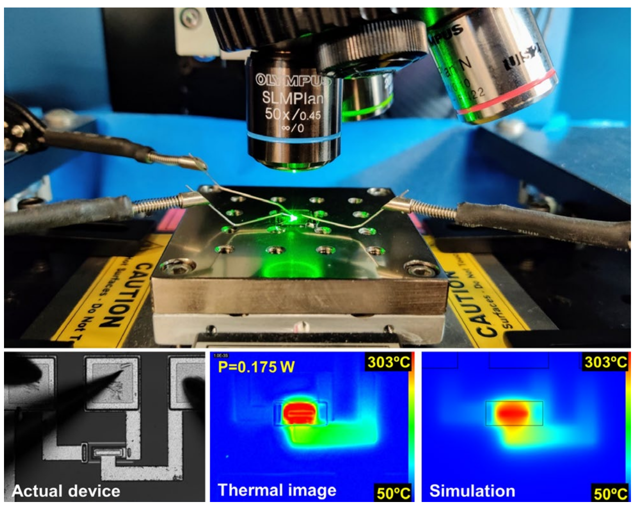
SAND2022-8584C

Deep-ultraviolet thermoreflectance imaging of ultra-wide bandgap semiconductor devices

2022 IEEE ITherm Featured Paper Presentation

This work was partially supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.



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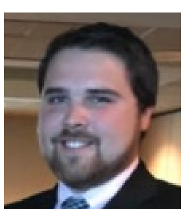

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PennState Electronics & Thermography Lab

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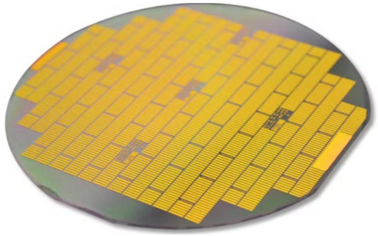
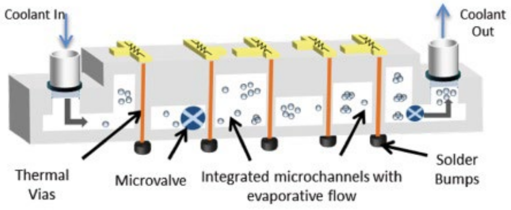


DARPA Near Junction Thermal Transport (NJTT) program



DARPA Intra/Inter Chip Enhanced Cooling (ICECool) thermal packaging program

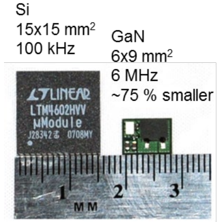
Introduction:

Electro-thermal co-design of UWBG electronics

From an **electrical** point of view, **UWBG semiconductors** can revolutionize high-power electronic device technologies

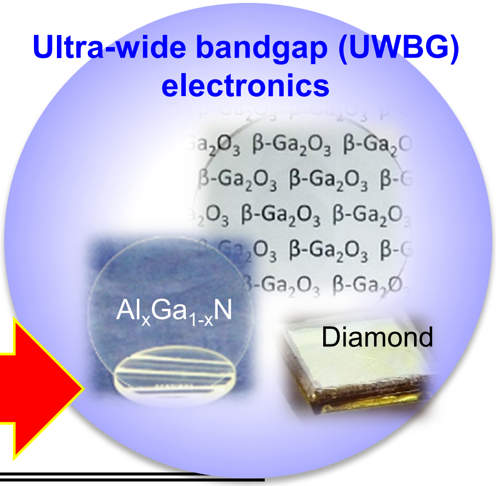
Si-electronics

Wide bandgap devices



1.2 kV, 12 A switch

Co-packaged 20 mOhm/1200 V SiC Junction Transistor/Rectifier



Improved SWaP (Size, Weight, and Power) & Efficiency

Property	Conventional		WBG		UWBG		
	Si	GaAs	SiC	GaN	$Al_{0.85}Ga_{0.15}N$	β-Ga_2O_3	Diamond
Bandgap, E_G (eV)	1.12	1.43	3.26	3.42	5.61	4.8	5.47
Relative dielectric constant, ε	11.9	13.1	10.1	9.7	8.68	10	5.7
Breakdown field, E_C (MV/cm)	0.3	0.4	3	3.3	10.7	8	10
Electron(channel) mobility μ (cm^2/Vs)	1400	8500	1020	1350(2000)	45(250)	200(180)	4500(69)
Saturated electron velocity, v_s (cm/s)	1×10^7	2×10^7	2×10^7	2.7×10^7	2.28×10^7	1.5×10^7	2×10^7

However, UWBG materials will not surpass the WBG Figure-of-Merit without overcoming **thermal reliability concerns**

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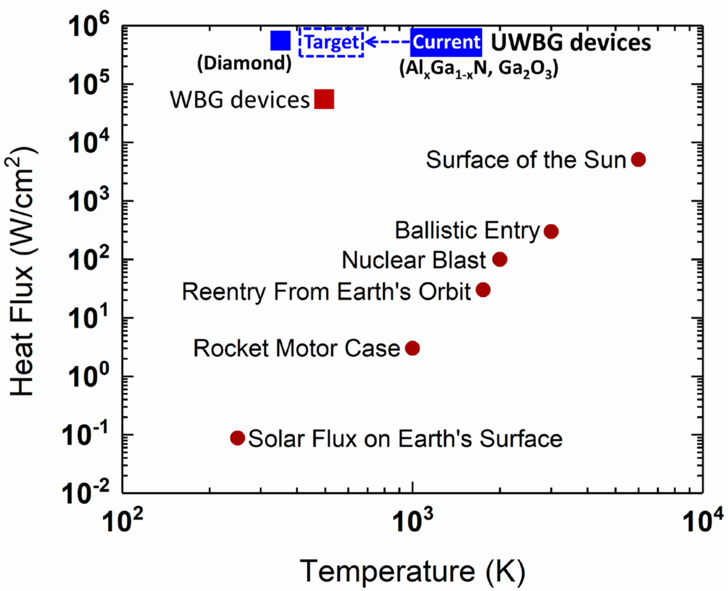
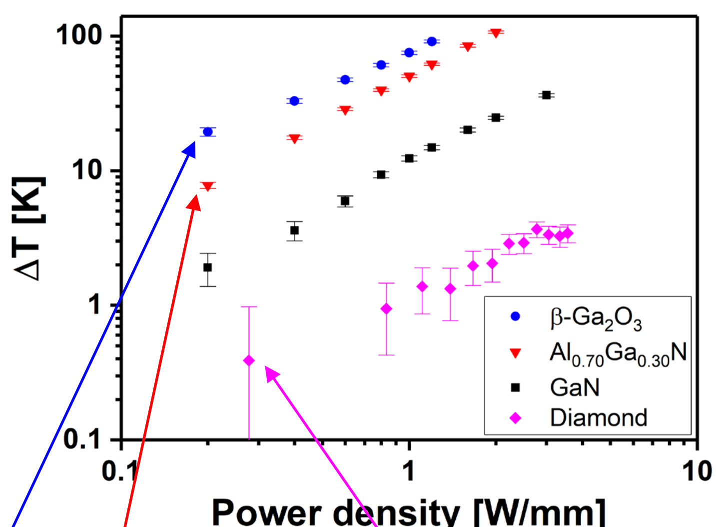
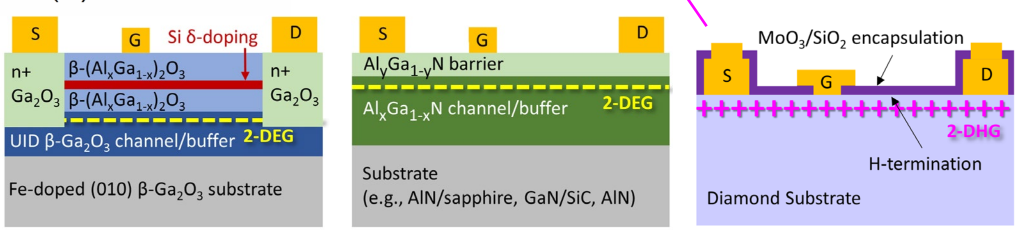
Thermal conductivity, k (W/mK)	150	46	490	130	8	20	2400

Poor thermal conductivity



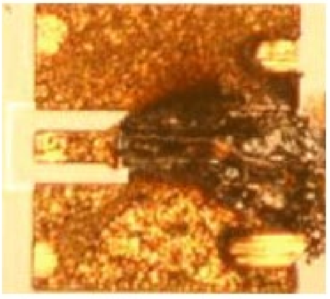




+ High power density

(>10 W/mm or >1 MW/cm^2)

= Thermal Failure



J. Lundh, S. Choi et al., APL (2021), DOI: https://doi.org/10.1063/5.0061948

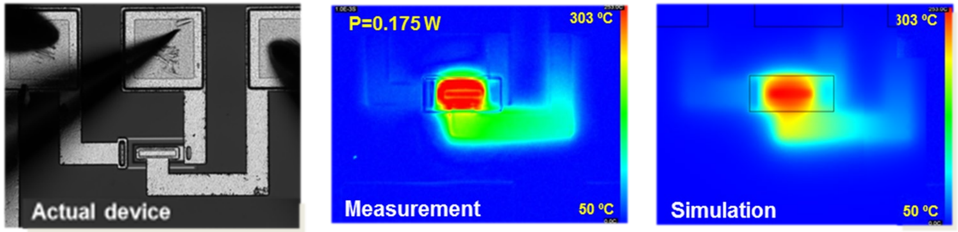
Electro-thermal co-design techniques are necessary to overcome device overheating concerns

Thermo-physical property measurement

- Laser-based pump-probe techniques

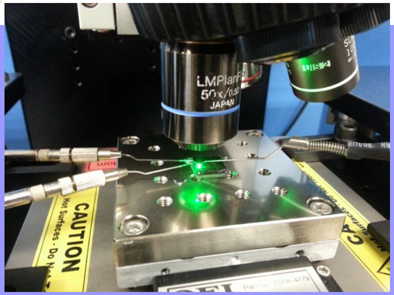
Electro-thermal device modeling

- Thermal/electronic transport
- Energy conversion (heat generation)
- Electrical output characteristics
- Device self-heating behavior



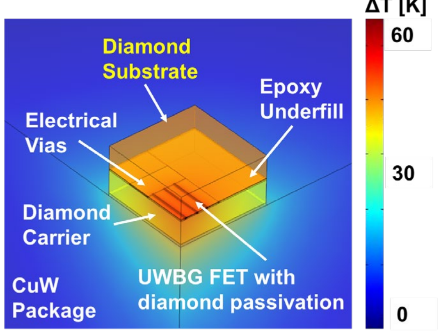
Device thermal imaging

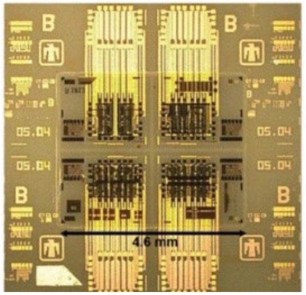
- Sub-μm resolution optical thermography techniques



Device-level thermal management

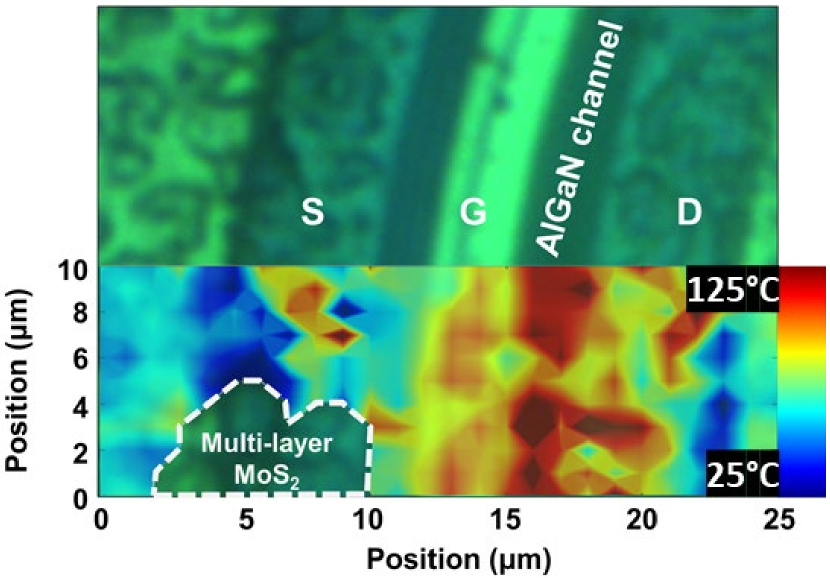
- Low thermal resistance composite substrate
- High thermal conductivity passivation overlayer
- Thermally-augmented flip-chip integration





Package level thermal management, heterogeneous integration, etc.

S. Choi, C. D. Nordquist et al., IEEE TCPMT (2016)
DOI: 10.1109/TCPMT.2016.2541615



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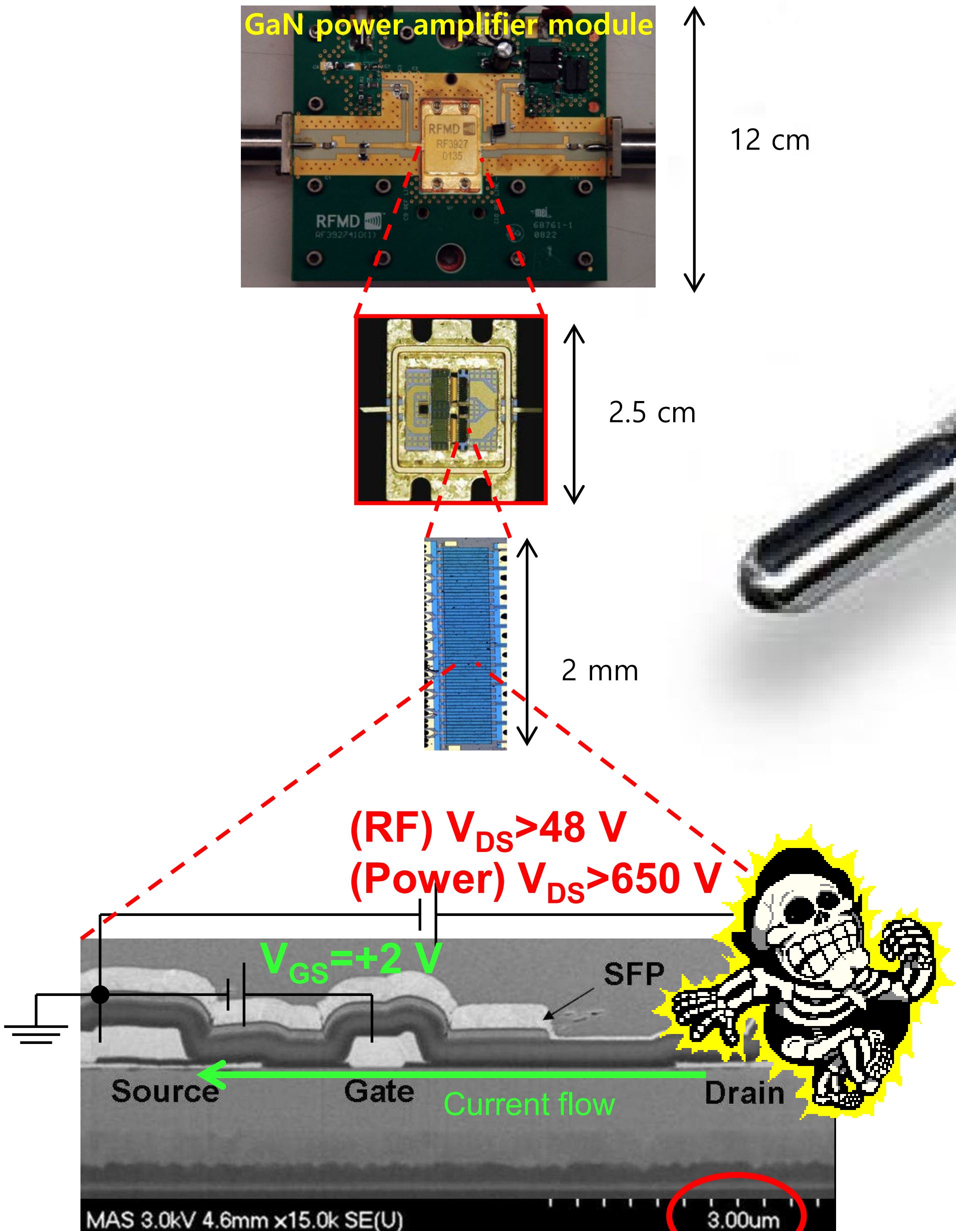
Optical thermography:

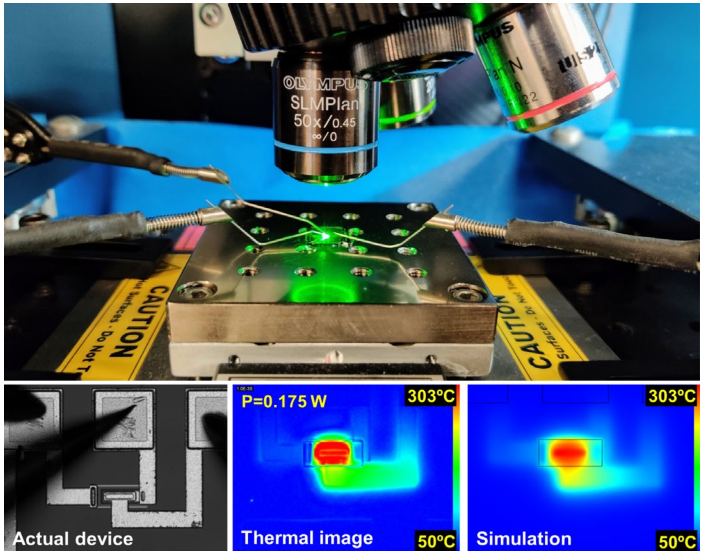
The current state-of-the-art and need for a new technique compatible with UWBG devices

Why optical methods? - Non-invasive and non-contact measurement, high spatial resolution



R. Therrien, IEEE IEDM, 2005

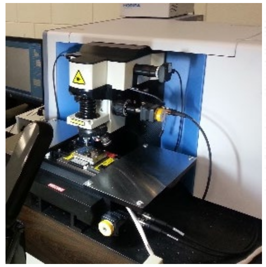
S. Choi, C. D. Nordquist et al., IEEE TCPMT (2016)
DOI: 10.1109/TCPMT.2016.2541615

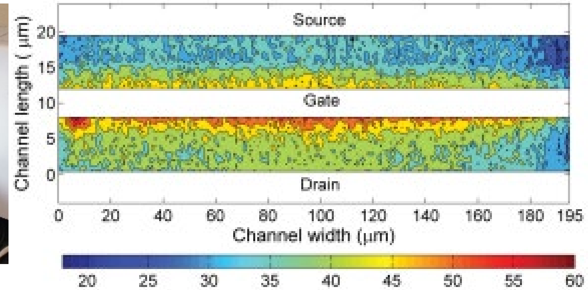


Current state-of-the-art optical methods for device thermal imaging

J. Lundh, S. Choi et al., ASME JEP (2020), DOI: https://doi.org/10.1115/1.4047100

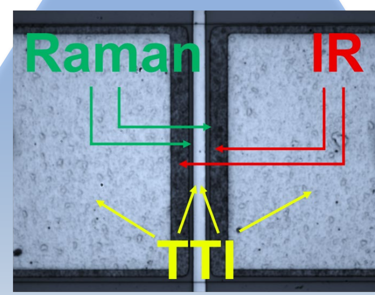
Raman thermography

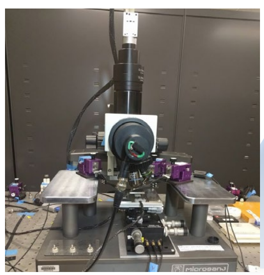


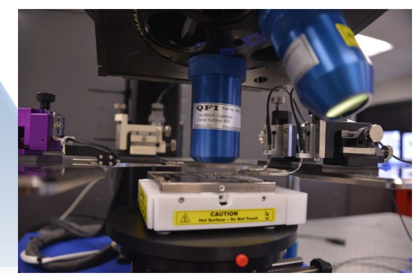


GaN HEMT

S. Choi, S. Graham et al., IEEE TED (2013)
DOI: 10.1109/TED.2013.2255102

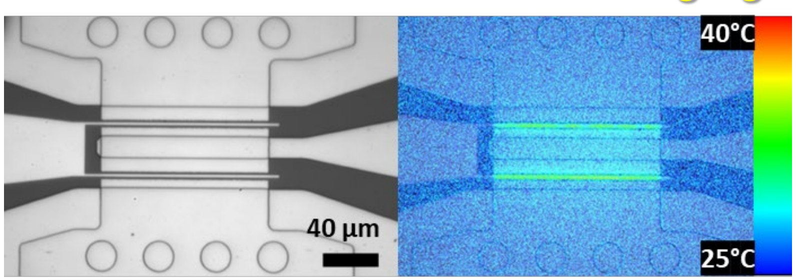






$$d = \frac{\lambda}{2NA}$$

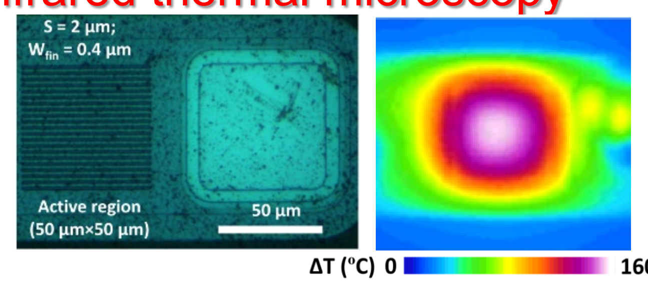
Thermoreflectance thermal imaging



H-terminated diamond FET

J. Lundh, S. Choi et al., APL (2021)
DOI: https://doi.org/10.1063/5.0061948

Infrared thermal microscopy

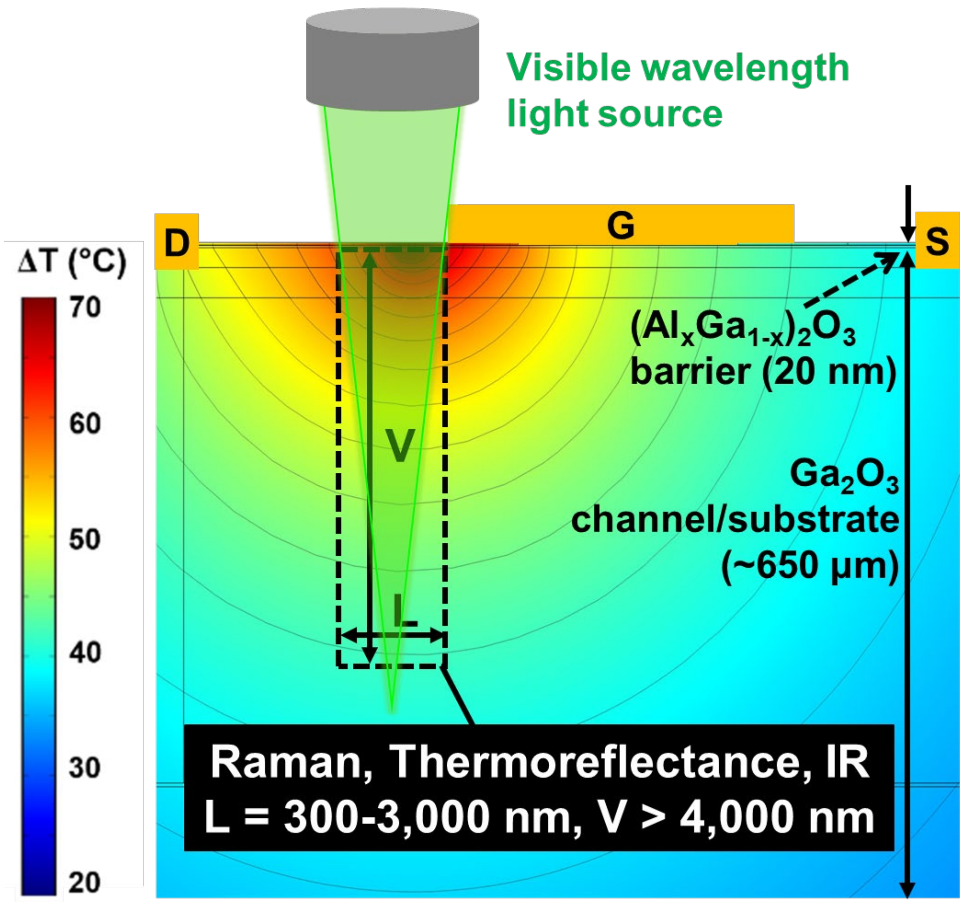


Ga_2O_3 vertical FinFET

B. Chatterjee, S. Choi et al., IEEE EDL (2021)
DOI: 10.1109/LED.2021.3065362

Limitations associated with using existing methods for the channel temperature measurement of UWBG transistors

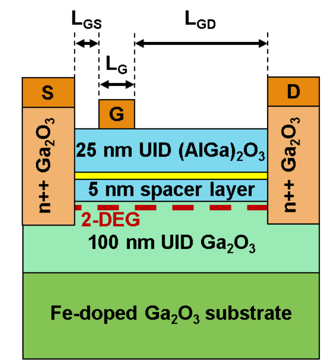
- UWBG materials are transparent to visible wavelength light
- Deep UV lasers induce unacceptably high photocurrent that alters the device I-V characteristics and damages the device



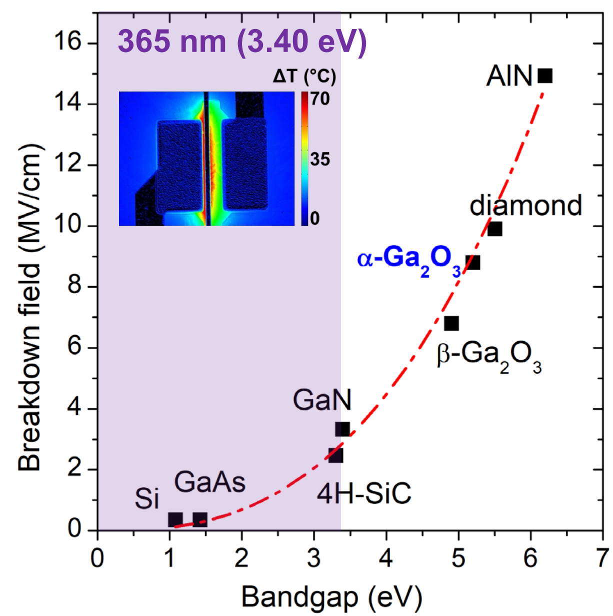
$E_{laser(532\ nm)} = 2.33$ eV

$E_{g,Ga2O3} = 4.8$ eV

$(Al_xGa_{1-x})_2O_3/Ga_2O_3$ MODFET



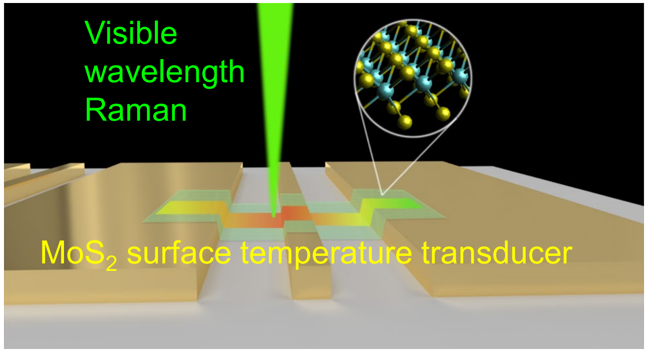
L_{GD}=1 µm, L_G=3 µm, L_{GD}=3 µm

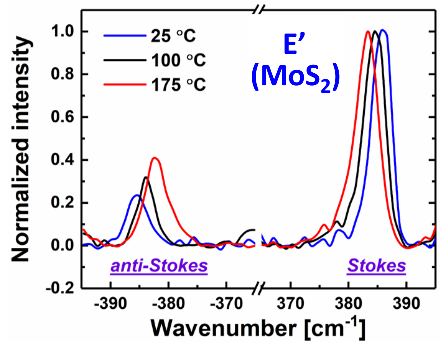


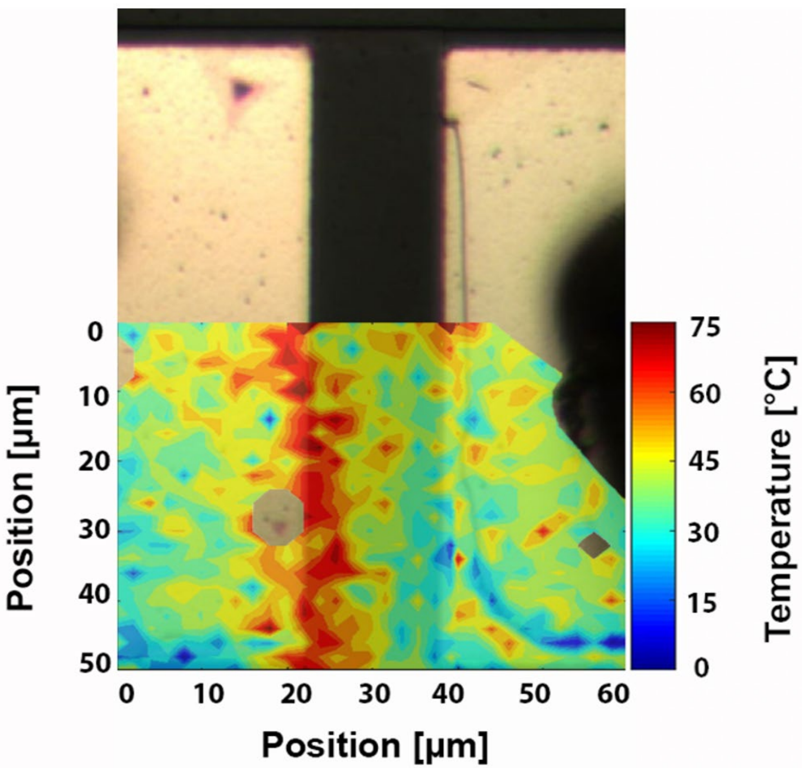
Temperature mapping of a Ga_2O_3 MODFET using nanomaterial-assisted Raman thermometry techniques

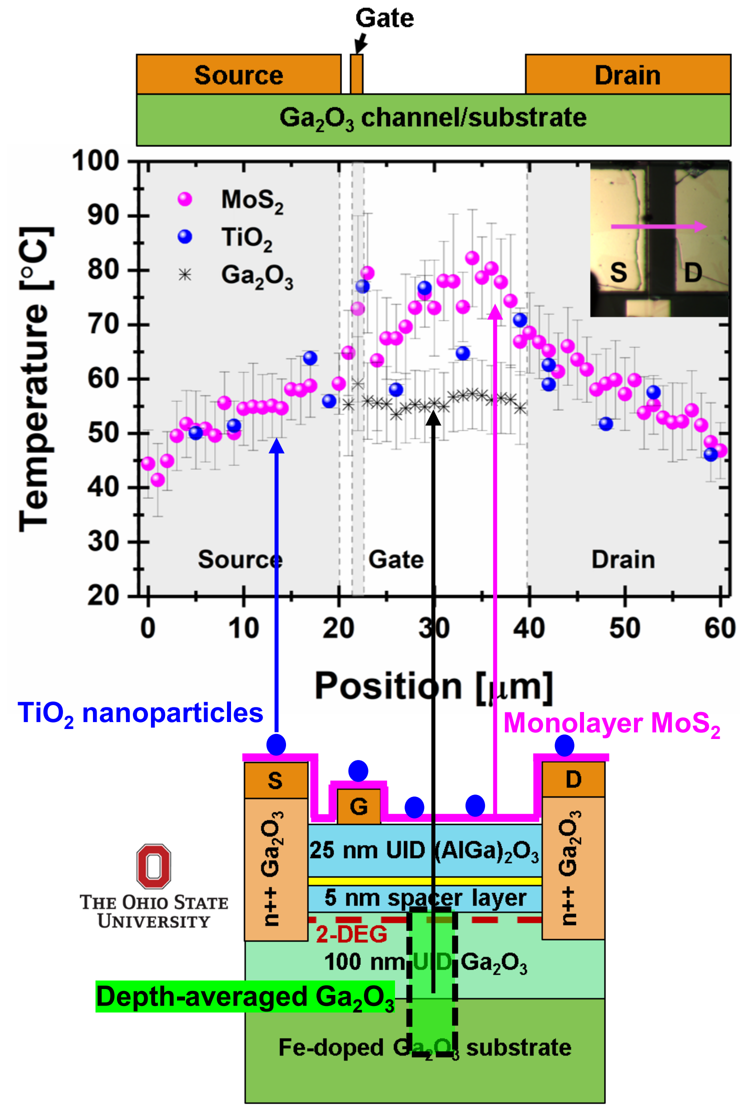
2D material-assisted Raman thermography

J. Lundh, S. Choi et al., ACS AEM (2020),
DOI: https://doi.org/10.1021/acsaelm.0c00574





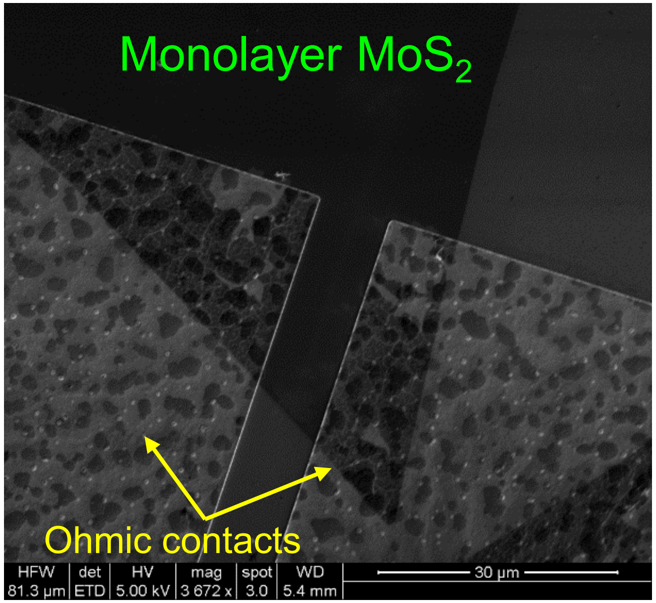


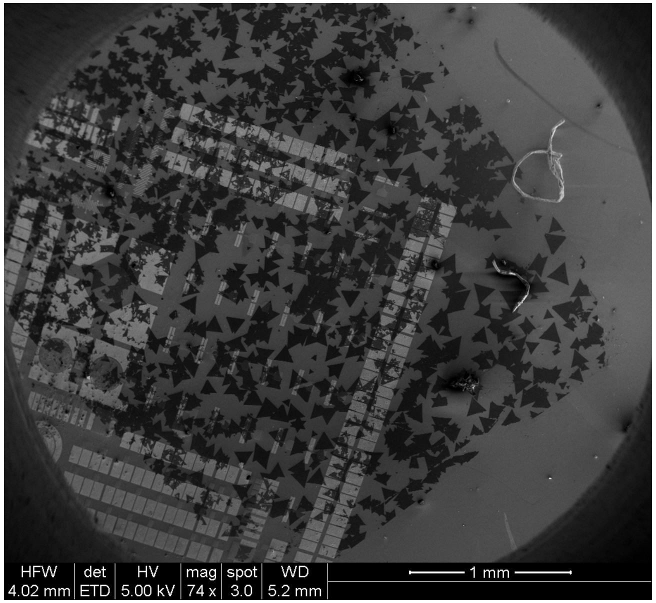


Nanoparticle-assisted Raman thermometry

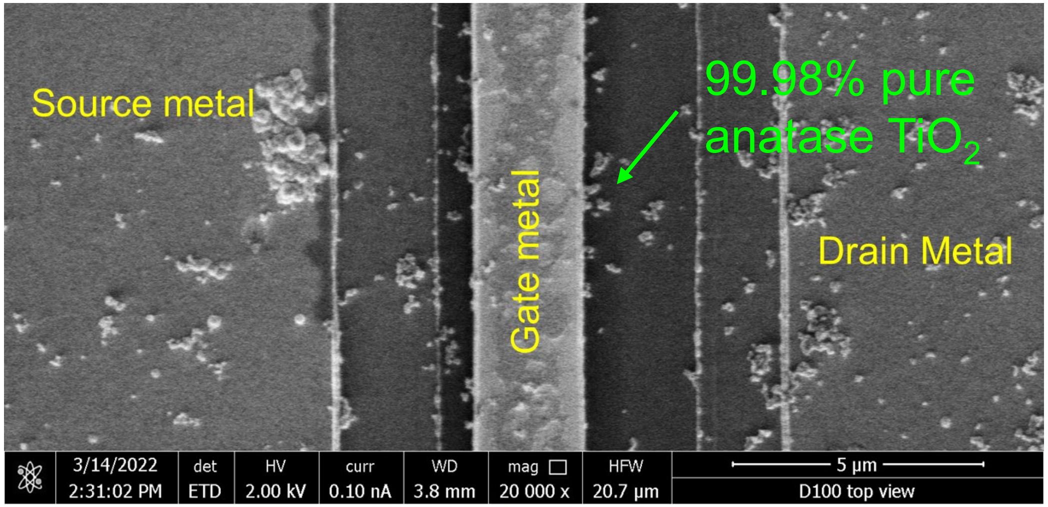
The motivation of this work is to **get rid of the use of surface temperature transducers** that contaminate the device surface

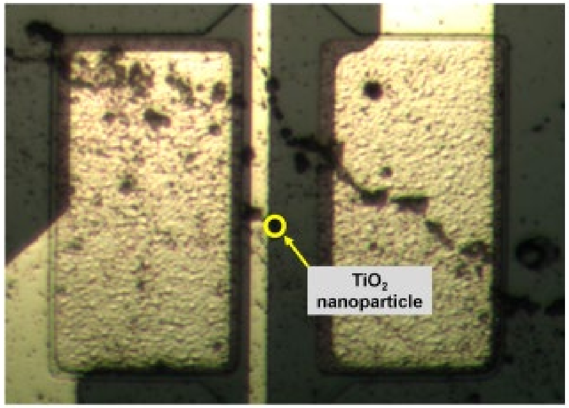
2D material-assisted Raman

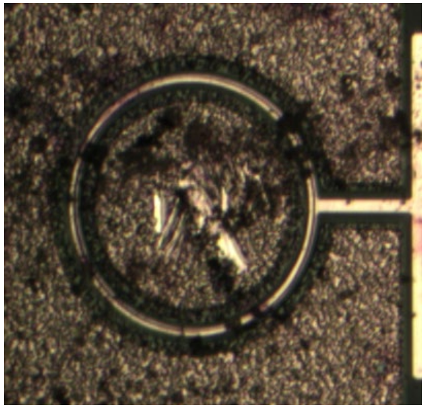


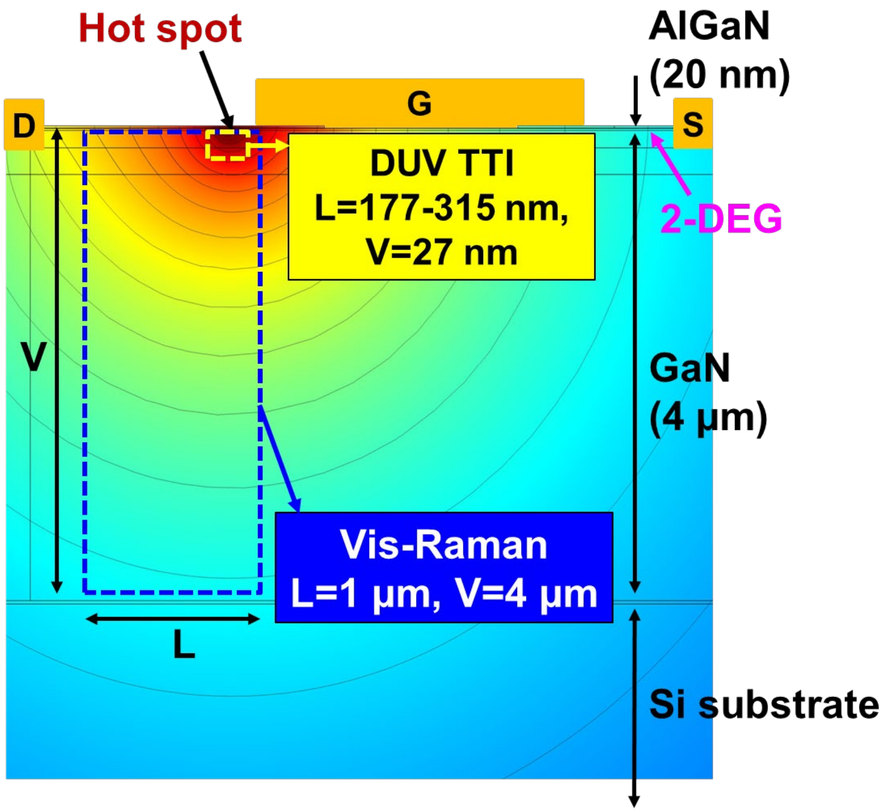


Nanoparticle-assisted Raman









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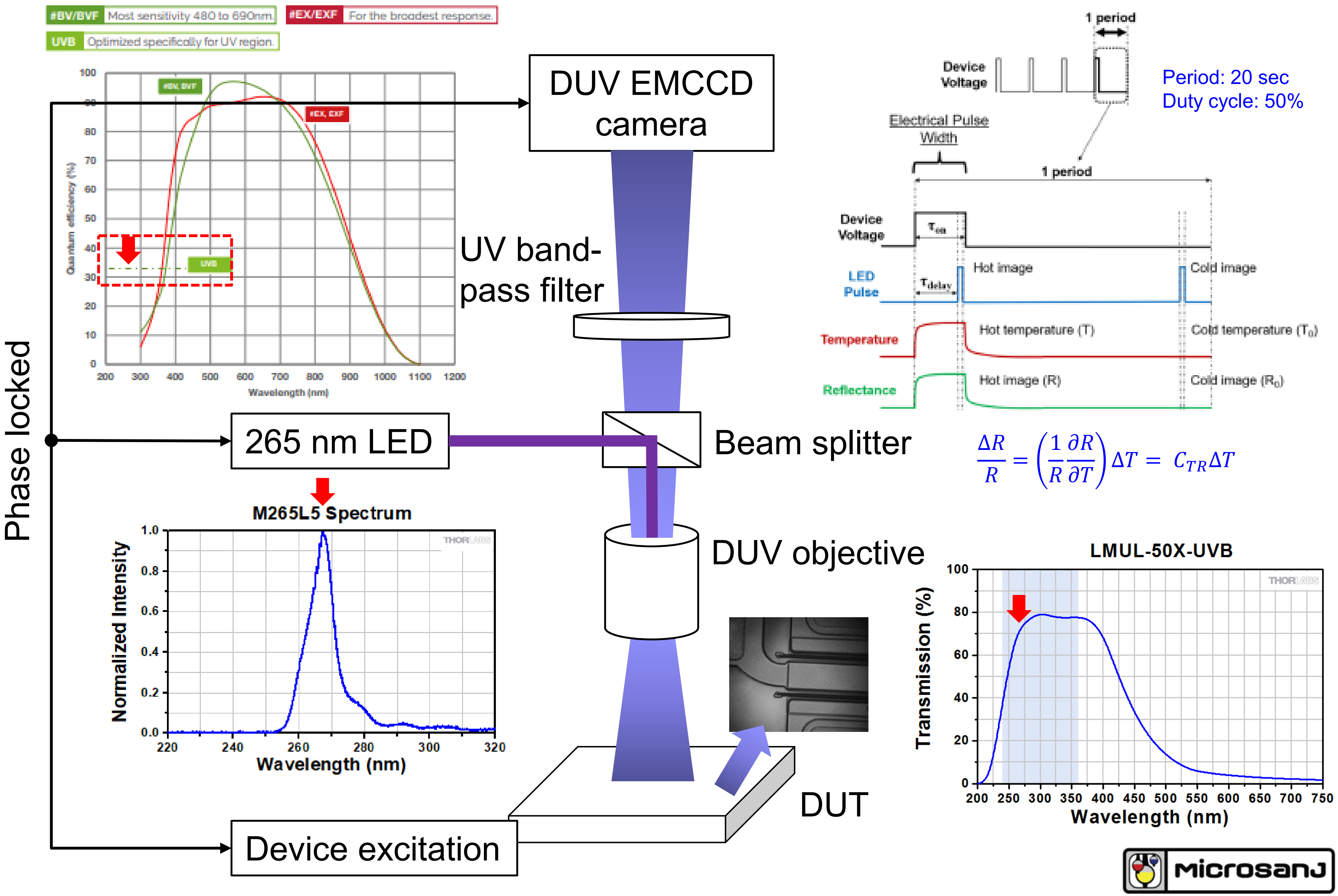
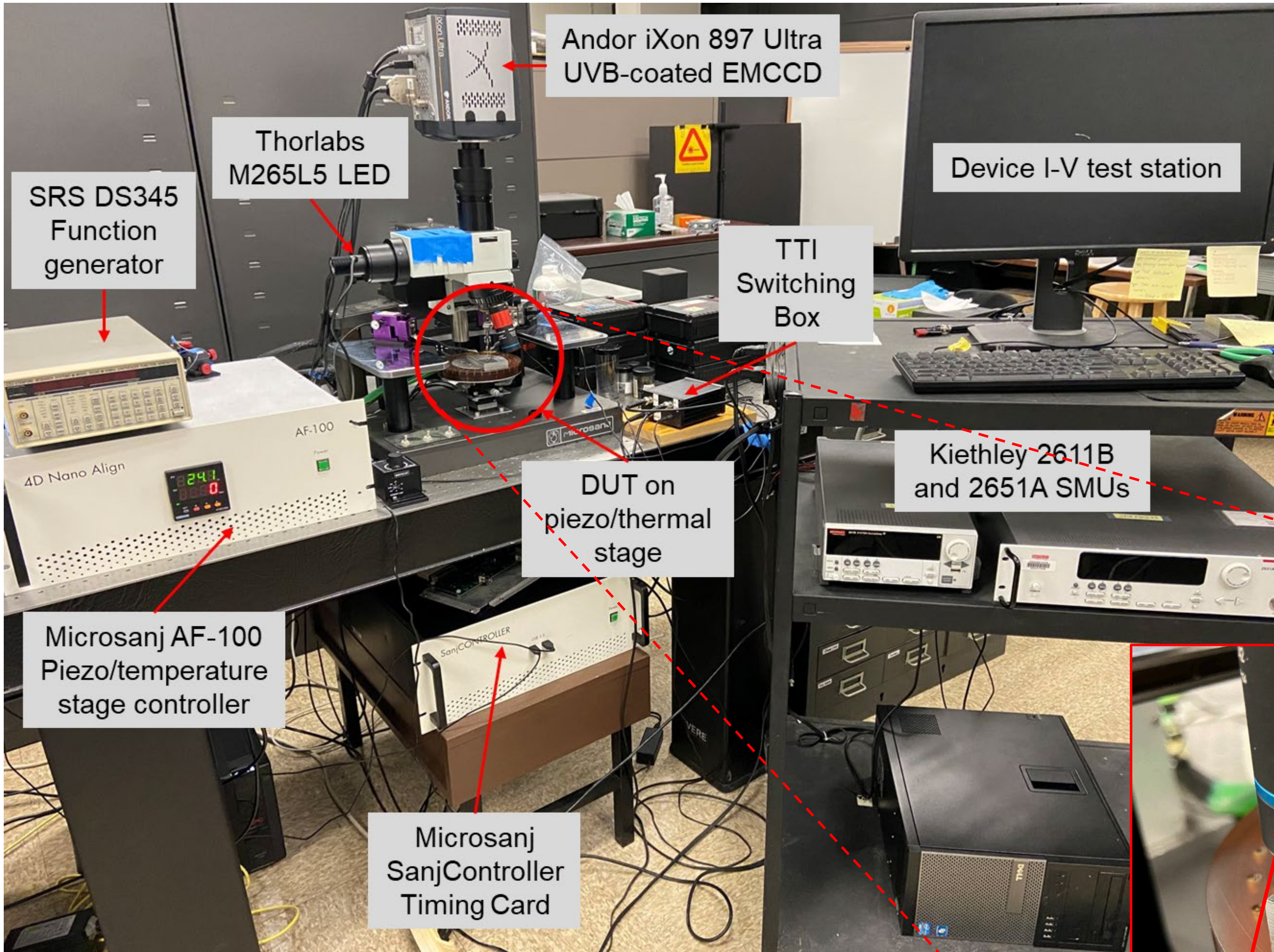
DUV thermoreflectance imaging:

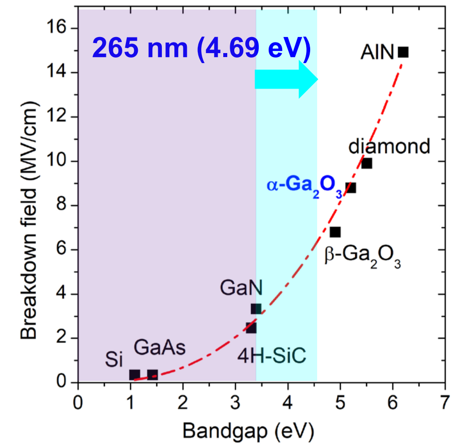
Nonlocal thermal transport in a GaN HEMT

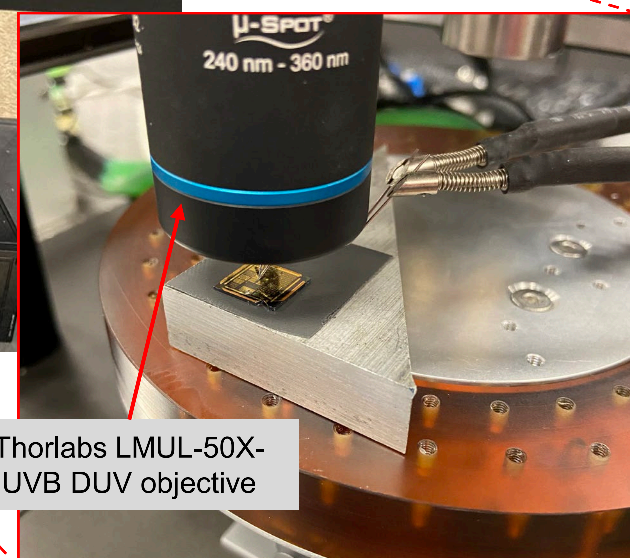
Measurement schematic



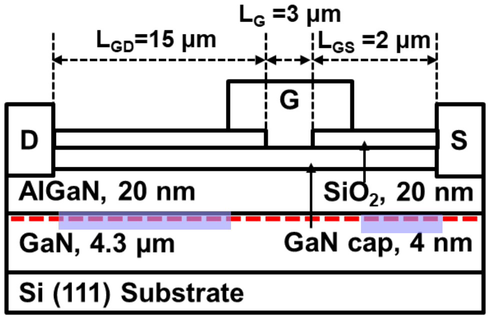
DUV thermoreflectance imaging system







DUV thermoreflectance imaging of an AlGaN/GaN HEMT

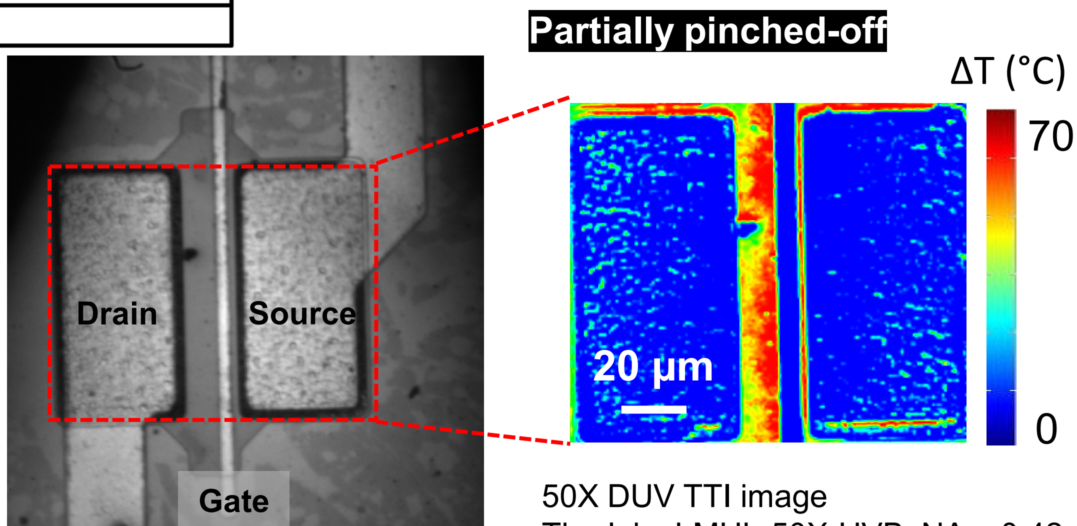


W_G =100 µm

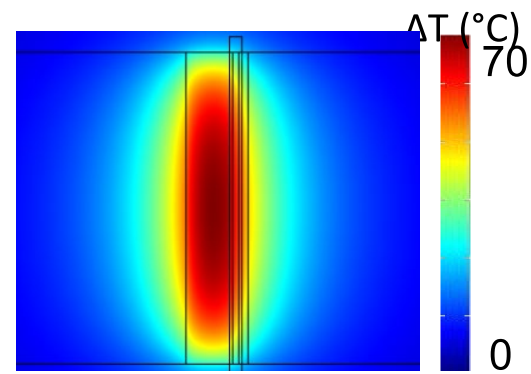
P=500 mW or 5 W/mm

Partially pinched off: V_{GS}=-1V, V_{DS}=41.2V, I_{DS}=12.1 mA

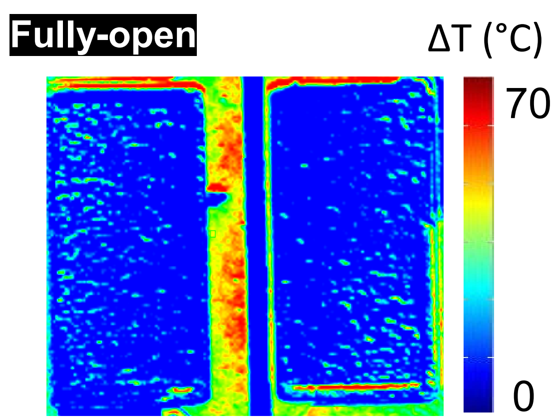
Fully open: V_{GS}=2.5V, V_{DS}=17.3V, I_{DS}=28.9 mA

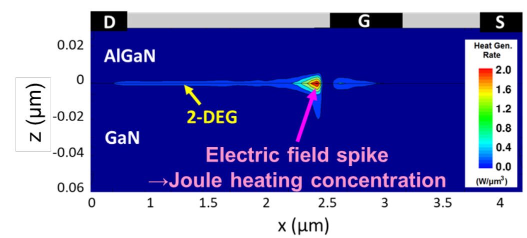


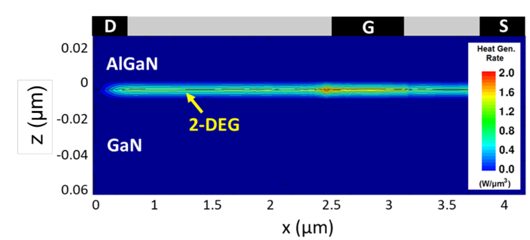
50X DUV TTI image
Thorlabs LMUL-50X-UVB, NA = 0.42

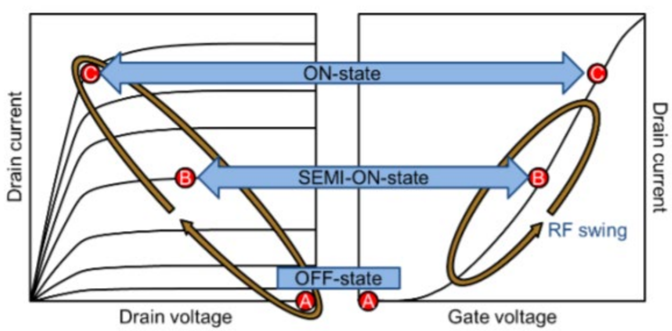


Electro-thermal modeling





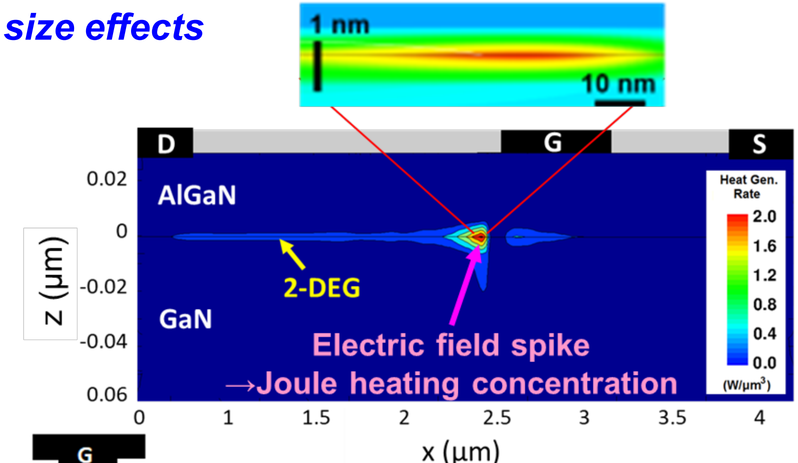


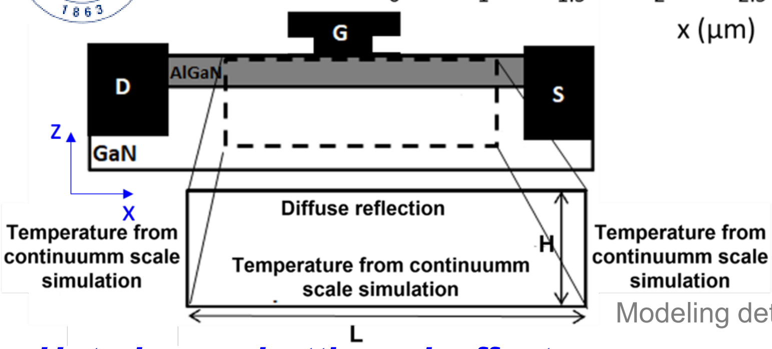


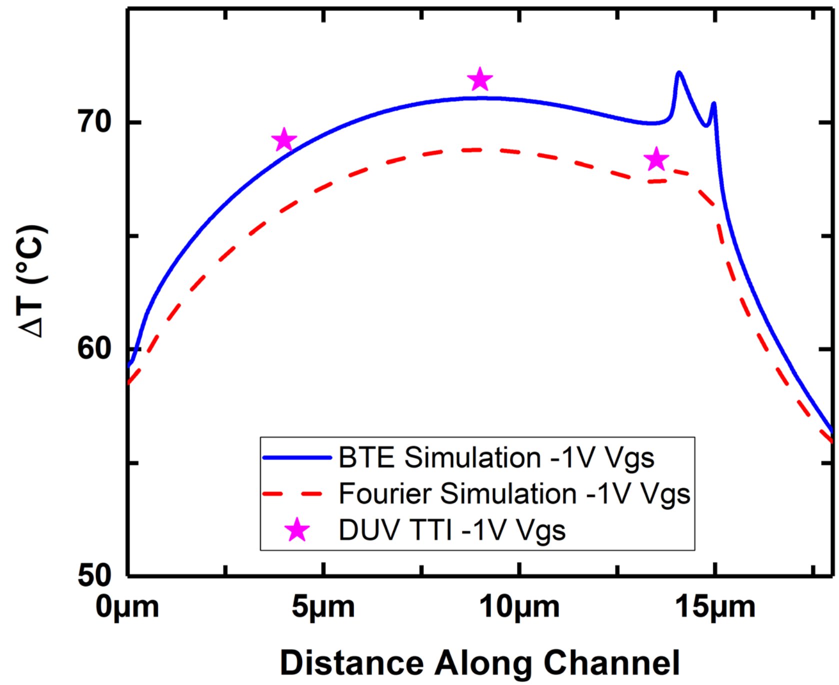
S. Burnham et al., JEDEC ROCS (2017)

Subcontinuum thermal transport effects caused by small dimensions of the heat source that are amplified under high electric field conditions

Heat source size effects

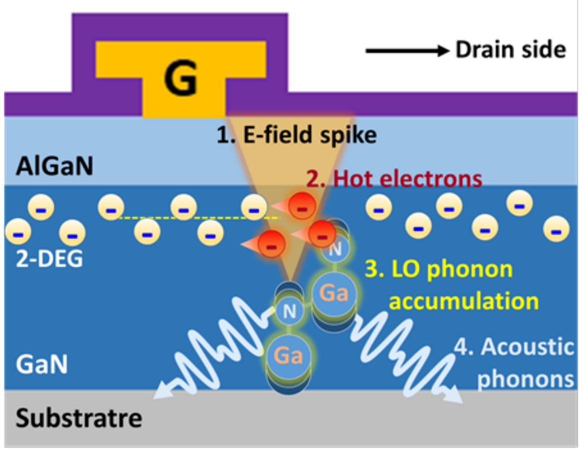


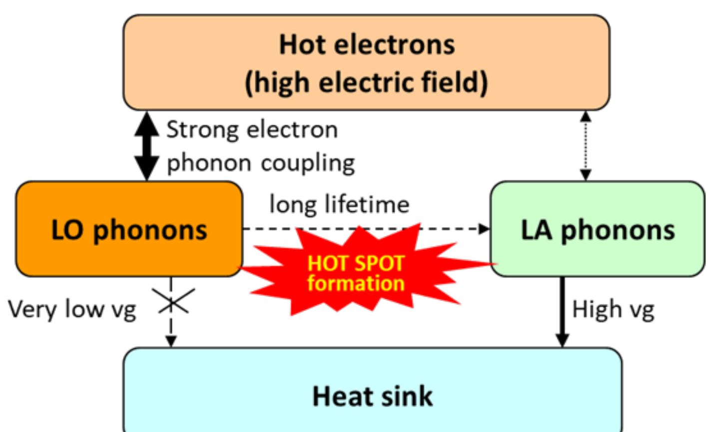


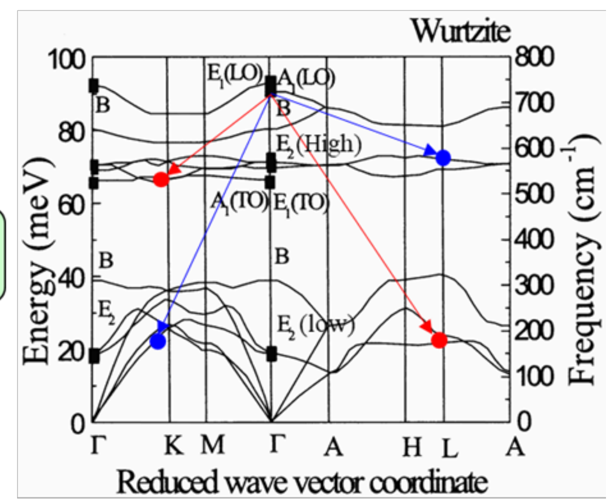


Modeling details: B. Chatterjee, S. Choi et al., APL (2020), DOI: https://doi.org/10.1063/1.5123726

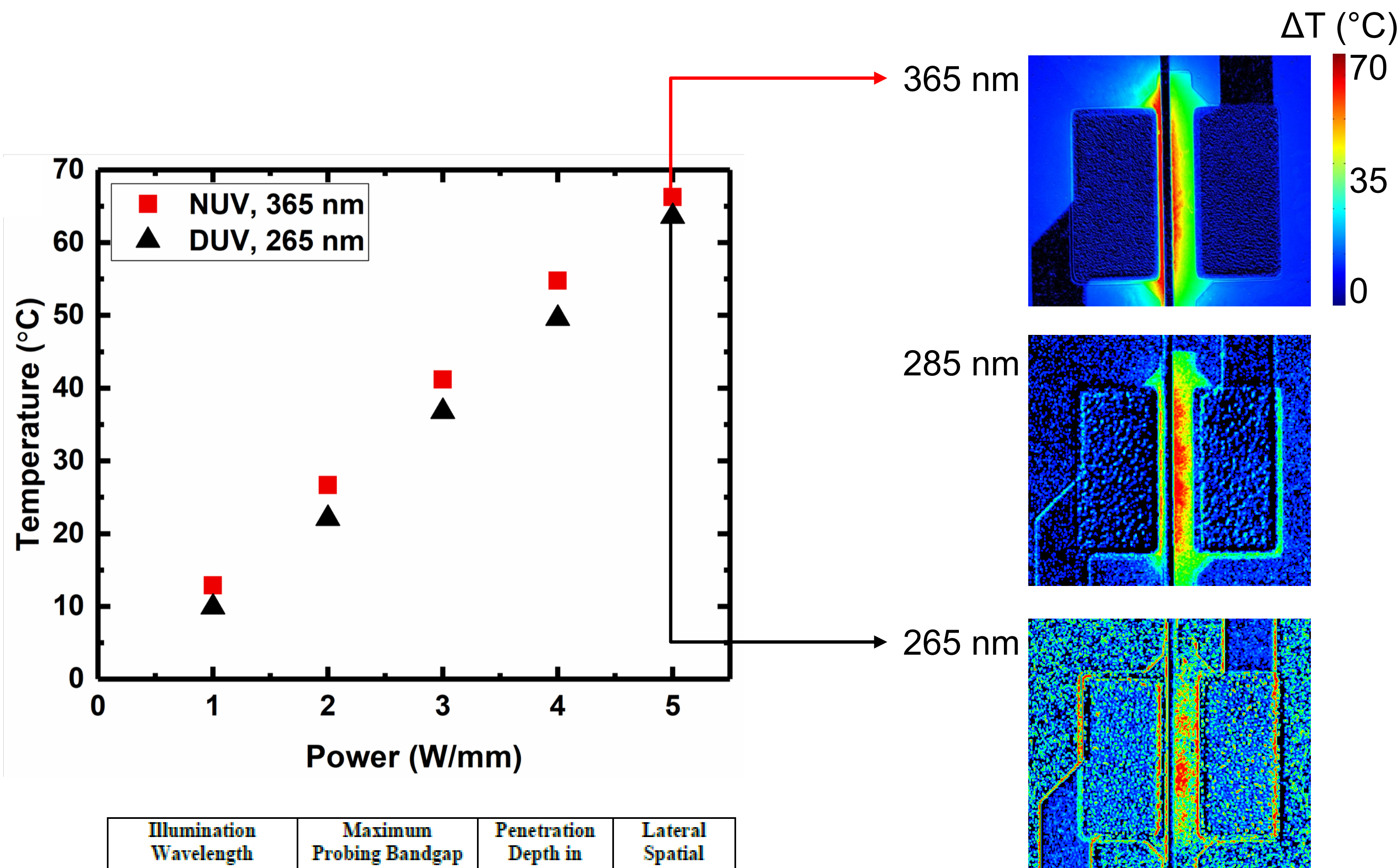
Hot phonon bottleneck effect







Comparison with NUV TTI measurement results



Illumination Wavelength	Maximum Probing Bandgap Energy	Penetration Depth in GaN	Lateral Spatial Resolution
Visible (530 nm)	*2.3 eV*	*N/A*	*~0.44 μm*
Near-UV (365 nm)	*3.4 eV*	*~50 nm*	*~0.31 μm*
Deep-UV (265 nm)	*4.7 eV*	*~27 nm*	*~0.22 μm*

*Assuming NA=0.6

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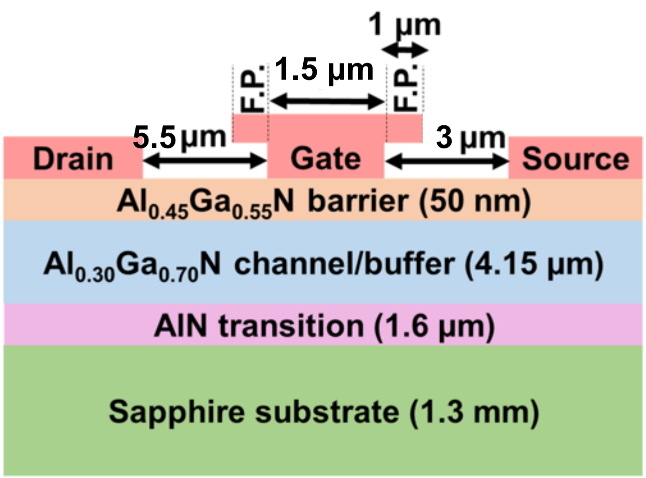
Thermography Lab
ET Lab

Illumination Wavelength	Maximum Probing Bandgap Energy	Lateral Spatial Resolution (NA=0.42)	Lateral Spatial Resolution (NA=0.75)	Penetration Depth in GaN	Penetration Depth in $Al_{30}Ga_{70}N$
Visible (530 nm)	*2.3 eV*	*~0.63 μm*	*~0.35 μm*	*N/A*	*N/A*
Near-UV (365 nm)	*3.4 eV*	*~0.44 μm*	*~0.24 μm*	*~50 nm*	*N/A*
Deep-UV (265 nm)	*4.7 eV*	*~0.32 μm*	*~0.18 μm*	*~27 nm*	*~32 nm*

DUV thermoreflectance imaging:
UWBG AlGaN-channel HEMT

Surface temperature measurement of an $Al_{0.45}Ga_{0.55}N/Al_{0.30}Ga_{0.70}N$ HEMT



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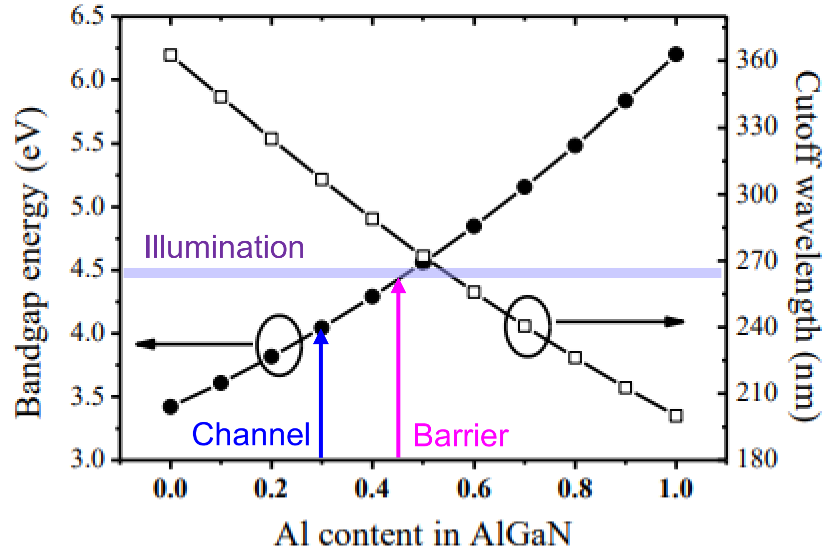
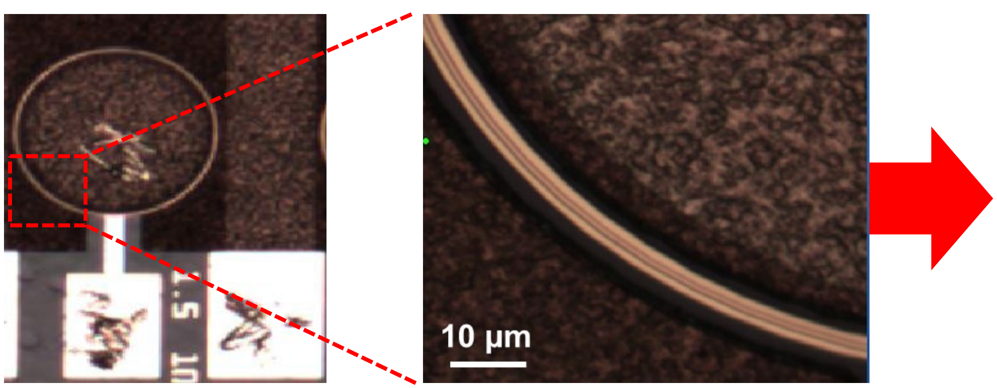
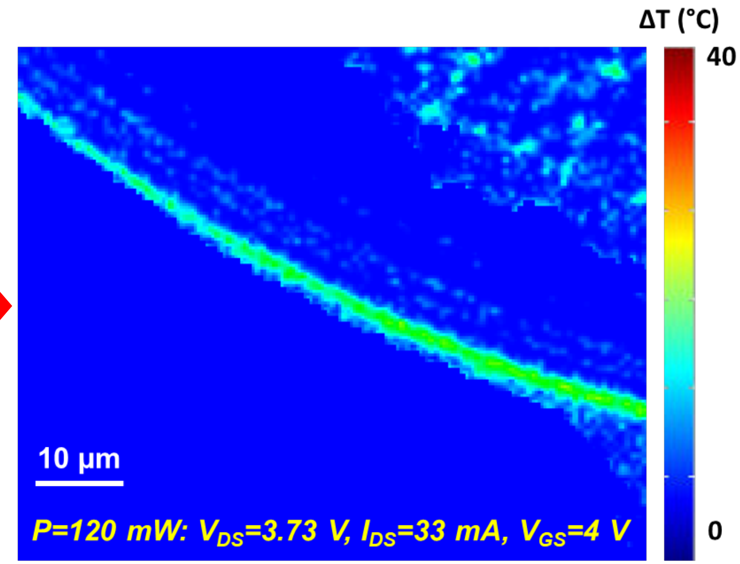
L. Sang et al., Sensors (2013), DOI: https://doi.org/10.3390/s130810482





20X optical image

50X optical image

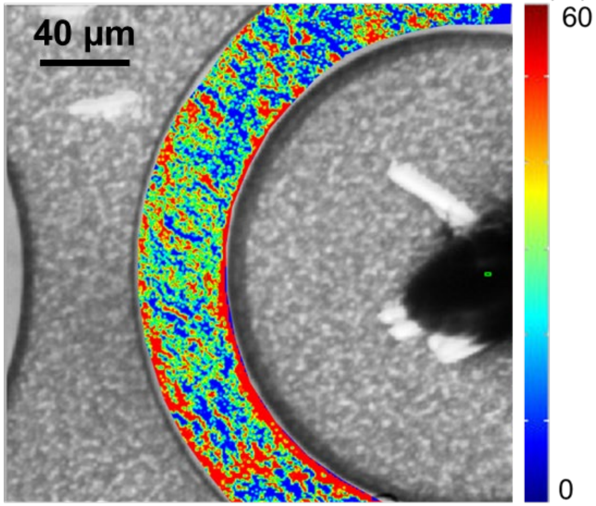


100X DUV TTI image
LEICA PL FLUORAR, NA=0.75

Validation of the results using nanoparticle-assisted Raman thermometry by testing a TLM structure

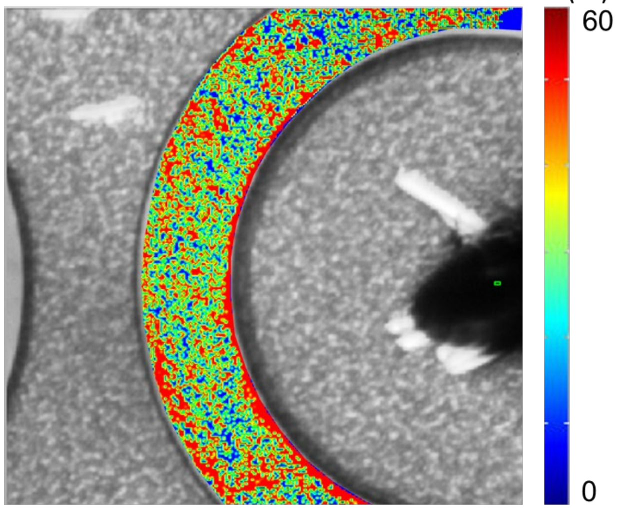
50X DUV TTI images, Thorlabs LMUL-50X-UVB, NA = 0.42

250 mW



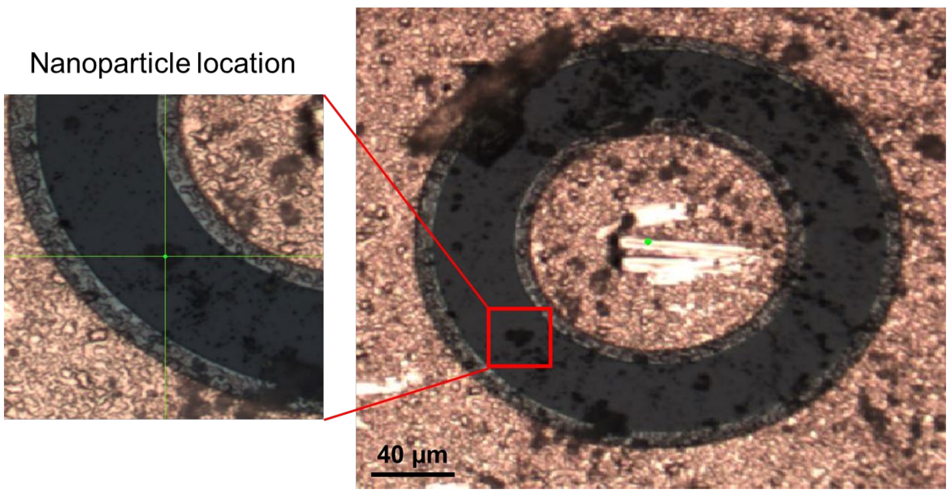
V_{DS}=9.7 V, I_{DS}=25.7 mA

500 mW

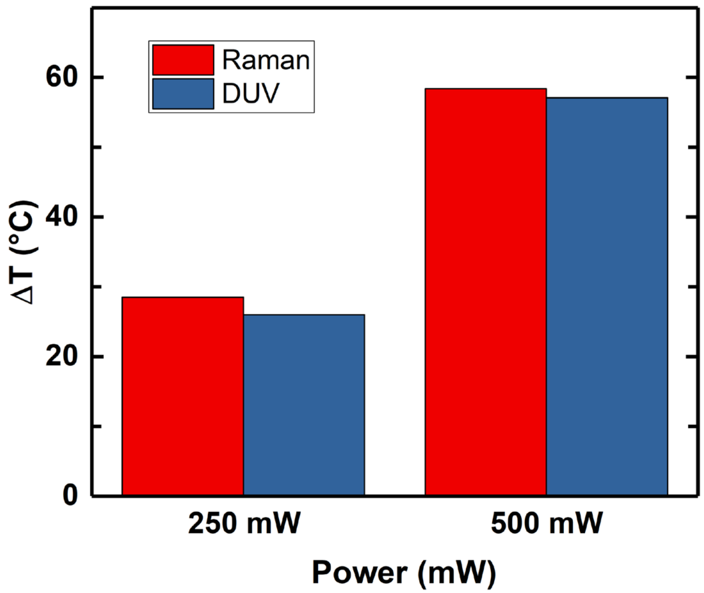


V_{DS}=14.9 V, I_{DS}=33.3 mA

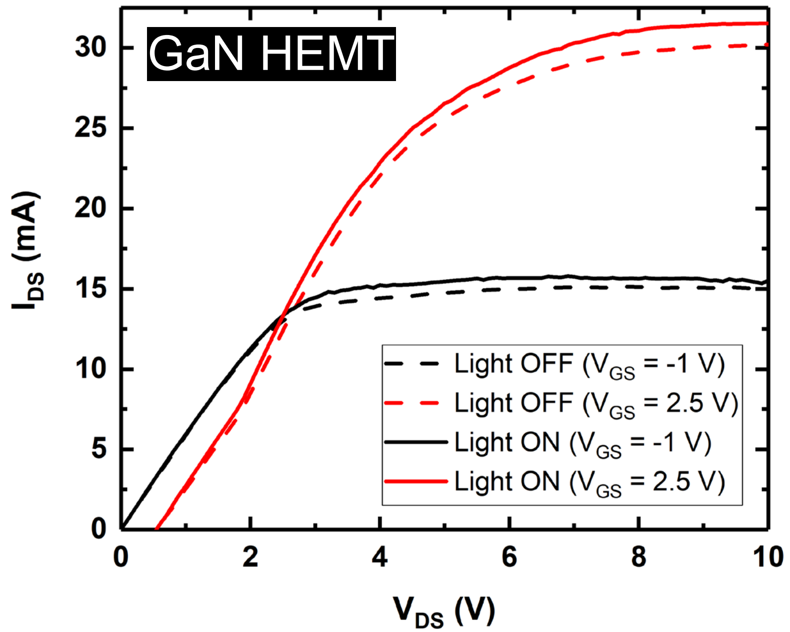
Nanoparticle location

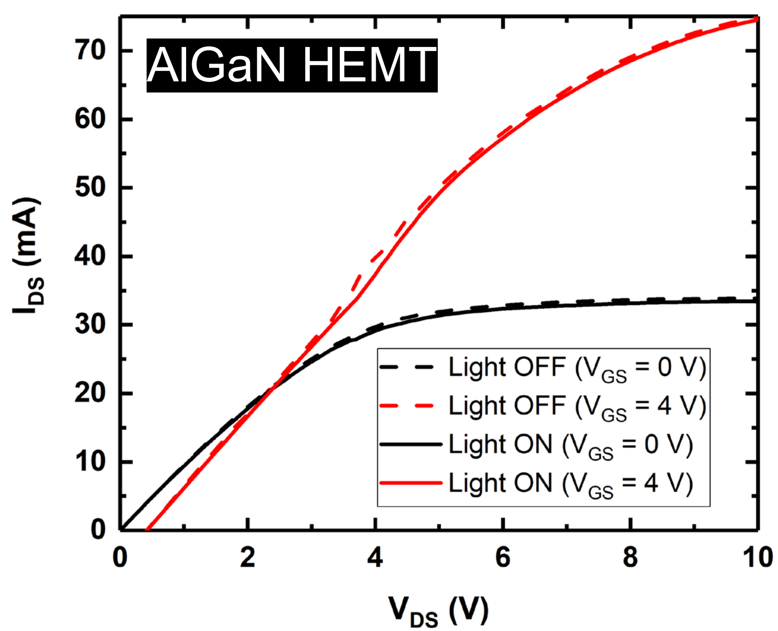


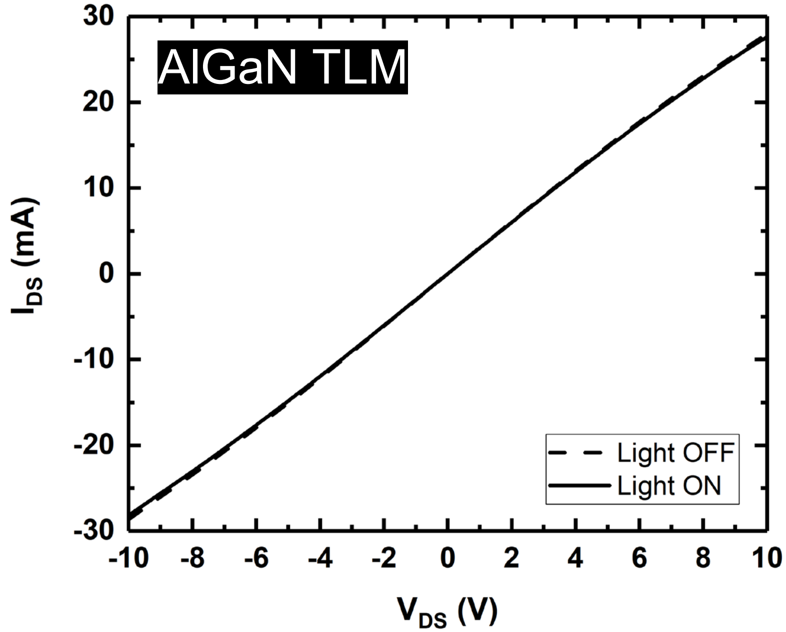
20X optical image



Impact of DUV illumination on the device electrical output characteristics







Thank you!

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