Optimizing semiconductor thermal management with diamond heat spreaders

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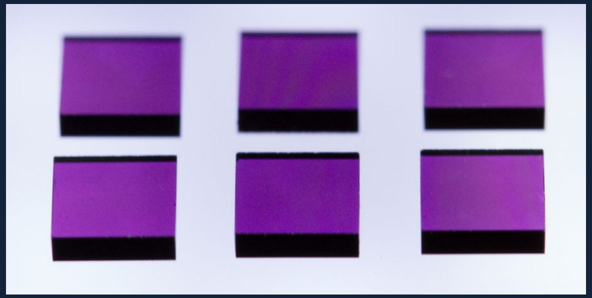

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Topics

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- CVD Diamond from Element Six
- CVD Diamond for Thermal Management
- Diamond Heat Spreader Case Study
- Optimizing Effectiveness of Diamond Heat Spreaders

CVD Diamond from Element Six

70 years of turning natural curiosity to engineered material

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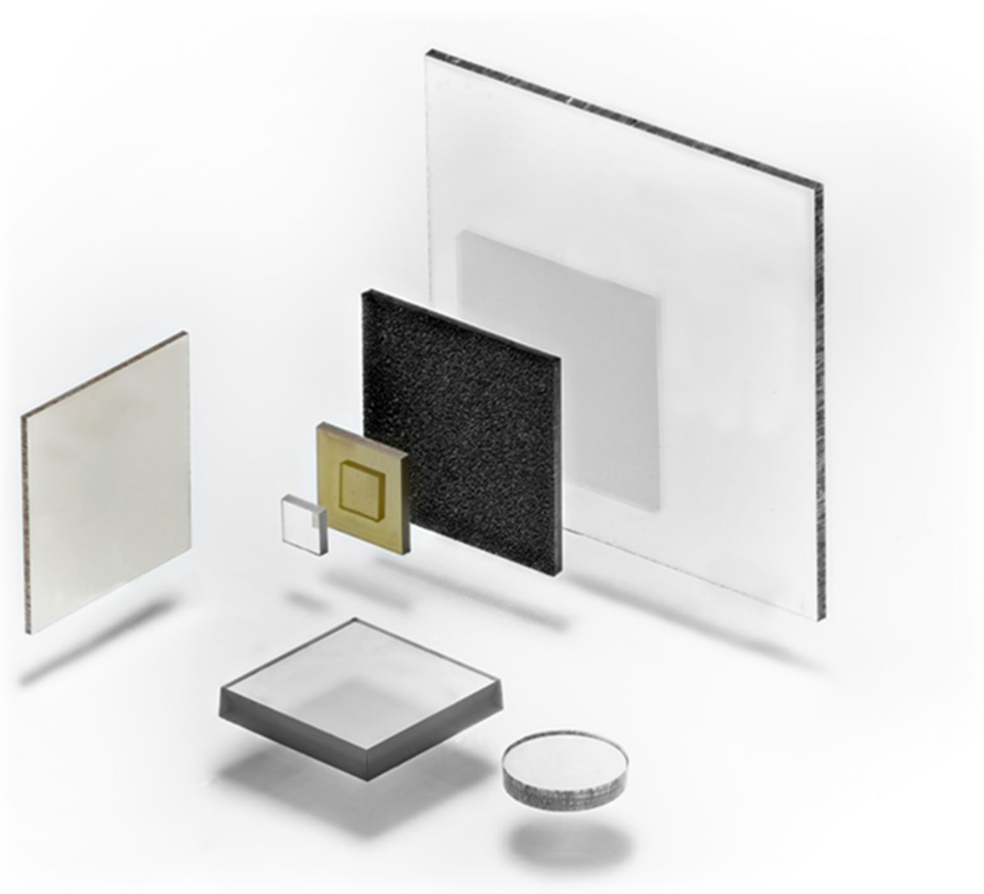


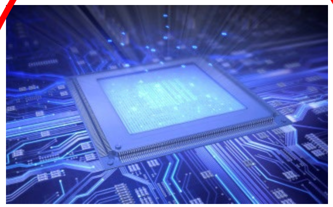
Element Six on one slide

Automotive & Aerospace

Consumer Electronics & Semiconductors

Oil & Gas Energy

Mining, Road Planing, Forestry, & Agriculture



Optical, Thermal, Water, Quantum, & Acoustics

HPHT synthesis of synthetic diamond and Cubic Boron Nitride (cBN) grits, powders and polycrystalline discs

Tungsten carbide sintering for hardmetal tooling applications
HPHT synthesis of synthetic diamond grit and polycrystalline cutters

CVD diamond for applications beyond hardness, exploiting the many other extreme properties

Applications enabled by CVD diamond

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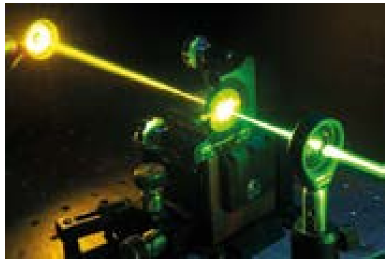
Optical Transmission

High Power Laser Windows

Raman Lasers



Thermal Conductivity

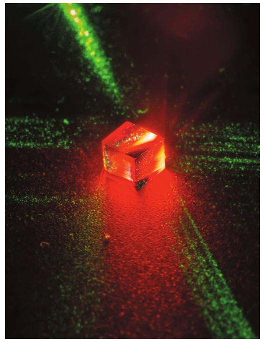
Semiconductor Heat Spreaders

Stiffness (Acoustic)

Speaker Domes

Sensors

Quantum Devices



Detectors

Water

Electrodes

Jewelry

Lab Grown Diamonds

CVD Diamond for Thermal Management

For High-end Semiconductor Devices

Applications for High-Power GaN devices

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Discrete HEMTs

MMICs & Hybrid PAs

Switches & Diodes

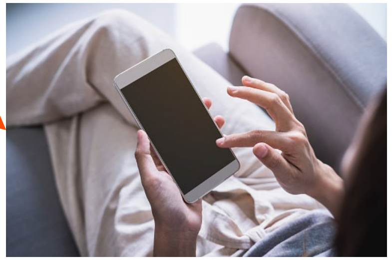
Defense Apps (e.g. Radar, EW, Avionics)

New & efficient Weather & Comm. Satellites

Energy-efficient wireless networking

More efficient Inverters for PV/Wind

More efficient Inverters for Hybrids/EVs



More powerful smartphones

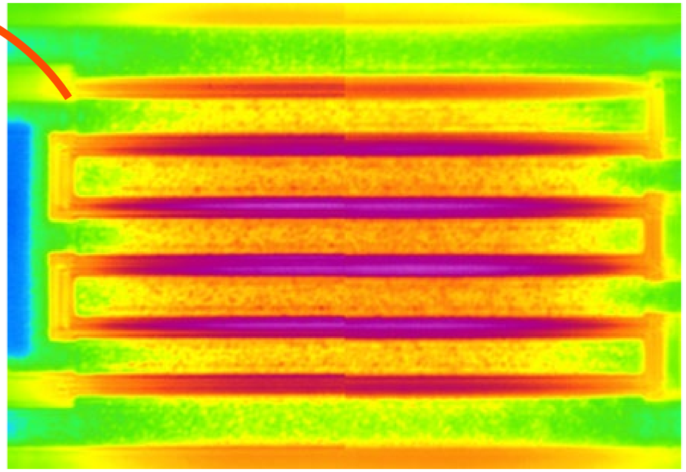
GaN devices - Thermal management challenge

GaN devices enable **5x increase** in RF power density

Reduced area and RF losses
(Substrates: GaAs = 55 W/mK, versus SiC ~420 W/mK)

http://www.mpdigest.com/issue/Articles/2013/Feb/TriQuint/

GaN-on-SiC power density is thermally limited



GaN RF device thermal image

Higher power densities require improved near junction thermal transport

Extreme Power Densities in Modern GaN devices

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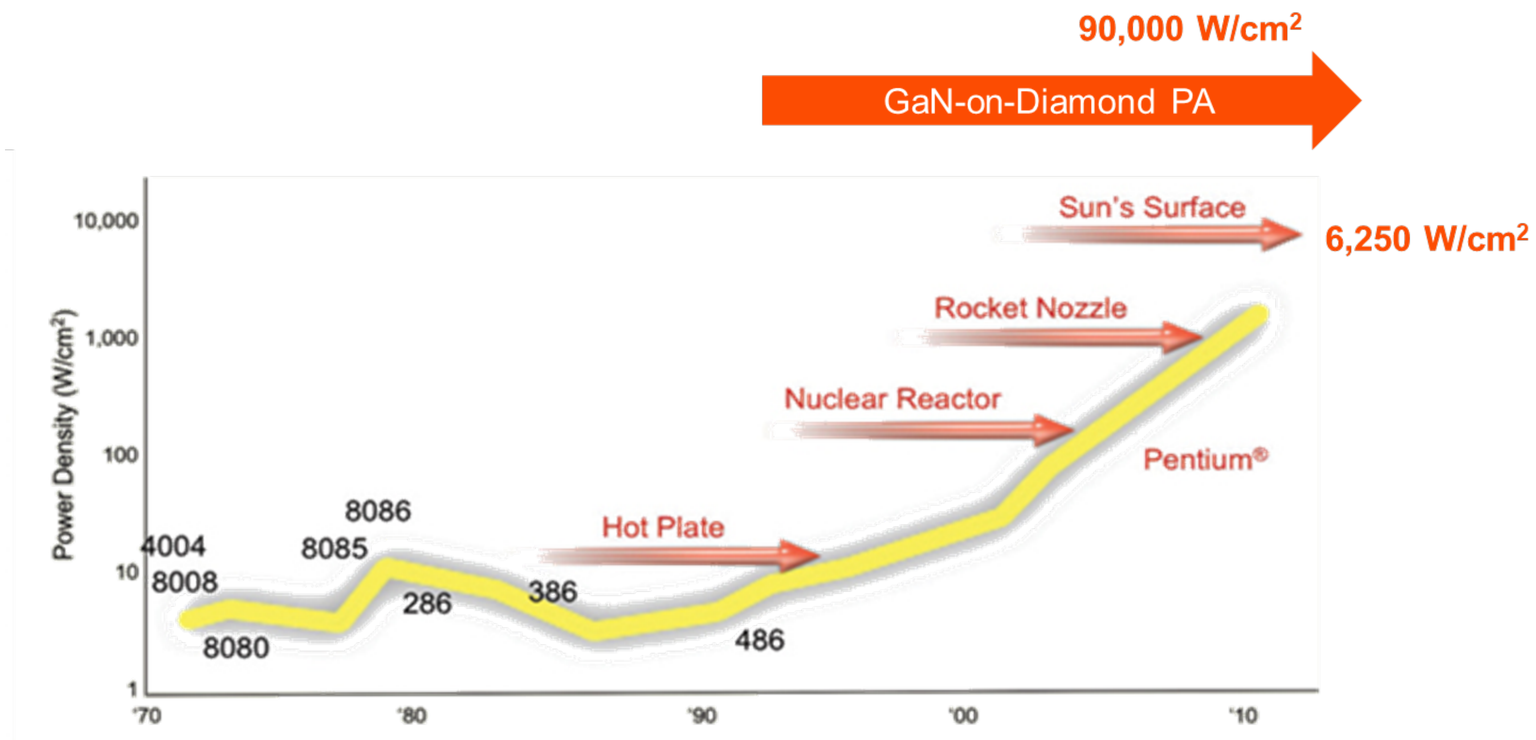
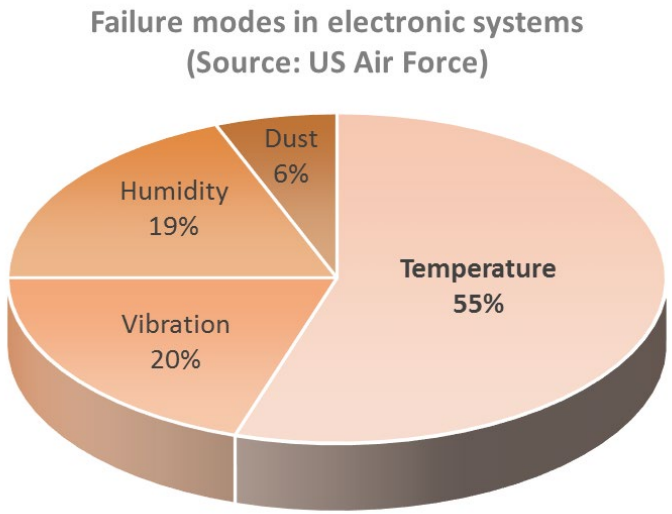
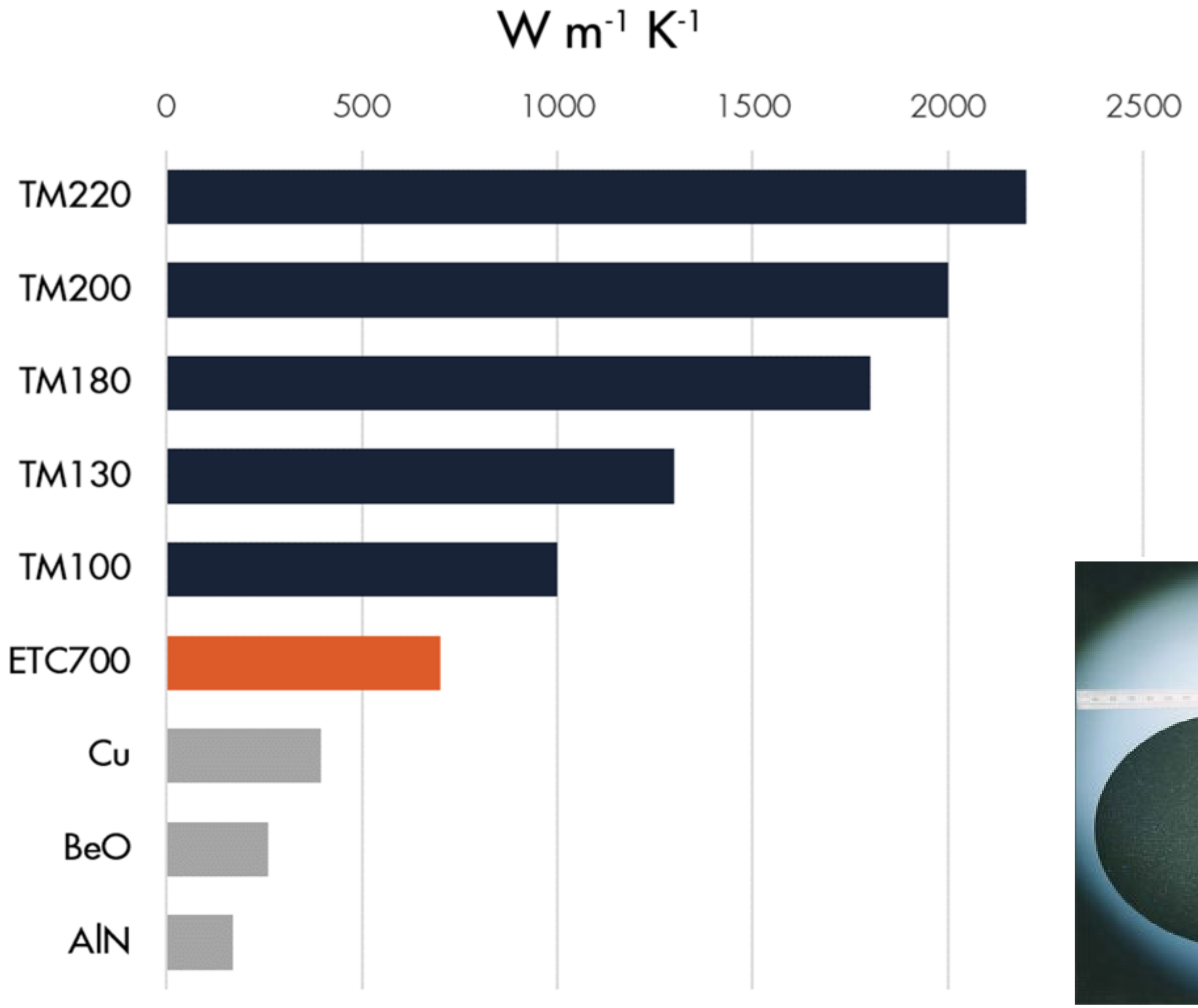
Power densities for GaN devices are rapidly increasing & temperature is a major failing mode

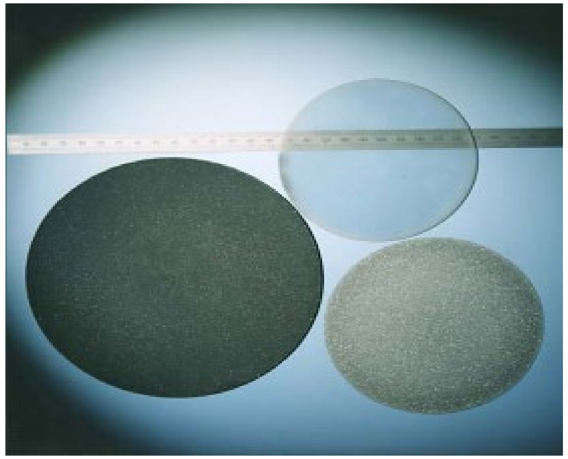




Superior thermal conductivity of CVD diamond



- Controlled synthesis and materials characterization opens up opportunities for different thermal grades
- Thermal conductivity controlled in the range 1000 to >2200 W/mK
- Diameters up to 140 mm & thicknesses of 300 – 3600 µm



CVD growth: Polycrystalline Diamond
for Heat Spreaders

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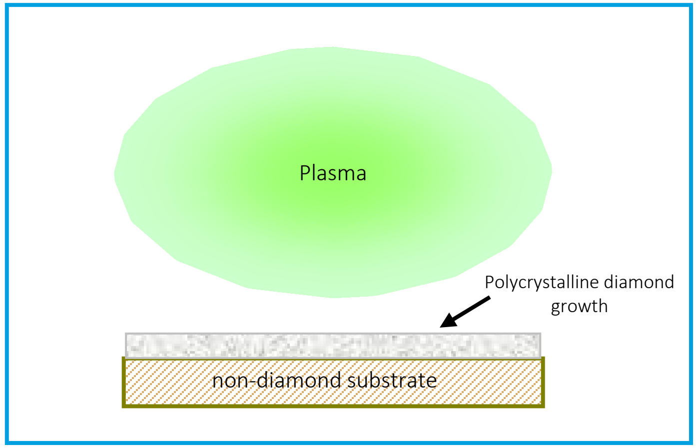
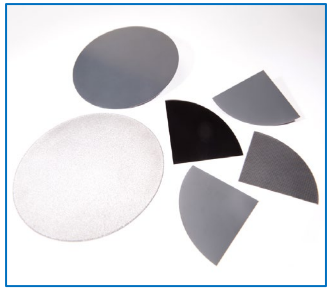
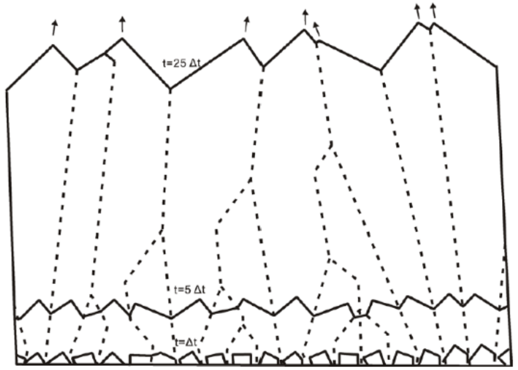
Non-diamond substrate → polycrystalline diamond growth



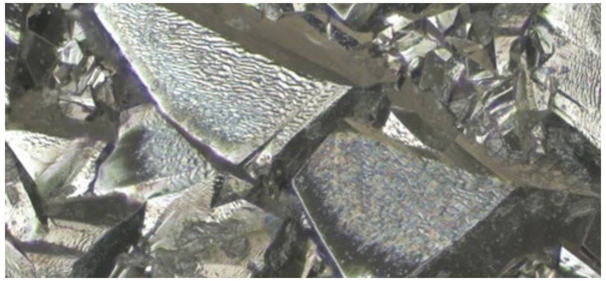


140 mm diameter & 3.6 mm thick

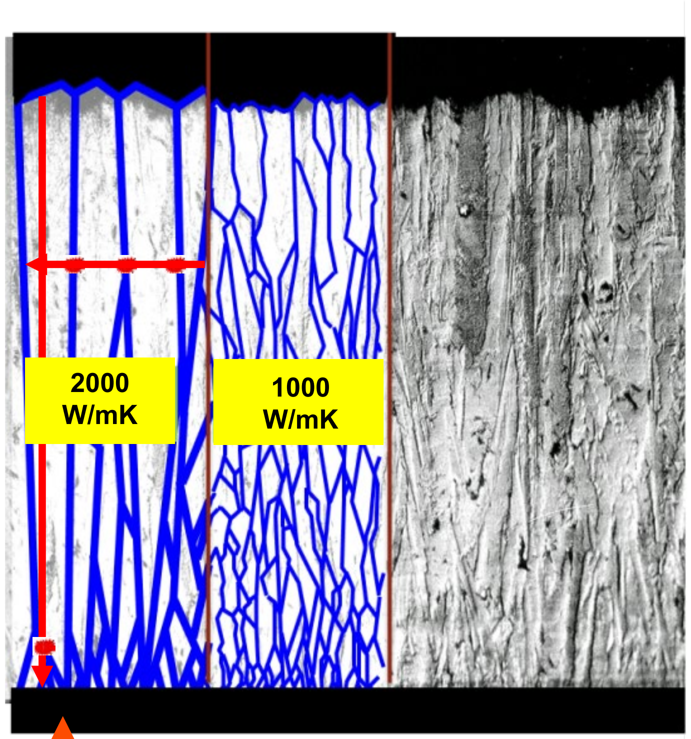
van der Drift growth model



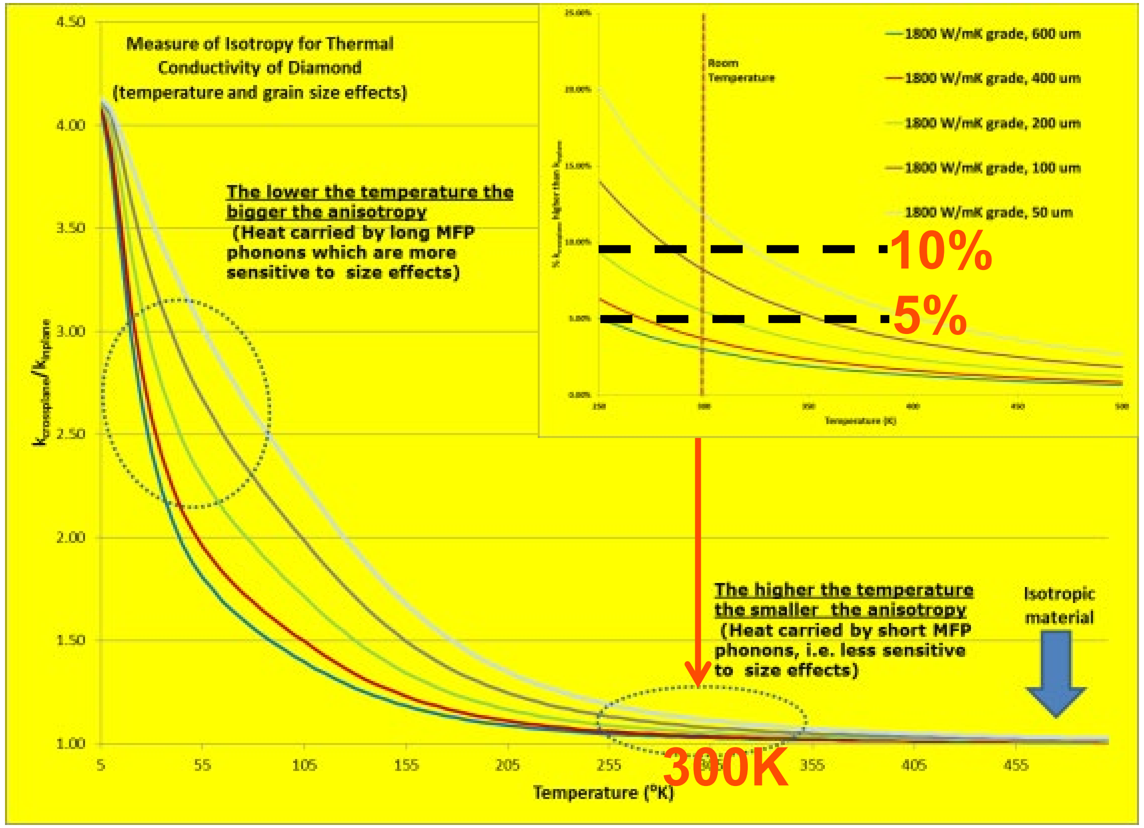
- Initial diamond nuclei are randomly oriented
  - Competitive grain growth ensues: Fastest growing grains dominate
  - Grains size ~5-10% of thickness



Through-plane vs in-plane anisotropy thermal conductivity < 10% for diamond thickness > 200 µm



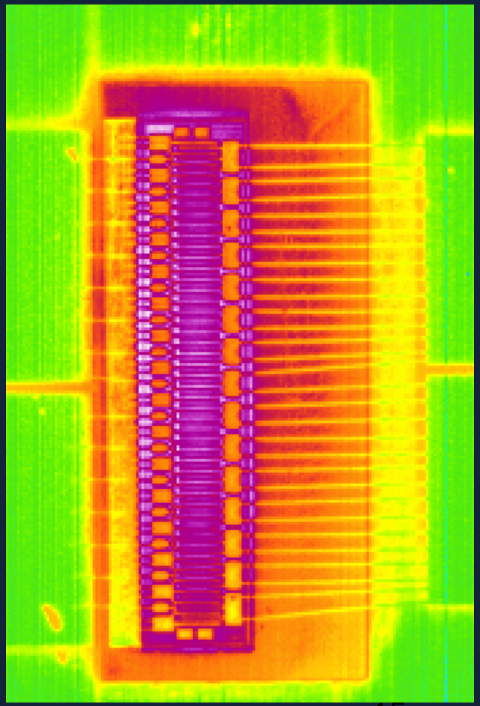
Worst scenario for a cross-plane / in-plane anisotropy
In-plane "k" limited by the lateral grain size vs cross-plane "k" of a single crystal diamond (MFP limited by the size of the grains vs MFP limited by dimensions of the sample (thickness)) .



Minimal anisotropy particularly important for new 2.5D and 3D semiconductor packaging – heat needs to be transported rapidly in all 3 dimensions (x, y, and z)

Case Study

CVD Diamond Heat Spreader Application



Simple introduction – *RF power amplifier stack of thermal resistors*

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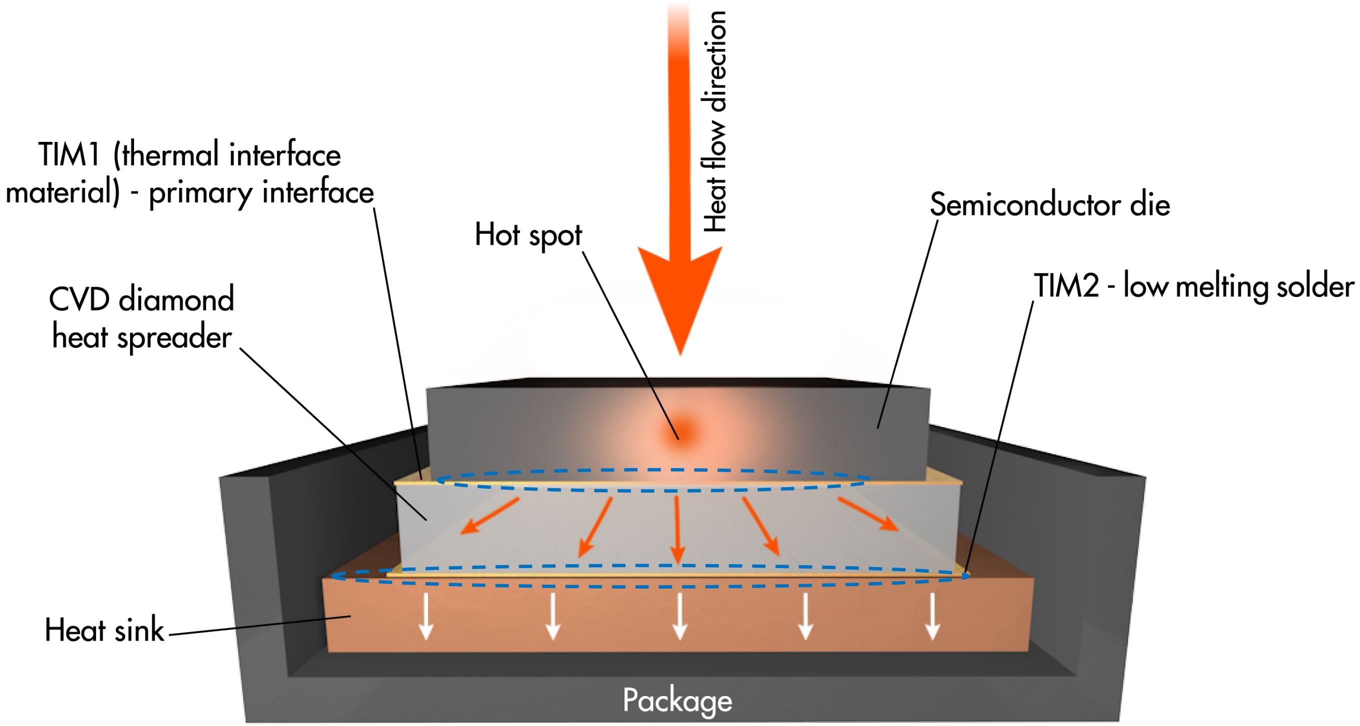
- Heat spreader reduces peak device temperature by reducing heat flux density

- RF power amplifiers' (HEMPTs) high power density require significant thermal management
  - Diamond heat spreader rapidly pulls heat away from hot spot
  - TIM1 thermal interface critical to effectiveness of heat spreader



Continuous Wave 160 W 2 GHz GaN Device

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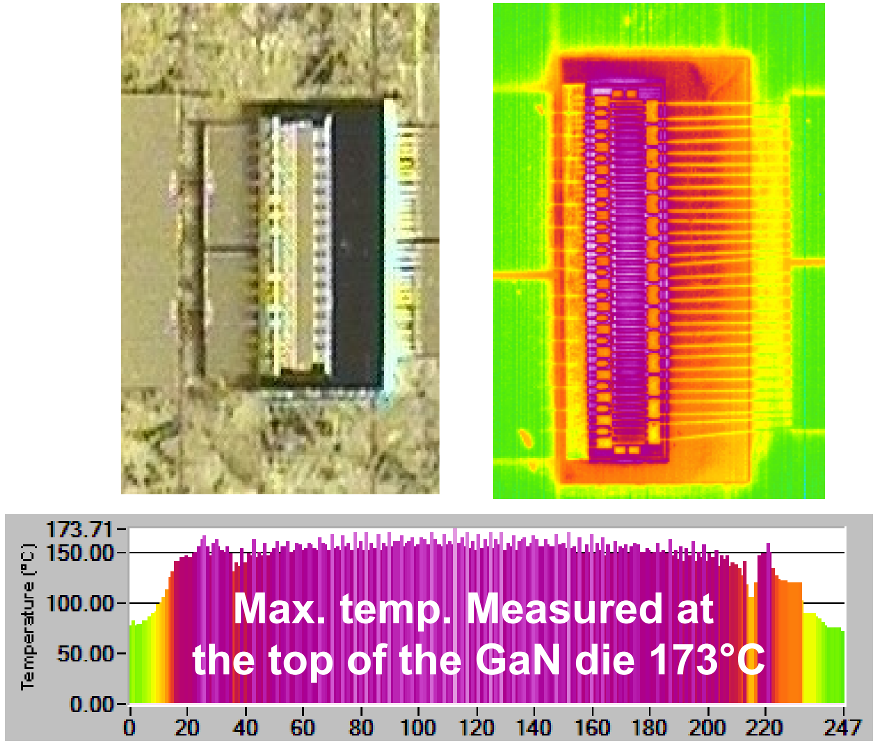
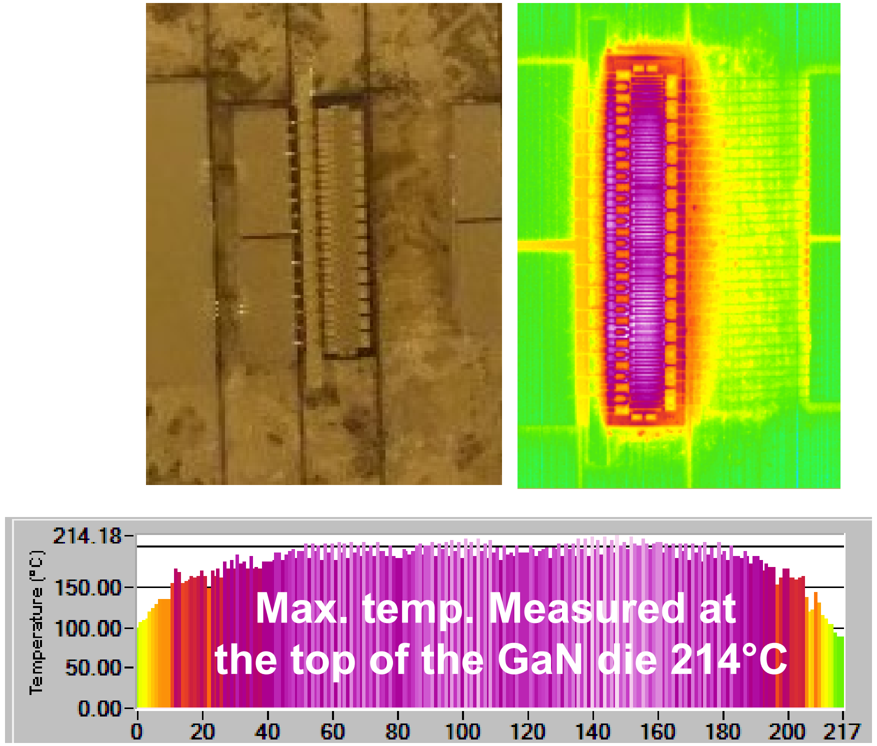
- SiC thinned with an E6 diamond metallized heat spreader
- **41°C reduction** in device surface temperature

SiC with diamond heat spreader



Assembly A
(SiC =100 µm – *Ti:Pt:Au:* TM180: Ti:Pt:Au: Cu Sink)

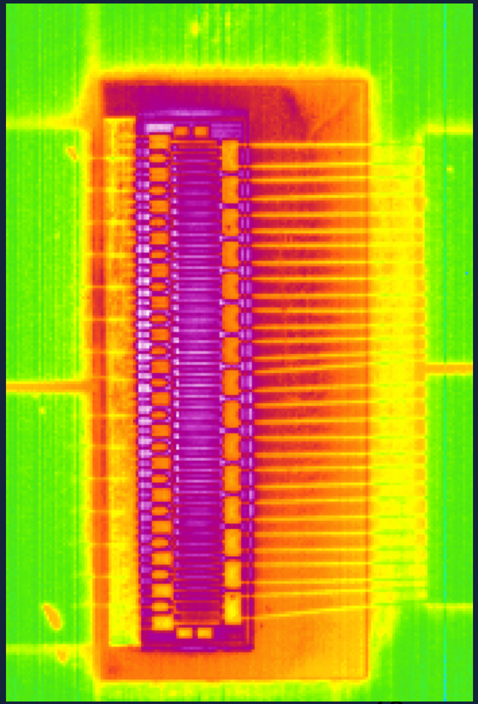
SiC - no diamond heat spreader



Assembly B
(SiC =400 µm – no heat spreader)

Optimizing Heat Spreader Effectiveness

CVD Practical Application Recommendations



Diamond properties and surface preparation

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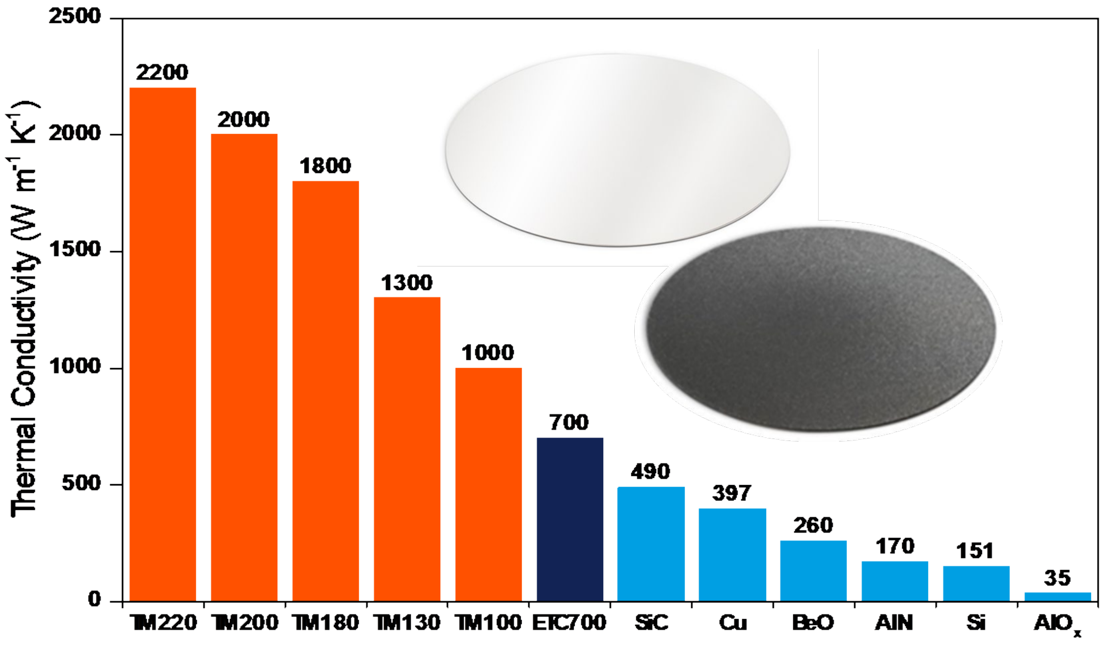
- Grade, size and thickness
  - Match CVD grade to application – grades range in Tc from 700 to 2200 W/mK
  - Keep size as small as possible for cost effectiveness
    - Lateral dimensions < 1 mm bigger than device in x and y, just enough for good wetting
    - Thickness between 0.25 and 0.4 mm is sufficient for devices with hot spot size < 1 mm
- Conducting or non-conducting
  - Insulating or conducting – 2 to 20 GHz RF devices require insulating, but laser diodes require conducting
  - Conducting: either wrap around metallization or boron-doped diamond
- Surface finish
  - Flat and smooth surface reduces thermal boundary resistance between diamond and device
  - Flatness < 1 mm and Ra < 50 nm (polished) is sufficient



Mounting devices on diamond heat spreaders

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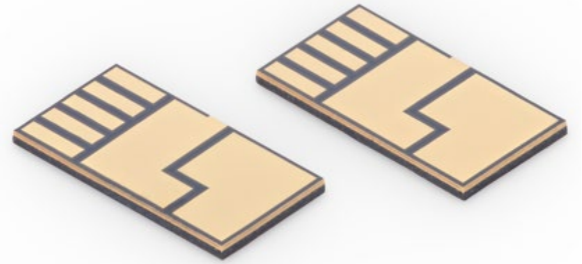
- Diamond metallization
  - Required for mounting device on heat spreader
  - Need carbide-forming adhesion layer – Ti, Cr, .. (< 100 nm thick)
  - Barrier layer (e.g. Pt) < 100 nm thick, the Au for bonding to device
  - High-quality, sputter-deposited, thin-film metallization required

- Attachment technique
  - Normally AuSn soldering or nano-AG sintering; not thermal gels
  - TIM1 is most important boundary, but cannot ignore TIM2 – use lower temp soldering material for TIM2
  - Keep bond lines to ~ 5 microns via sputter-deposited or evaporated – to minimize thermal boundary resistance
  - Solder can handle CTE mismatches for devices < 10 mm in size



Patterned metallization for high-power laser diodes

TABLE 1: SOLDERING MATERIAL OVERVIEW [2]

Solder Material	Composition (wt%)	Soft / Hard	Liquidus Temp. (°C)	Solidus Temp. (°C)
InSn	52/ 48	Soft	118	eutectic
InSn	50 / 50	Soft	125	118
InAg	97 / 3	Soft	143	eutectic
In	Pure	Soft	156.6	156.6
InPb	70 / 30	Soft	171	162
SnPbAg	62 / 36 / 2	Soft	179	eutectic
SnPb	63 / 37	Soft	183	eutectic
SnPb	60 / 40	Soft	191	183
AgSn	3.5 / 96.5	Soft	221	eutectic
AuSn	80 / 20	Hard	278	eutectic
AuSn	75 / 25	Hard	356	278
AuGe	88 / 12	Hard	361	eutectic
AuSi	82 / 18	Hard	363	eutectic
AuSn	73 / 27	Hard	370	278
AuSn	70 / 30	Hard	390	278

Summary

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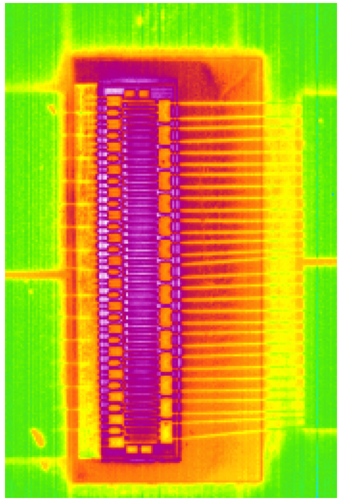
- CVD diamond heat spreaders provide superior thermal management for high-power semiconductor applications
  - Higher power operation for a given maximum operating temperature
  - Reduced peak temperatures (~25%) for a given power
- Thermal conductivity can be engineered to suit the application
  - Need to consider the system as a whole for maximum benefits
- CVD diamond heat spreader implementation should be optimized
  - Match diamond properties to the specific application
  - Prepare diamond surface appropriately – roughness and metallization
  - Use optimal materials and techniques to mount the device on heat spreader to minimize thermal resistance, particularly of TIM1



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Thank you for listening

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