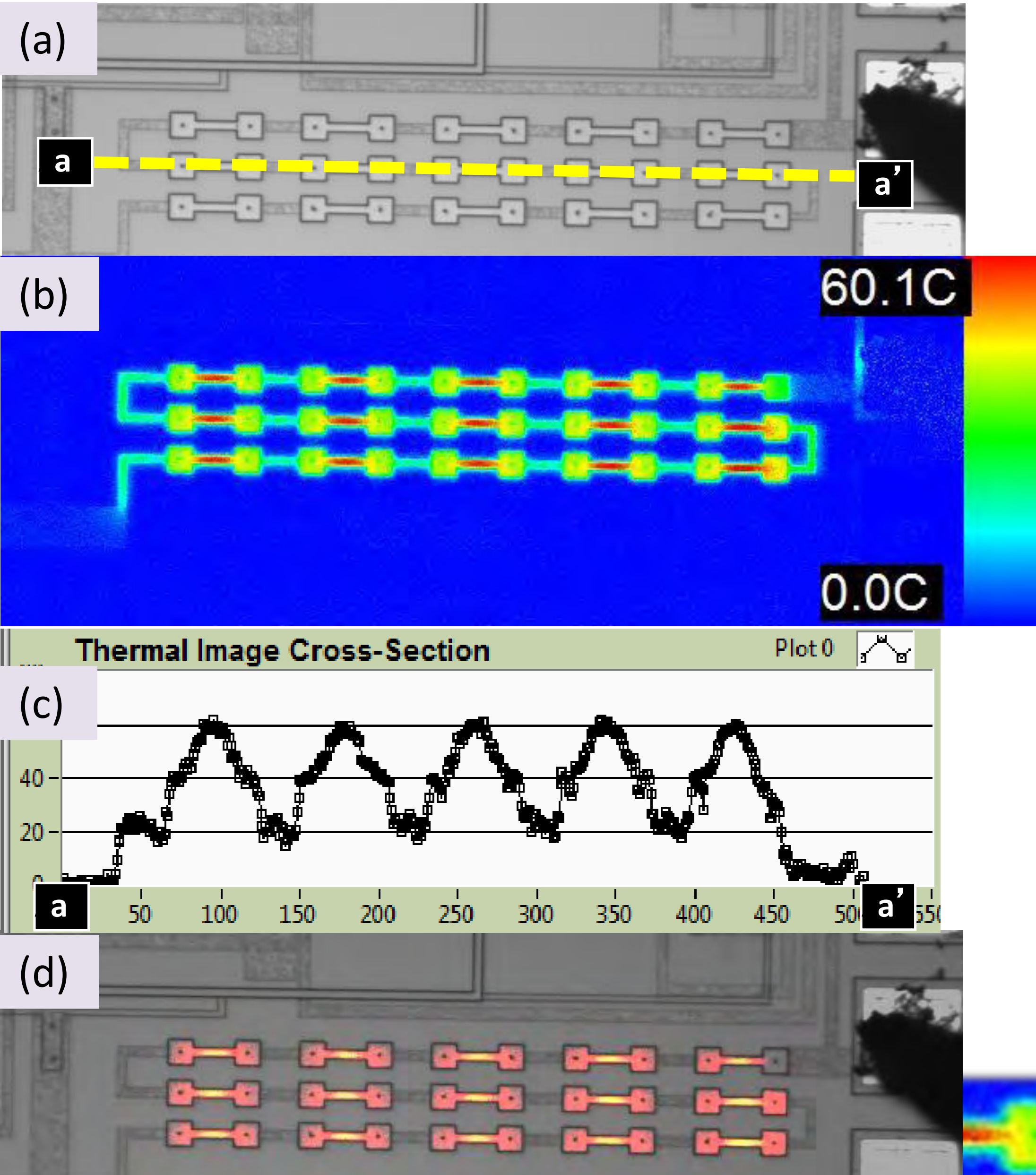
Study of heating in submicron interconnect via



J. Christofferson et al., *Proceedings of Int. Heat Transfer Conf., August 2010*



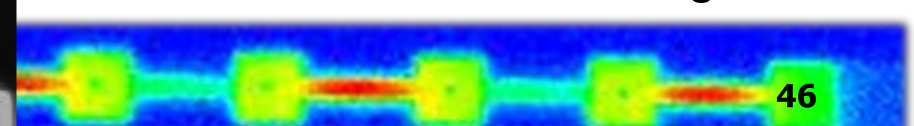
Verify Interconnect & Via Integrity

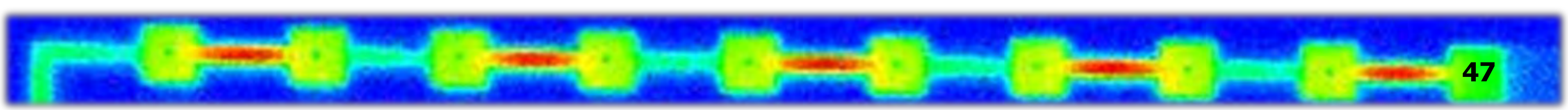


Determine if defects are due to single elements or are uniform throughout the whole chain. (2D temperature/power map instead of a 1 point electrical measurement)

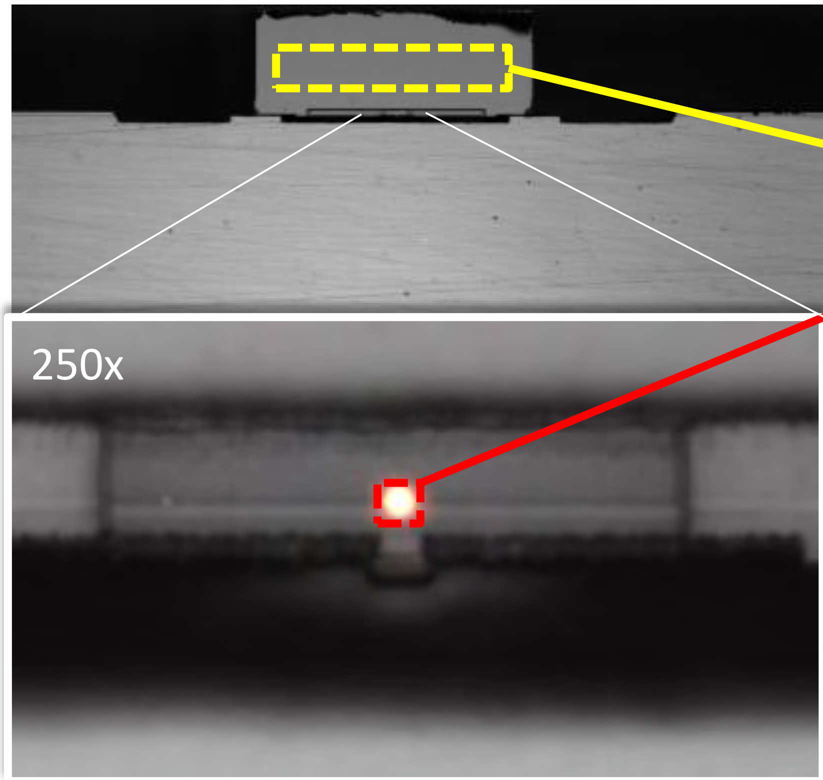
Polysilicon via chain shows uniform power dissipation. If single element is causing higher resistance in the chain, it would have higher temperature compared to the other vias.

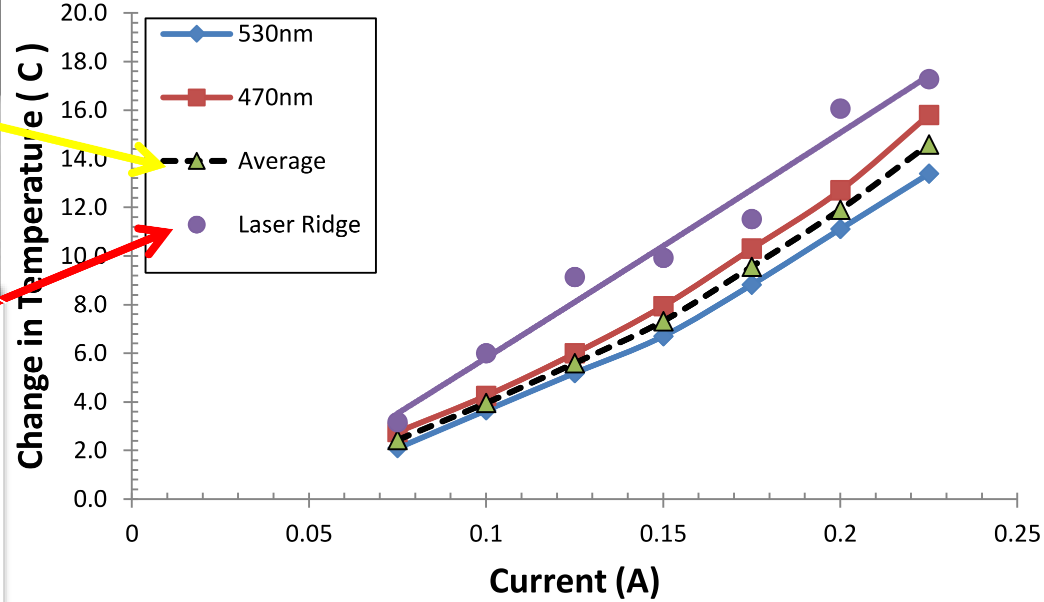
a) Optical image
b) Thermal image
c) Temperature profile
d) Merged optical/thermal image shows location of heating





InP Laser device (cross section)
with 530nm and 470nm LEDs

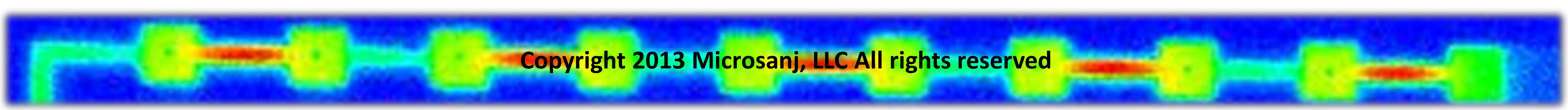




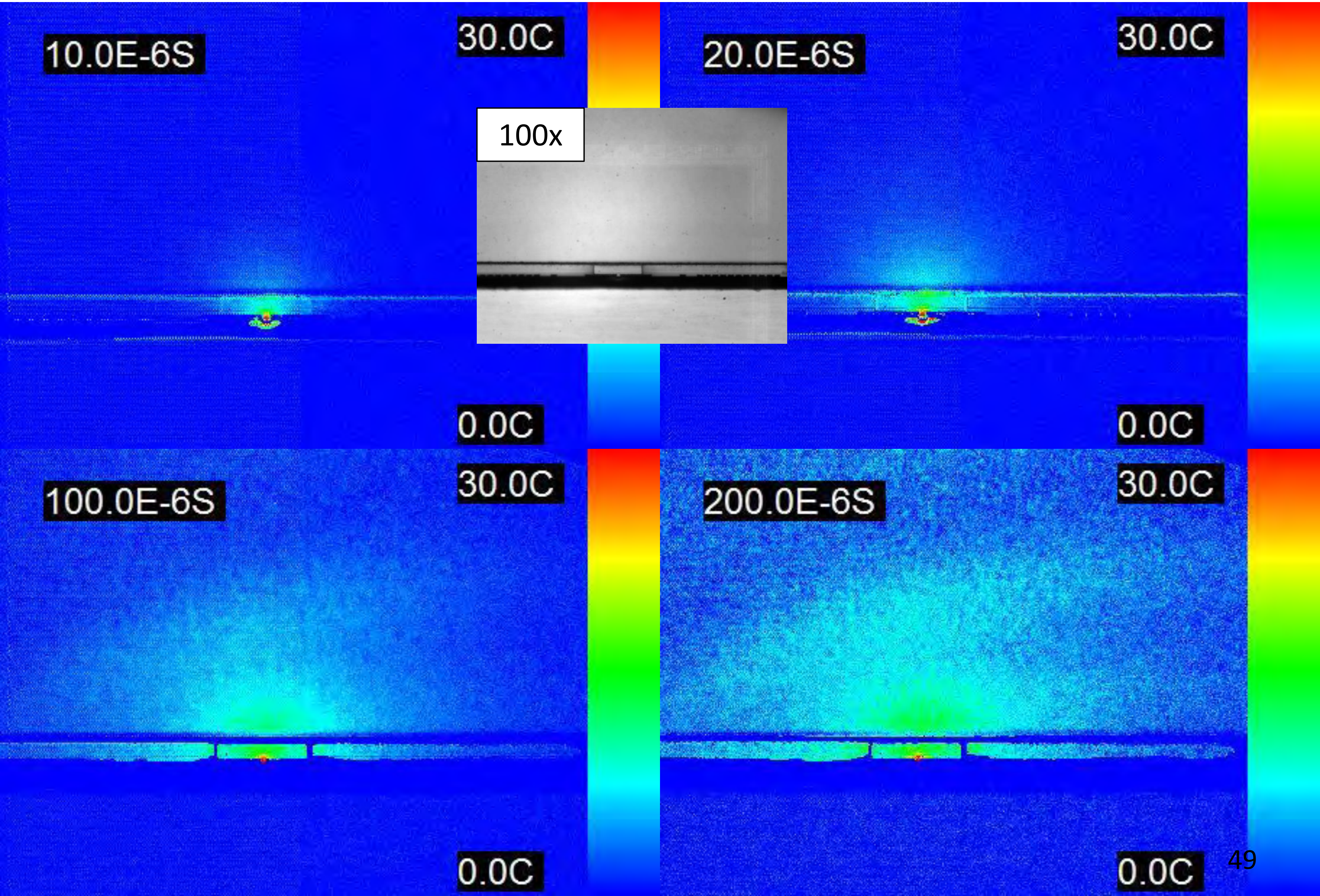
Areas of interest (0.5 mm x 1 mm)

In flip chip package

Forward diode voltage 0.73V

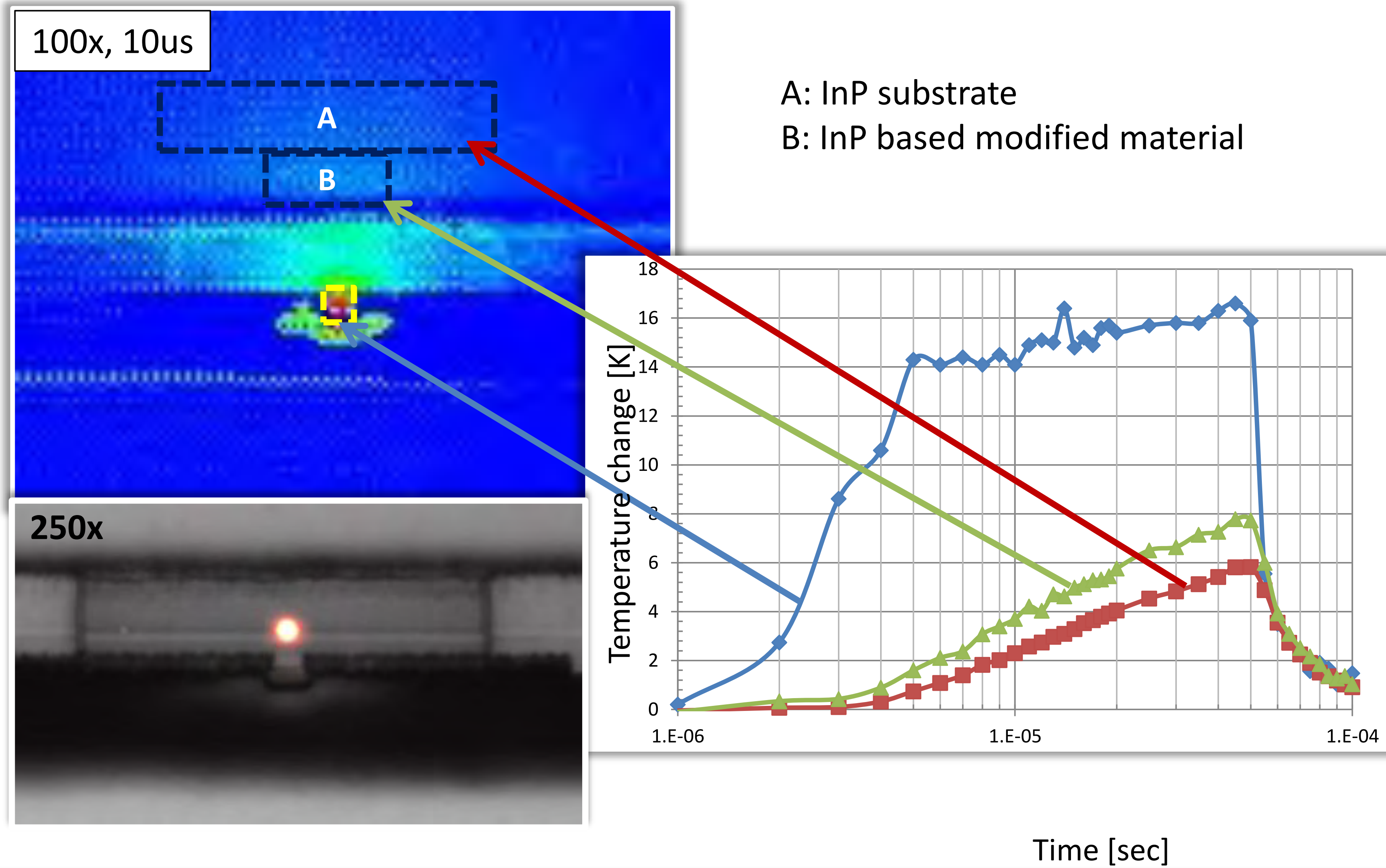


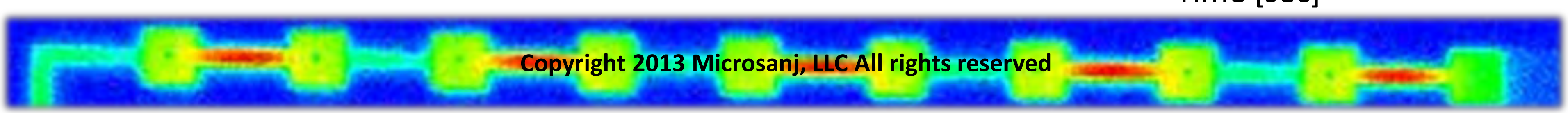
250mA transient thermal images at 10, 20, 100, 200μs



Transient response (250mA pulse)

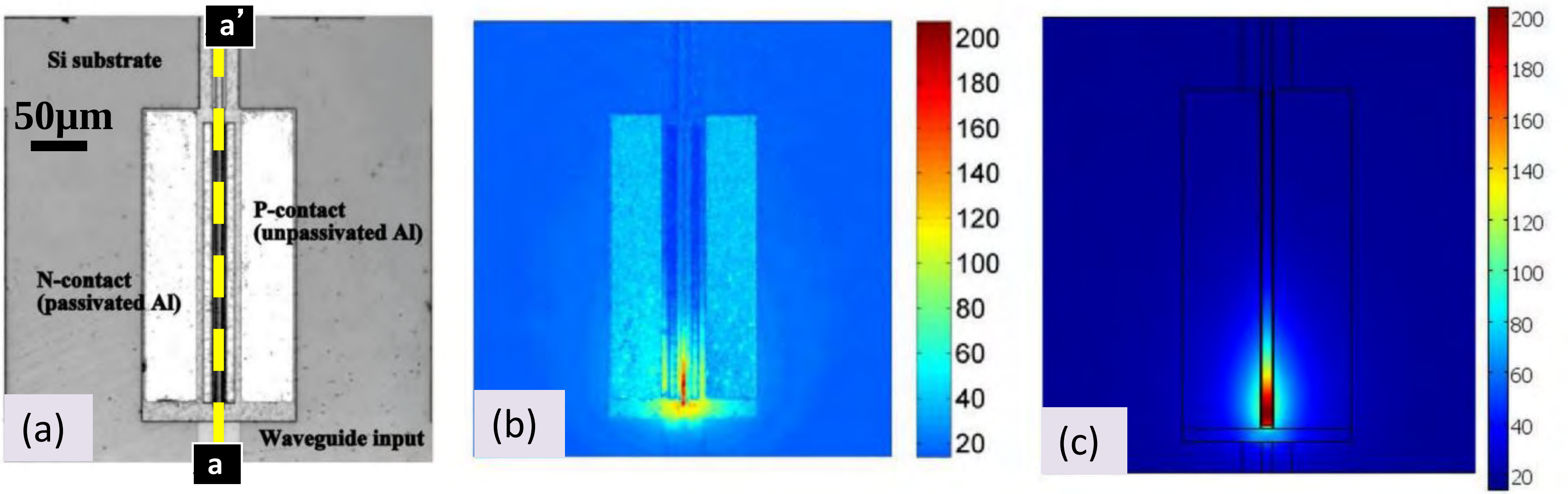
A: InP substrate
B: InP based modified material

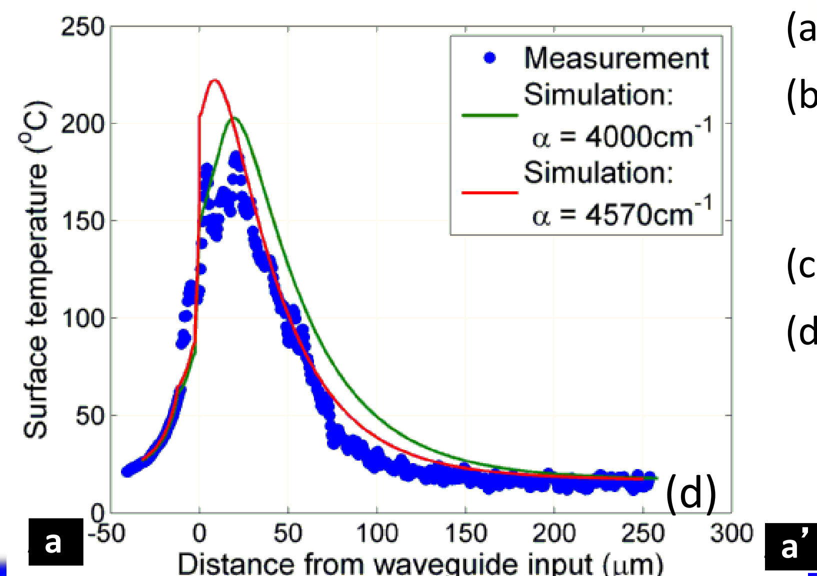




Ge/Si p-i-n Waveguide Photodiode

M. Piels et al., *Proc. of Integrated Photonics Research, Silicon and Nanophotonics (IPRSN)., July 2010*





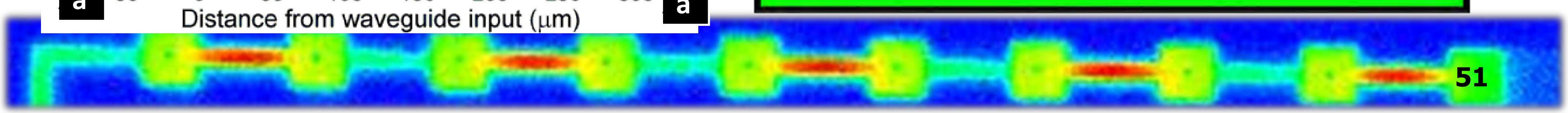
(a) Grayscale image of DUT (7.4 µm channel width)

(b) Thermoreflectance imaging result. Signal from unpassivated Al on p-contacts is below noise floor so these areas should be neglected

(c) COMSOL simulation results

(d) Surface temperature profile

Characterize Optoelectronic devices and verify thermal simulations



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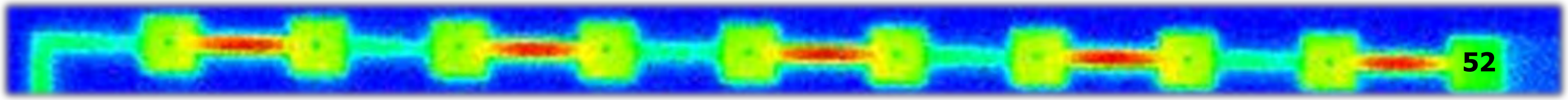
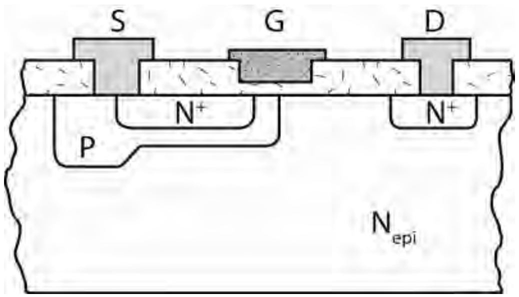
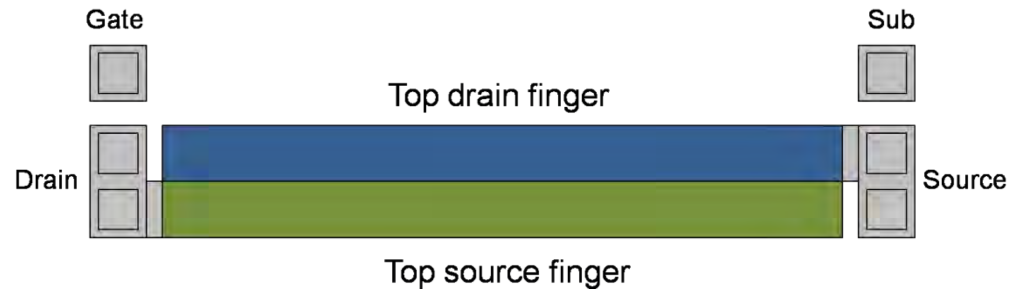
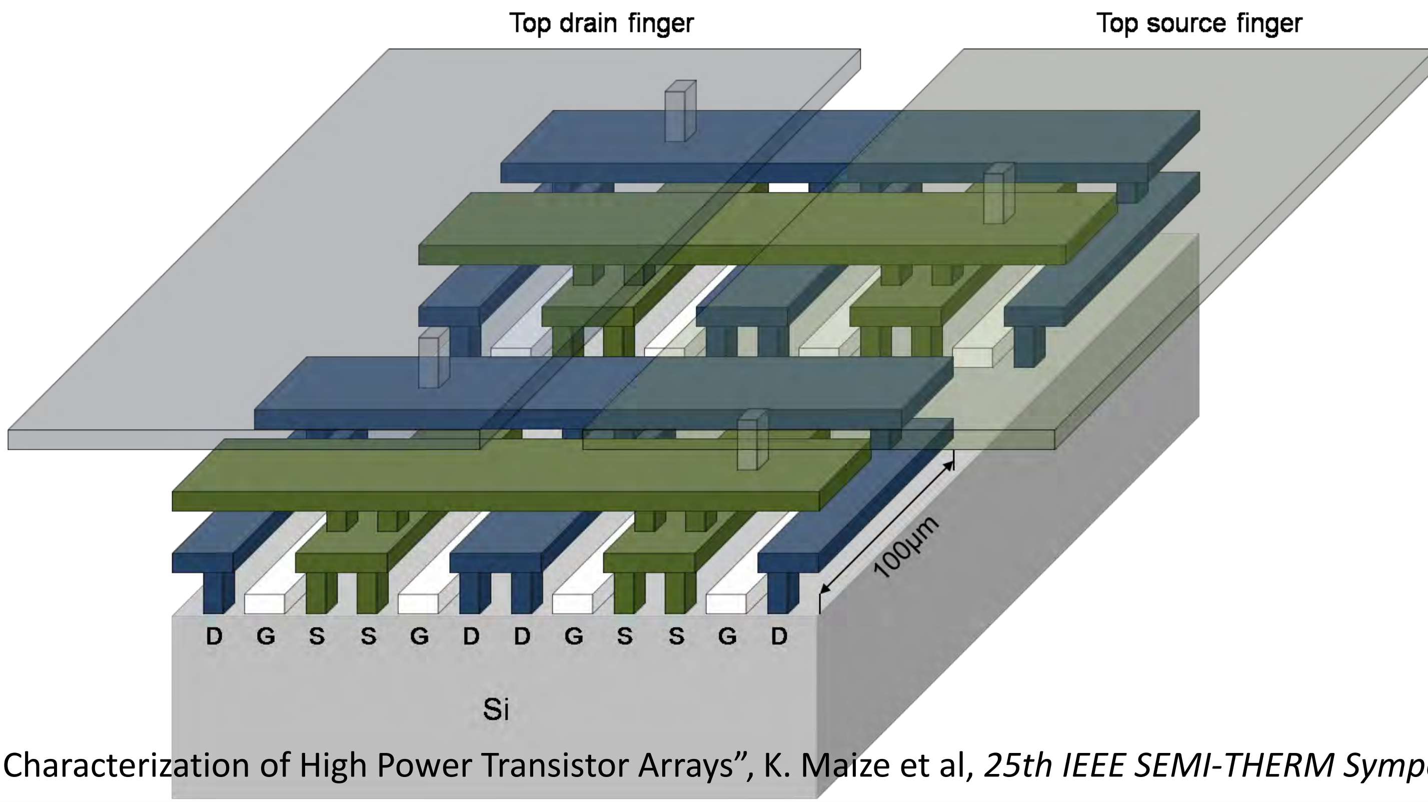


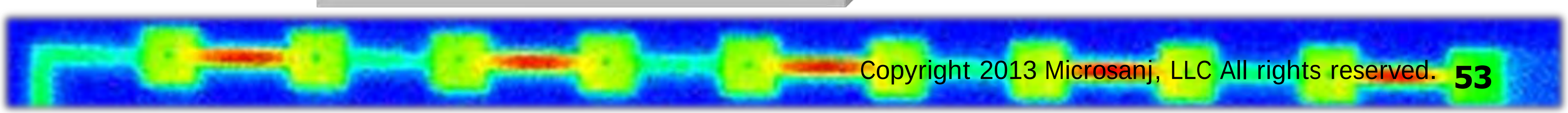
High Power MOSFET Transistor Array







"Thermal Characterization of High Power Transistor Arrays", K. Maize et al, *25th IEEE SEMI-THERM Symposium*, 2009.



SOA of Transistor Arrays

Vd=4V

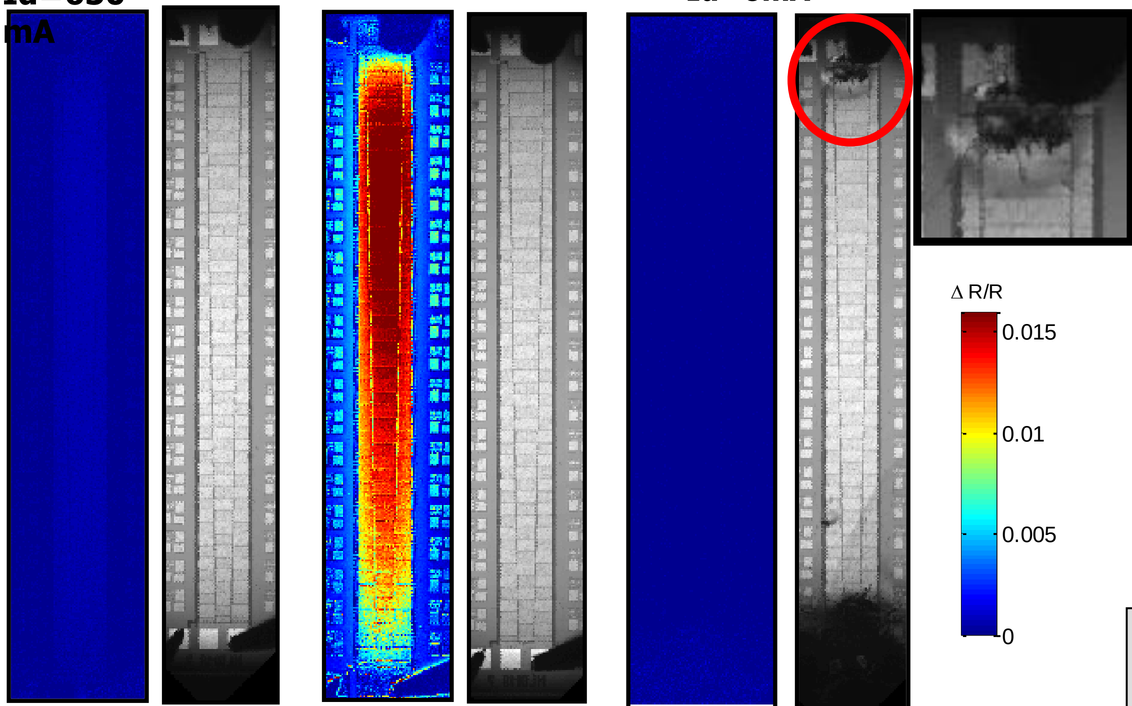
Id=650 mA

Vd=37V

Id=950mA

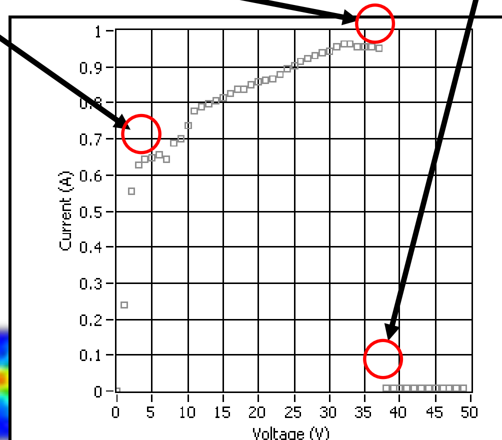
Vd=38V

Id=0mA



Thermal

DC



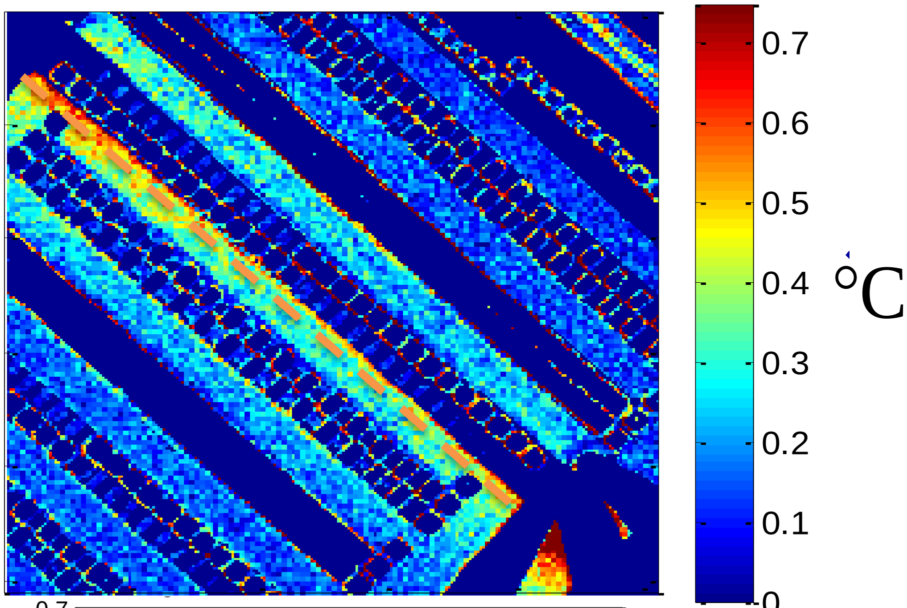
Catastrophic failure at V_{ds}= 37 V due to heating on source finger.

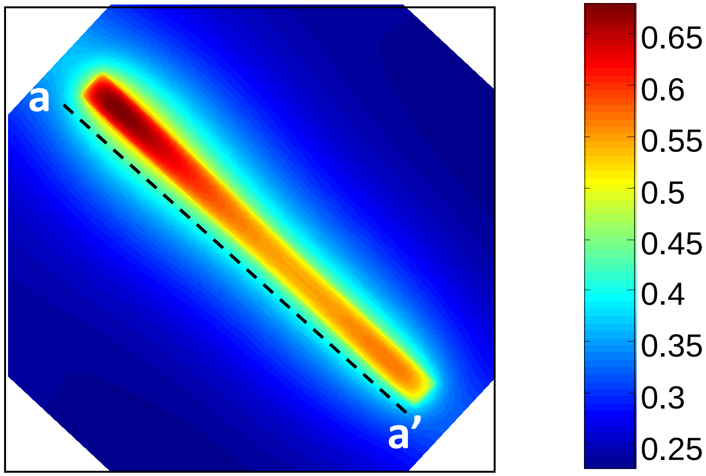
NLDMOS transistor array
Pulsed SOA thermoreflectance:
2.5 ms pulse width, 8% duty, Vg = 2V, Vd = 1 to 50V.

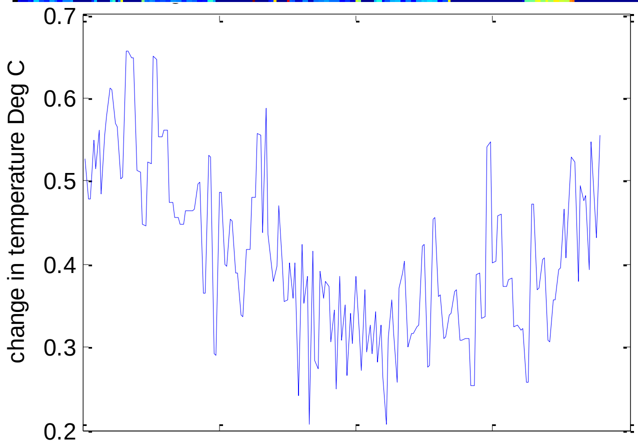
Safe operating areas (SOA) of devices can be used to identify and troubleshoot reliability issues in electronic devices.

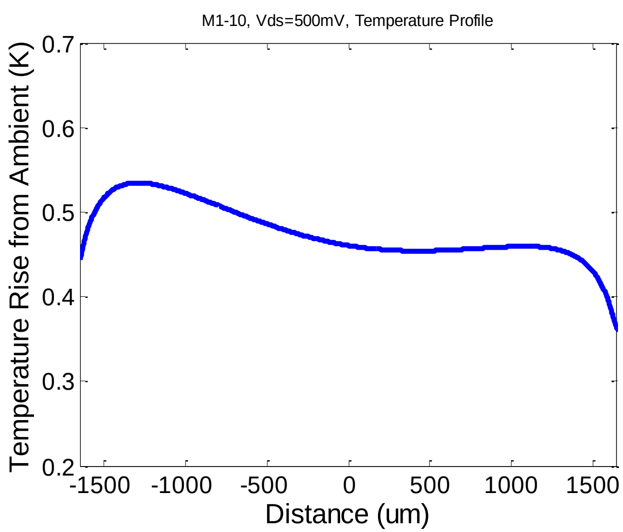
Thermal image *vs.* ***simulation*** at low bias

Vd = 0.5V, Id ≈ 0.5A 6 amps/mm^2

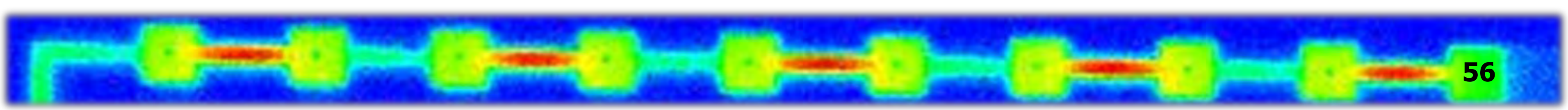




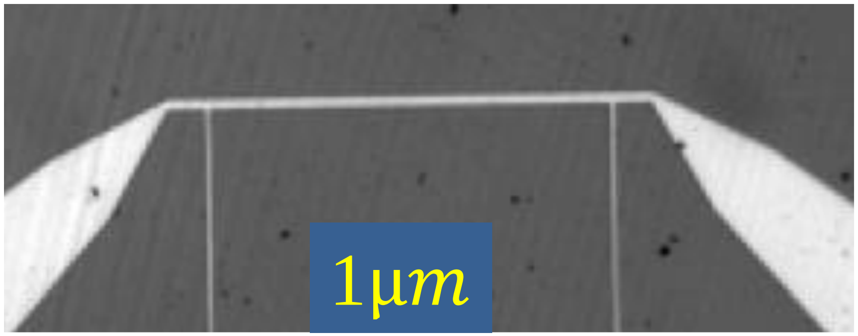


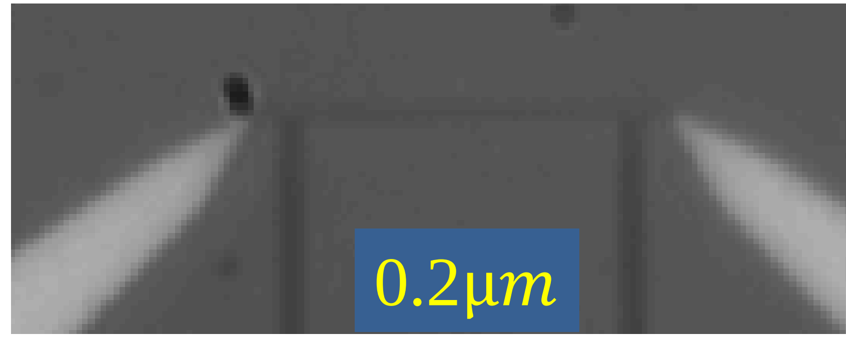


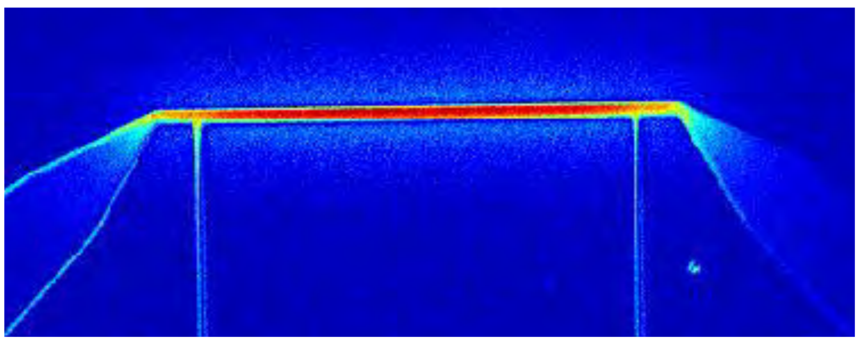
- Basic Principles of Thermoreflectance Imaging
- Measurement for HEMT Transistor
- Transient measurements
- GaN High Power Amplifiers
- ESD protection devices
- Failure Analysis (FA) HotSpot detection
- Vias and Interconnects
- Optoelectronics (Photodiodes, Solar Cells, LEDs, and Lasers)
- Power amplifiers
- **Sub-diffraction thermoreflectance thermal imaging**
- Summary

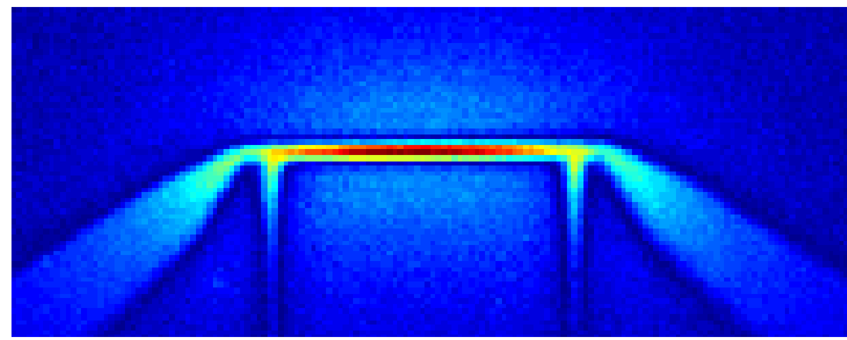


Sub-diffraction TR Imaging

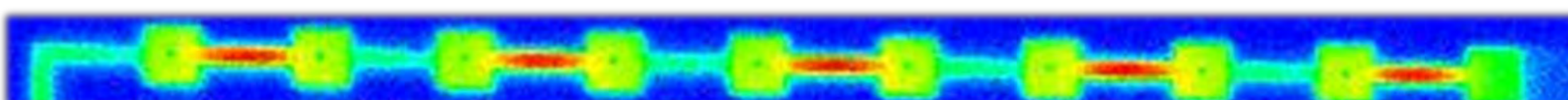




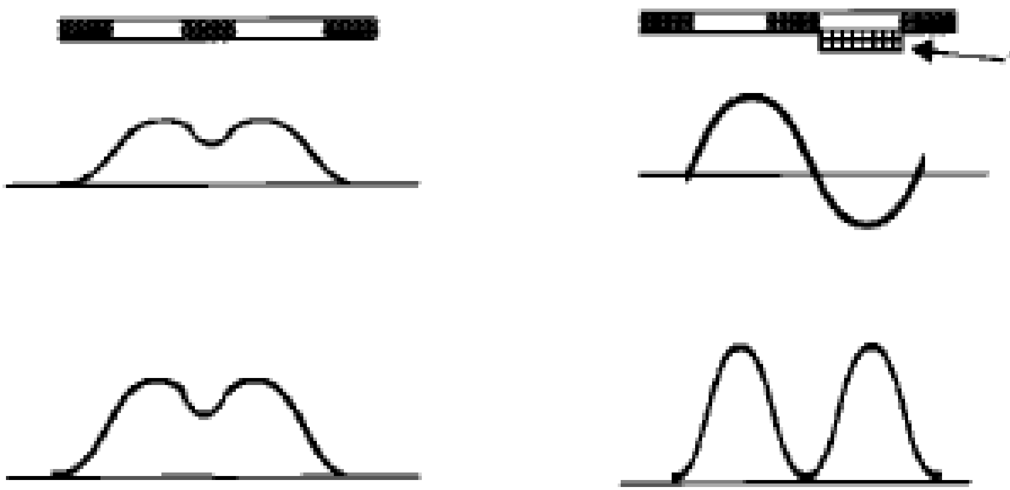




- λ=530nm and R≈360nm
- Then why we observe thermal images?



Sub-diffraction TR Imaging



180 Phase Shifter

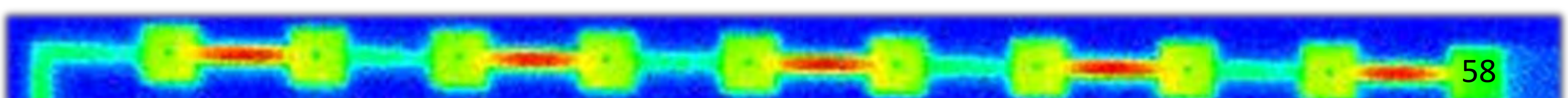
Electric field amplitude

Image Intensity

Binary Mask

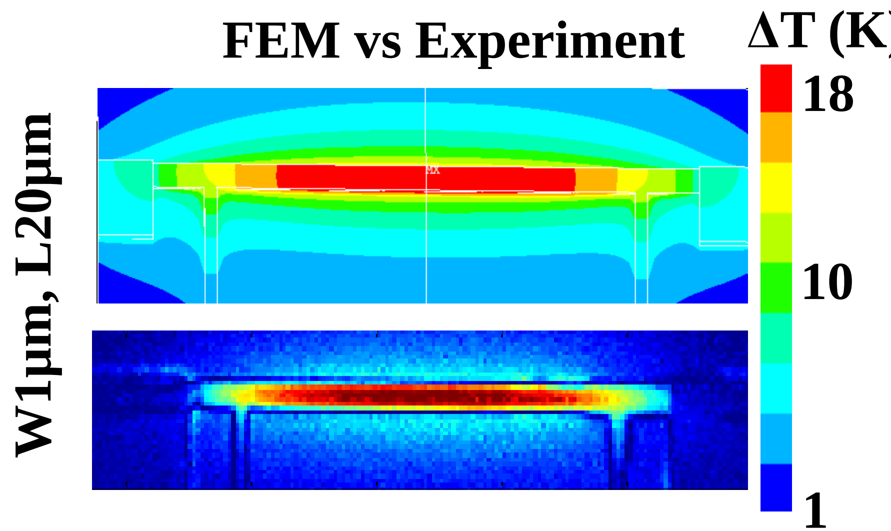
Phase Shift Mask

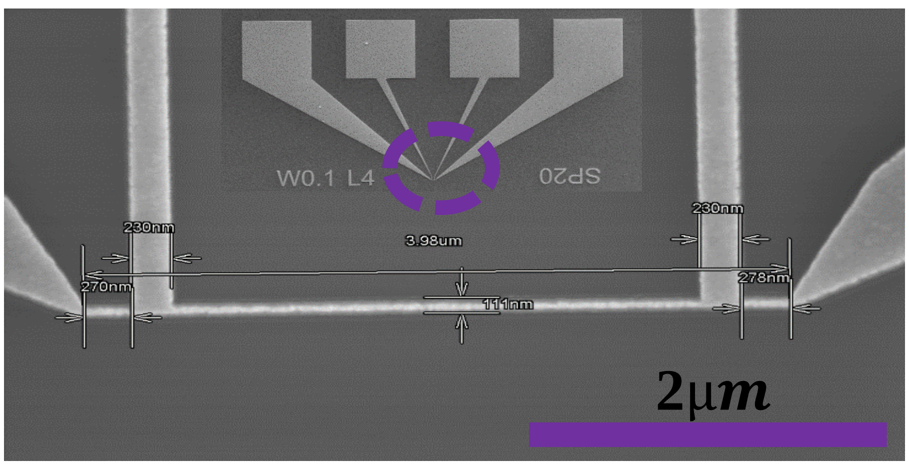
L.R. HARRIOTT , Limits of Lithogorophy, Proceedings of IEEE, 2001



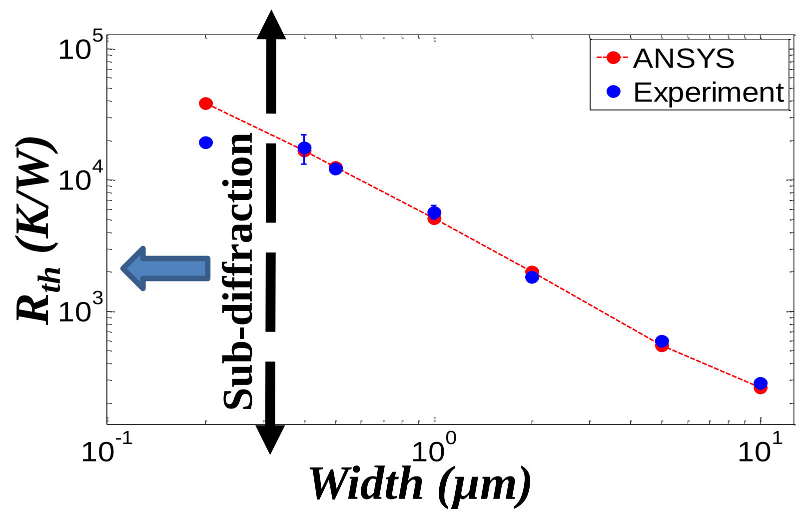
Comparison with Modeling

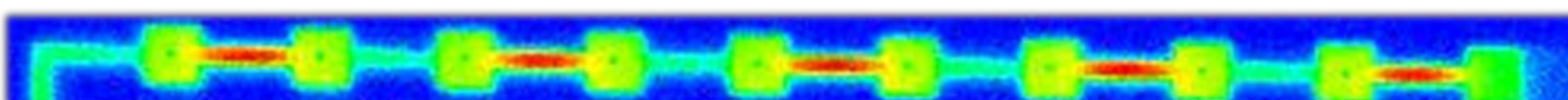
Cross Section (not to scale)





SEM of a 100nm heater line

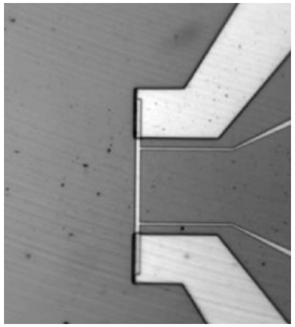


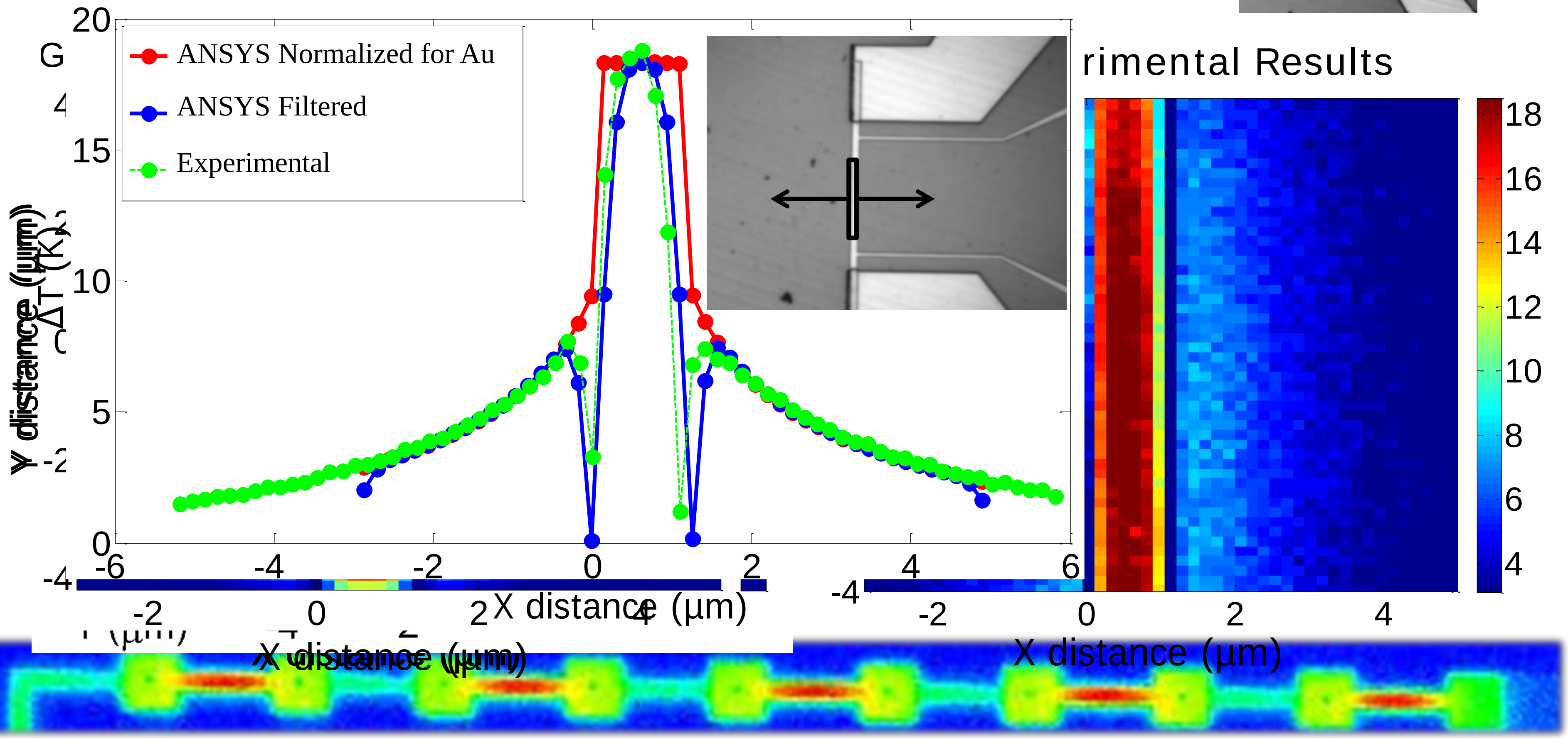


Thermal Blurring Model

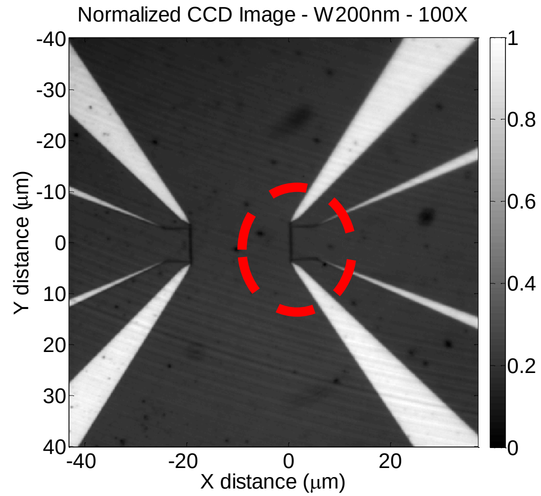
1. Temperature profile obtained from ANSYS
2. Calibrate the ANSYS result with Gold CTR only
3. Blur the thermal image with the Gaussian filter

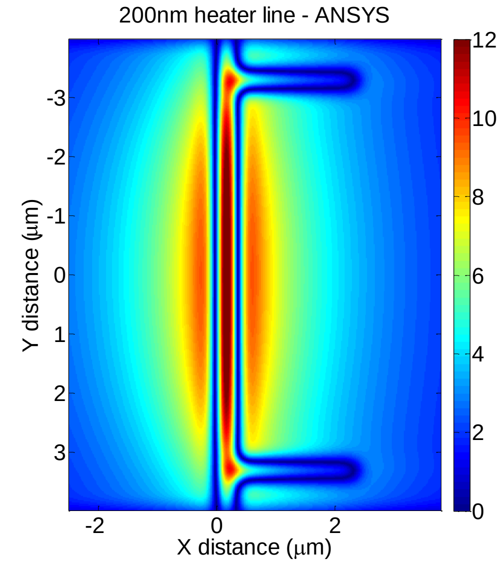
W1µm, L20µm

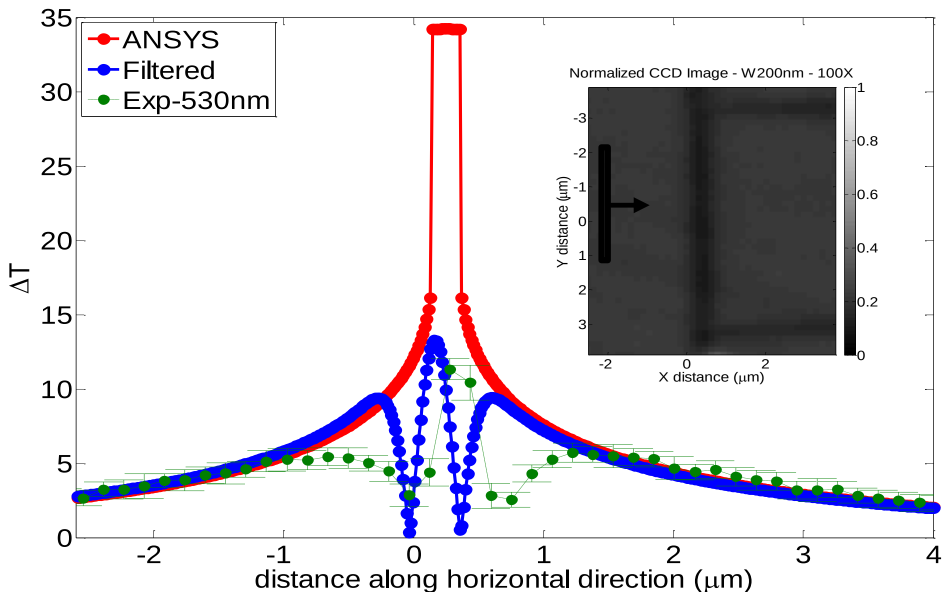


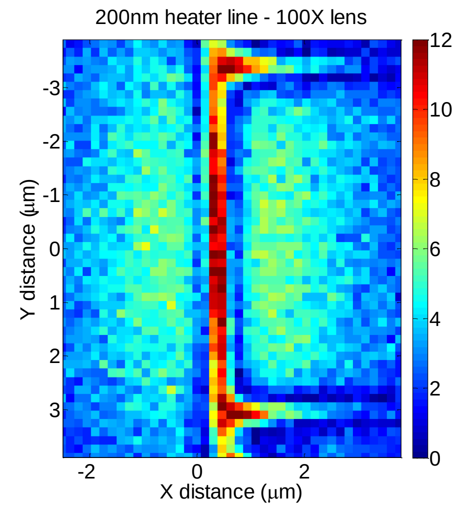


Sub-diffraction TR Imaging





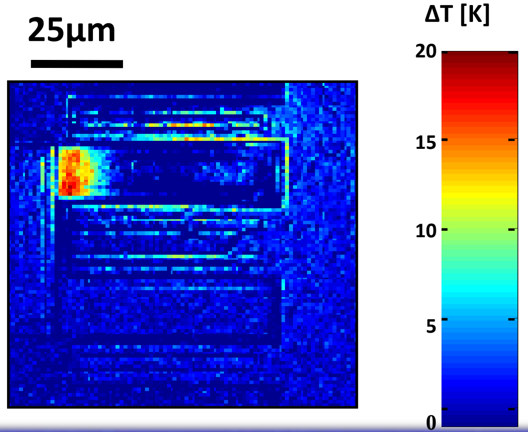




- ❑ We know how the forward process works, we are solving the inverse problem → Accurate TR imaging down to 30-50nm

Summary

- **250nm** thermal images lead to more accurate peak temperature measurements
- **800ps** Transient thermal measurements show unique characteristics of devices (time-varying hot spots)
- Lock-in thermal imaging allows detection of µW defects.
- Non-contact/Non-destructive



Publications

- Bias-Dependent MOS Transistor Thermal Resistance and Non-Uniform Self-heating Temperature
- Si/Ge uni-traveling carrier photodetector
- High-power high-linearity flip-chip bonded modified uni-traveling carrier photodiode
- Time and Frequency Domain CCD-Based Thermoreflectance Techniques for High-Resolution Transient Thermal Imaging
- Understanding the Thermoreflectance Coefficient for High Resolution Thermal Imaging of Microelectronic Devices
- High Speed Transient Thermal Imaging of Microelectronic Devices and Circuits
- Thermal Characterization of High Power Transistor Arrays
- Time and Frequency Domain CCD-Based Thermoreflectance Techniques for High-Resolution Transient Thermal Imaging
- Thermoreflectance Imaging of Defects in Thin-Film Solar Cells
- Thermal Imaging of Encapsulated LEDs
- Quantum Electronics Group, Jack Baskin School of Engineering at UC Santa Cruz
- Thermal Imaging for Reliability Characterization of Copper Vias
- Ultrafast Submicron Thermoreflectance Imaging
- Sub-diffraction thermal imaging in HEMT Transistors

More information at http://microsanj.com/news-and-papers

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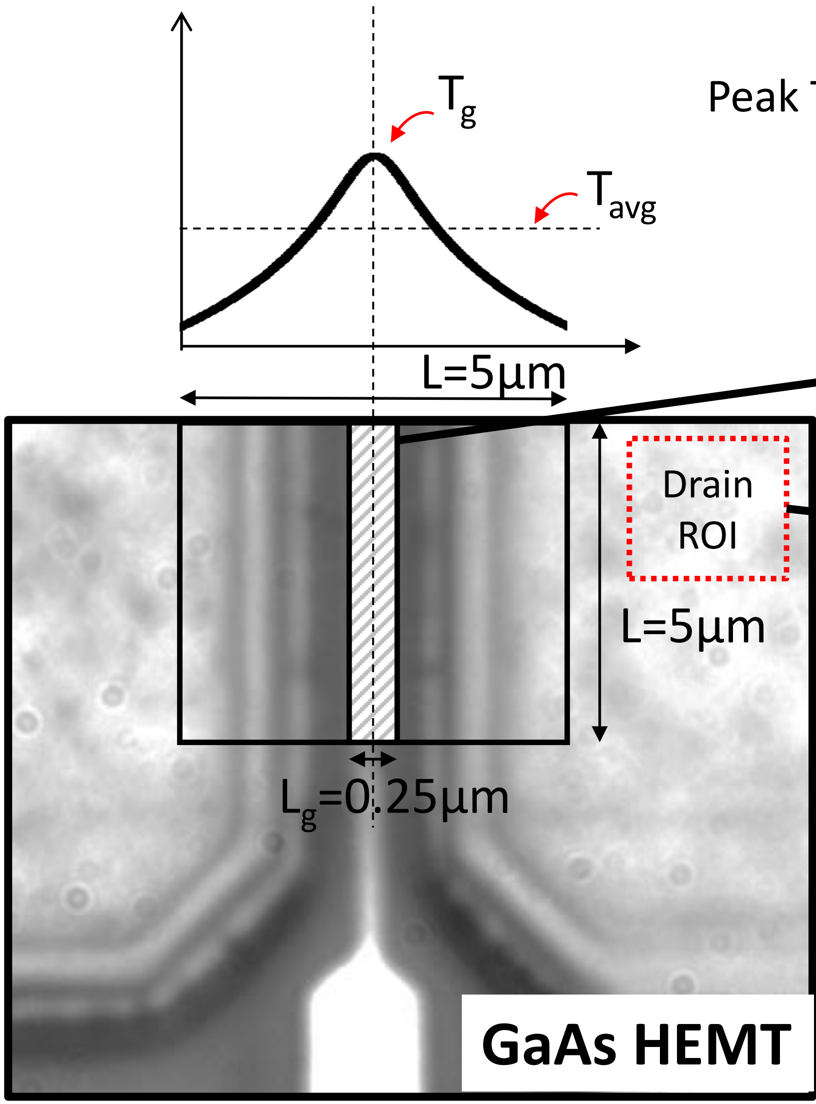
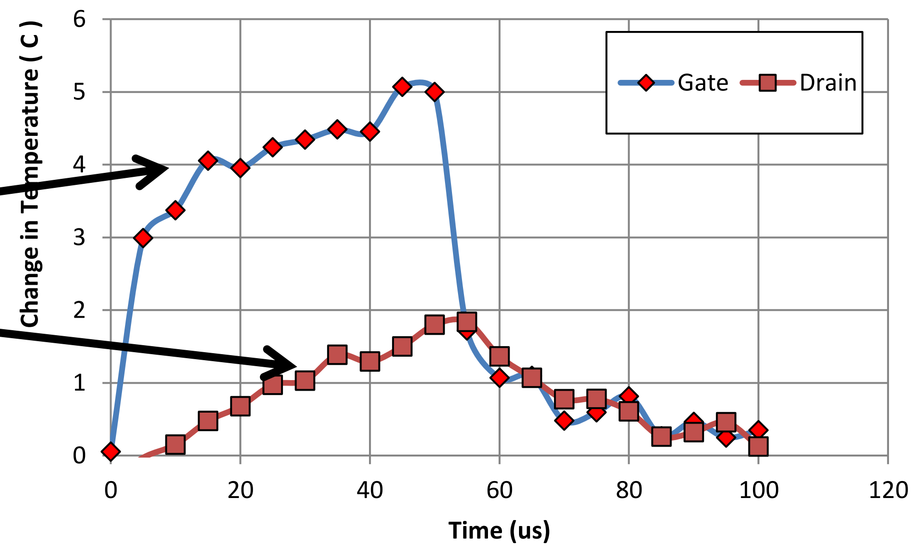
Bonus

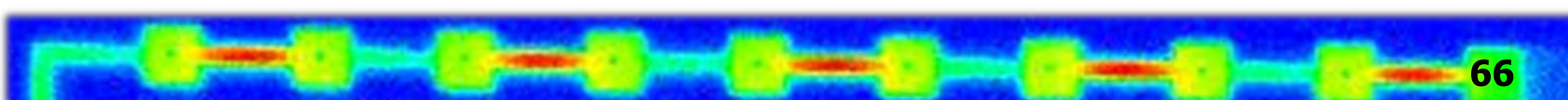
Gate and Drain Transient Response

Peak Temperature can be off by 30%

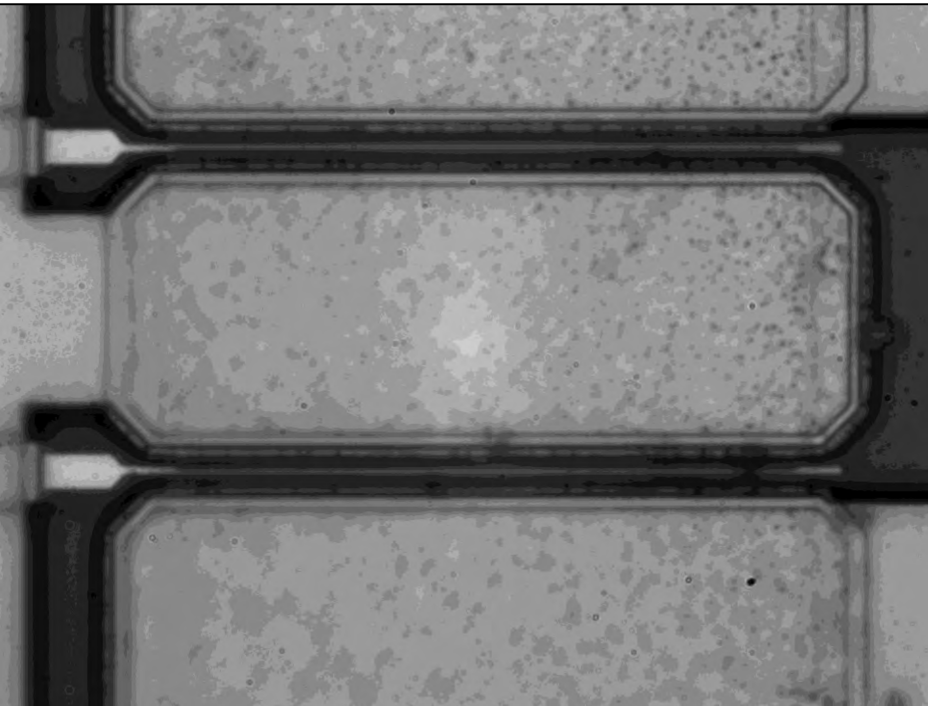
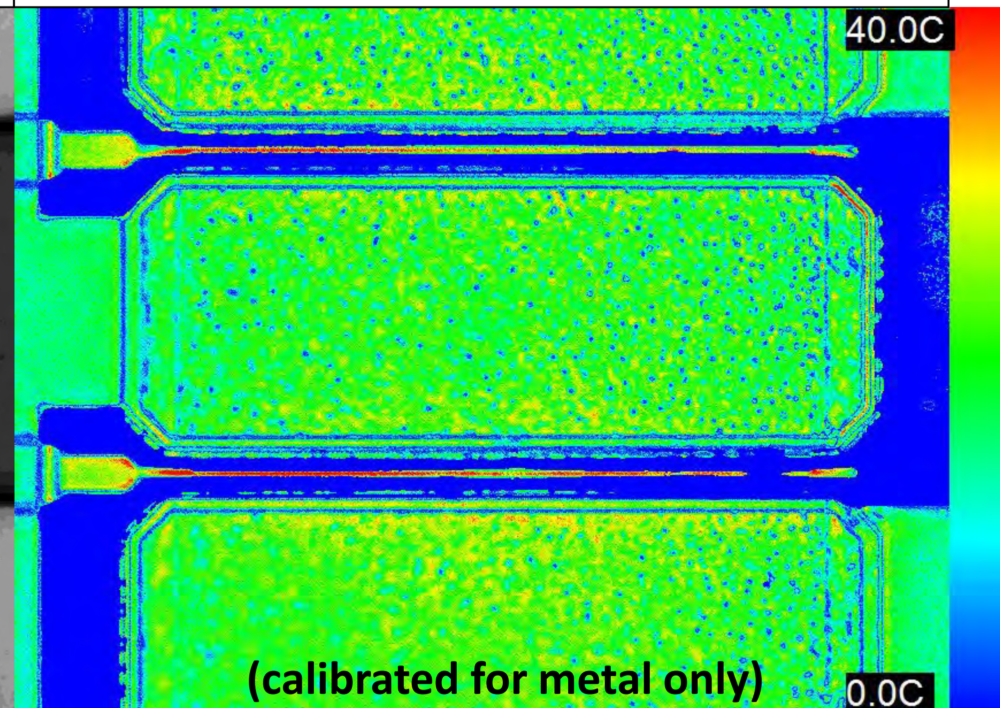




High Speed thermal measurements clearly show gate heating in first 5µs, then drain heating following behind. 44mA, 1V

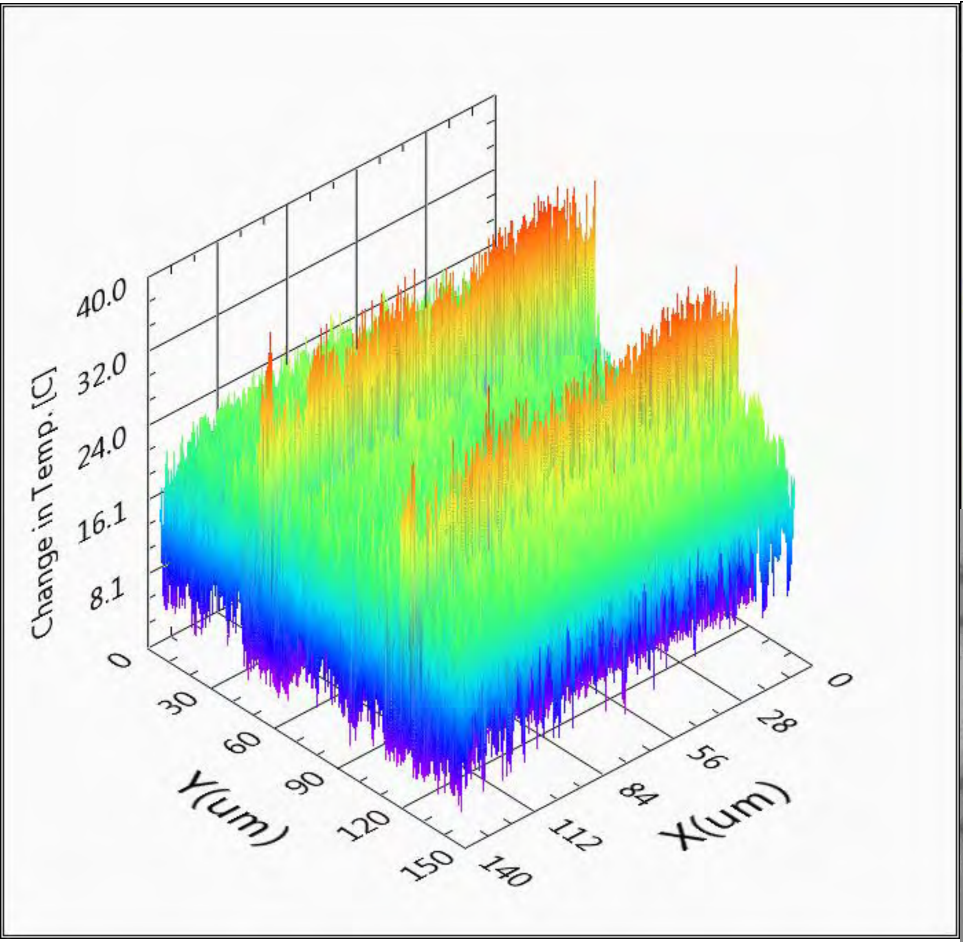


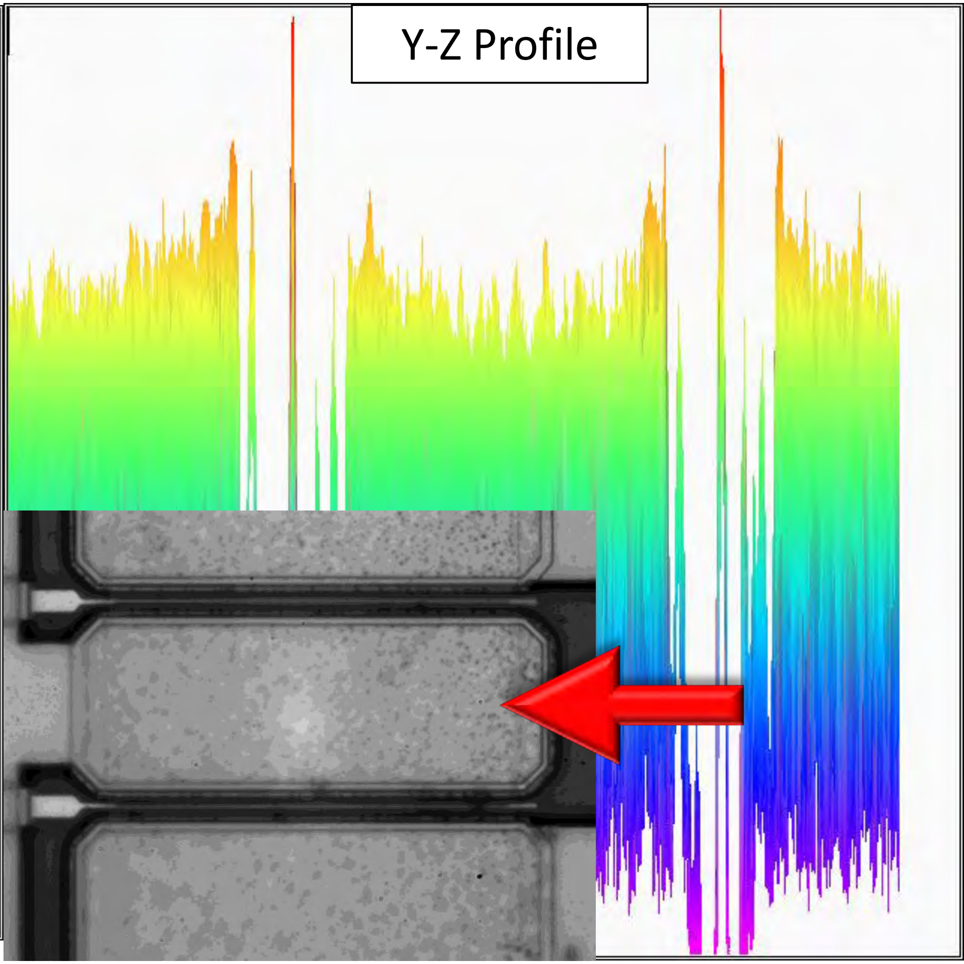
100x thermal image of gate

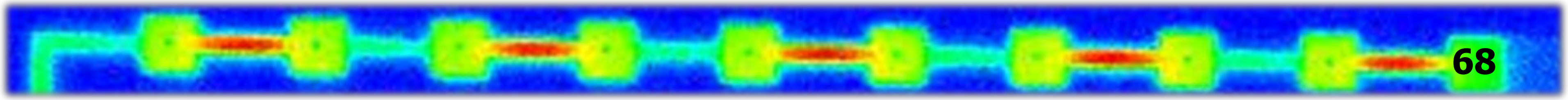
CCD Image	Thermal Image
	

This shows the side temperature profile of the center of the pHEMT. The dark channel region is not calibrated for, and did not show a strong signal.

3D Temperature Profiles of HEMT at 100x







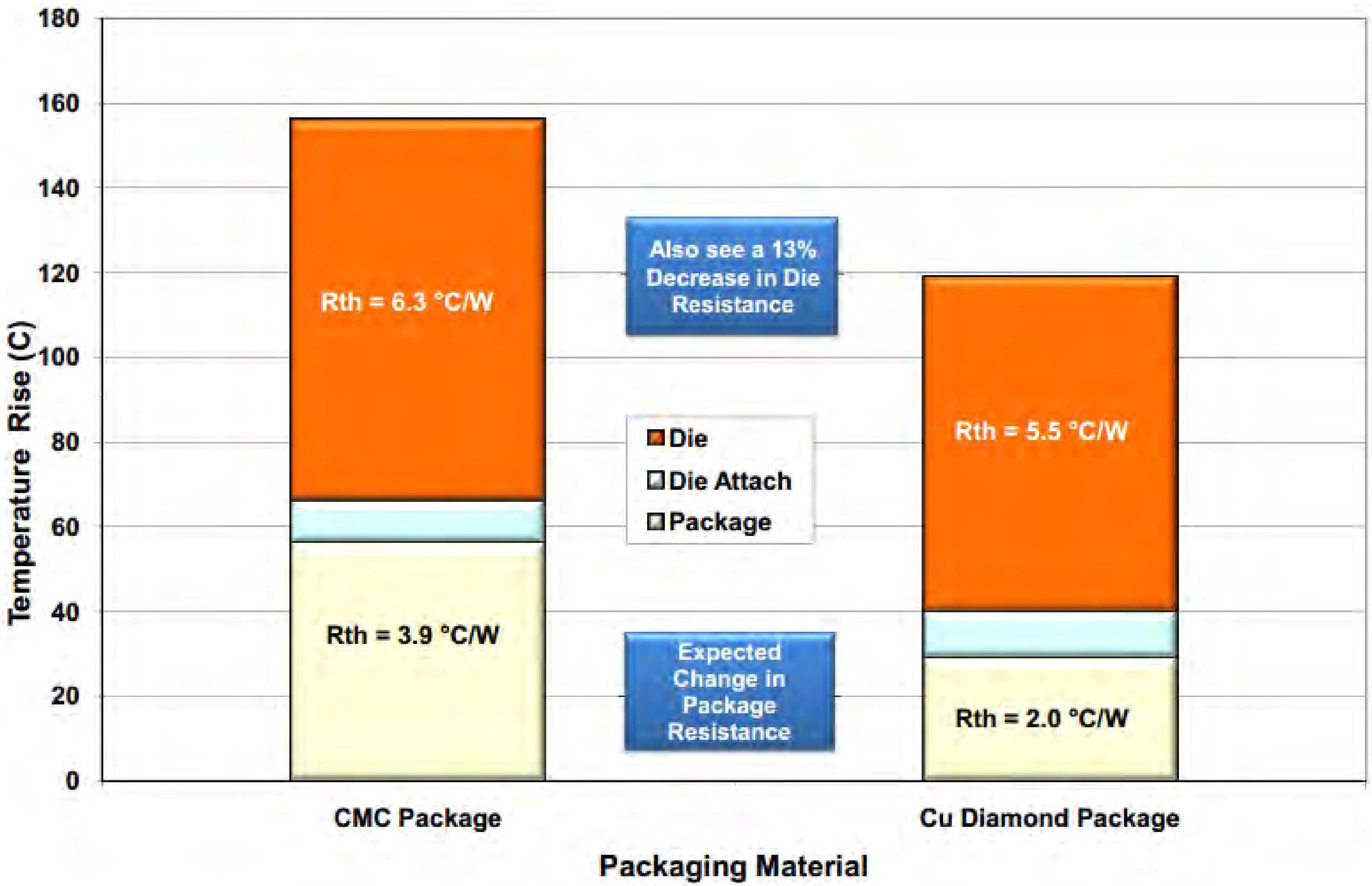
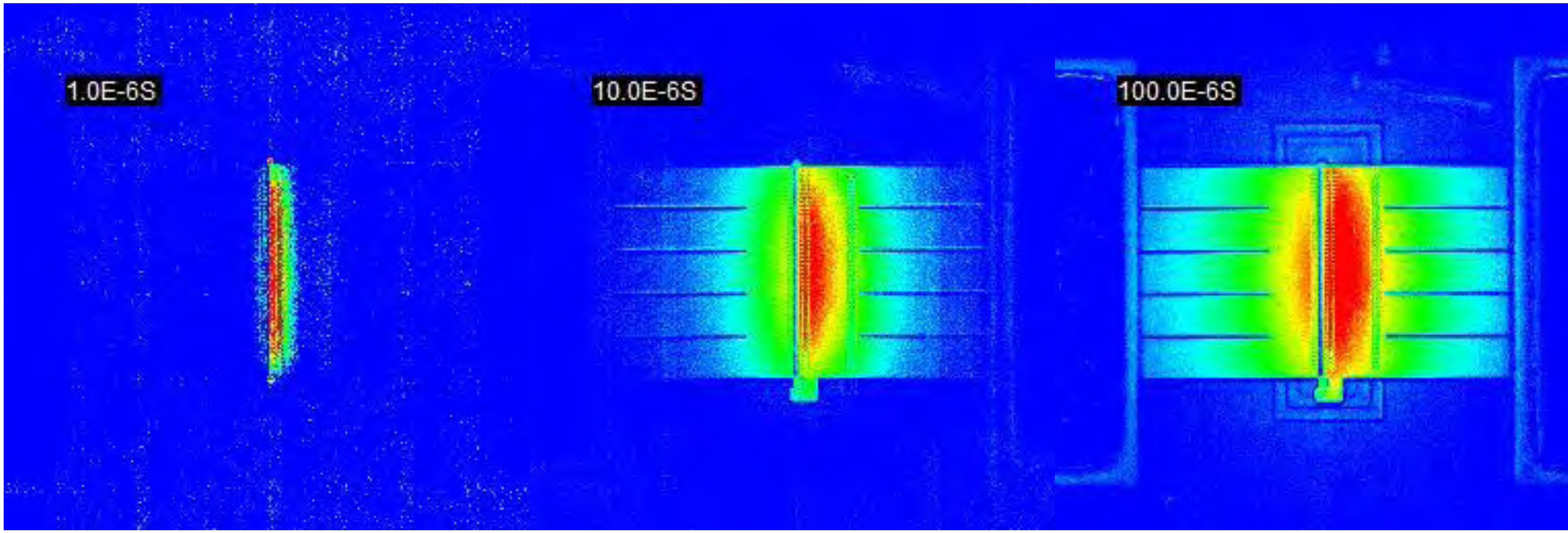


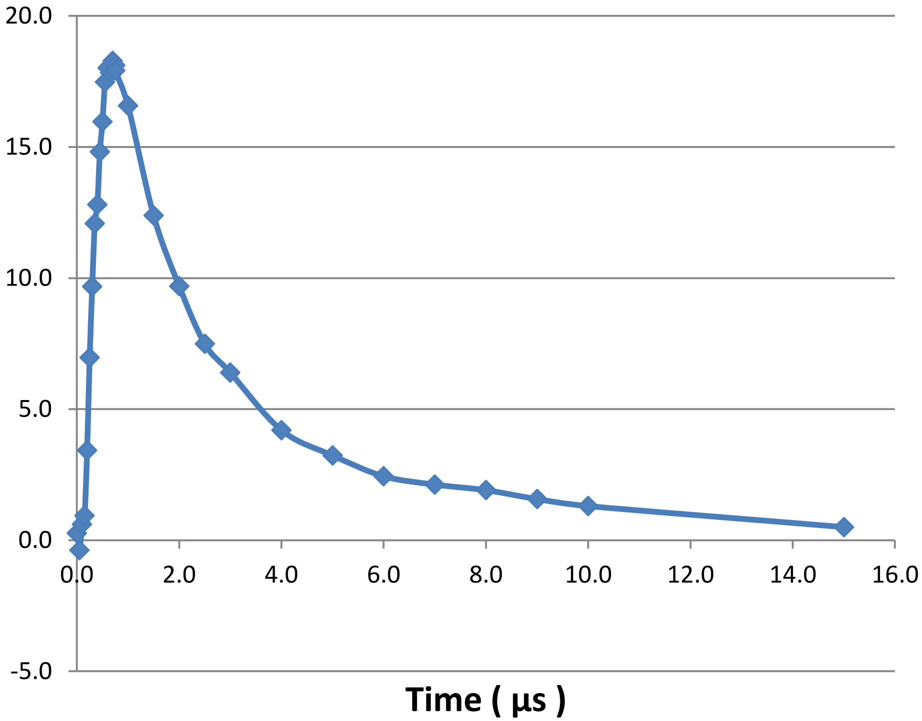
Figure 8 – Thermal resistance impacts due to material alterations

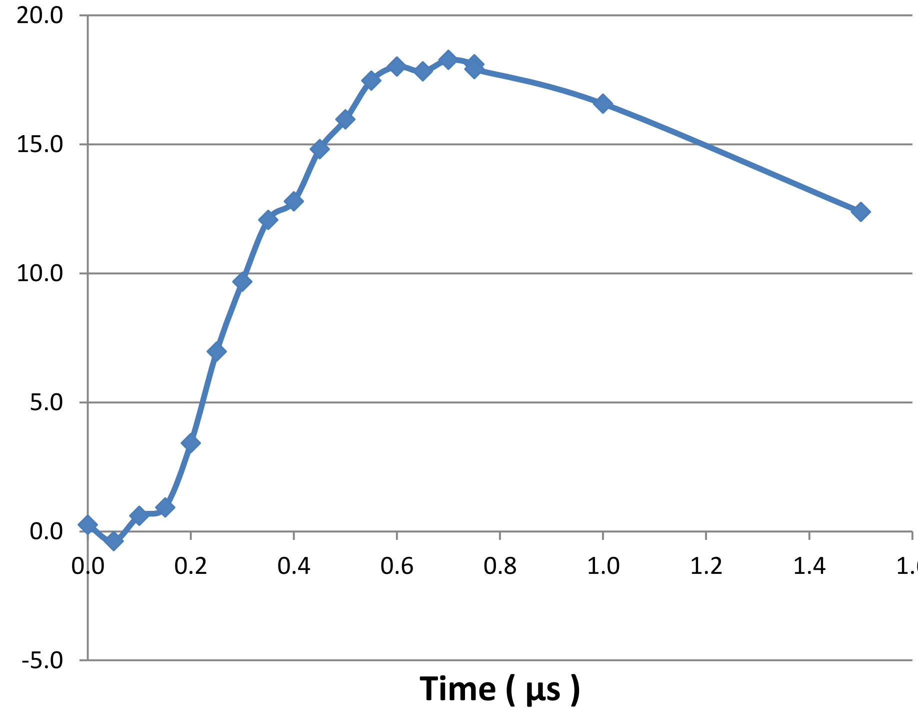
GGNFET Transient Images



- ❑ These are transient thermoreflectance images at 1, 10, & 100μs
- ❑ Each image is scaled to show the temperature distribution.

GGNFET, 200ns, 30V pulse





- This shows the temperature rise (a.u.) of the GGNFET in response to a 200 ns 30V pulse