Using Diamond Films to Enhance Thermal Performance in Electronics Packaging

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Outline

- Motivation;
- Why diamond?
- Diamond synthesis;
- Diamond for thermal management of power components:
    - Diamond and GaN HEMTs;
    - Diamond as chip-carrier;
    - Diamond as power board;
- Conclusions.

Thermal management of electronic systems: data center

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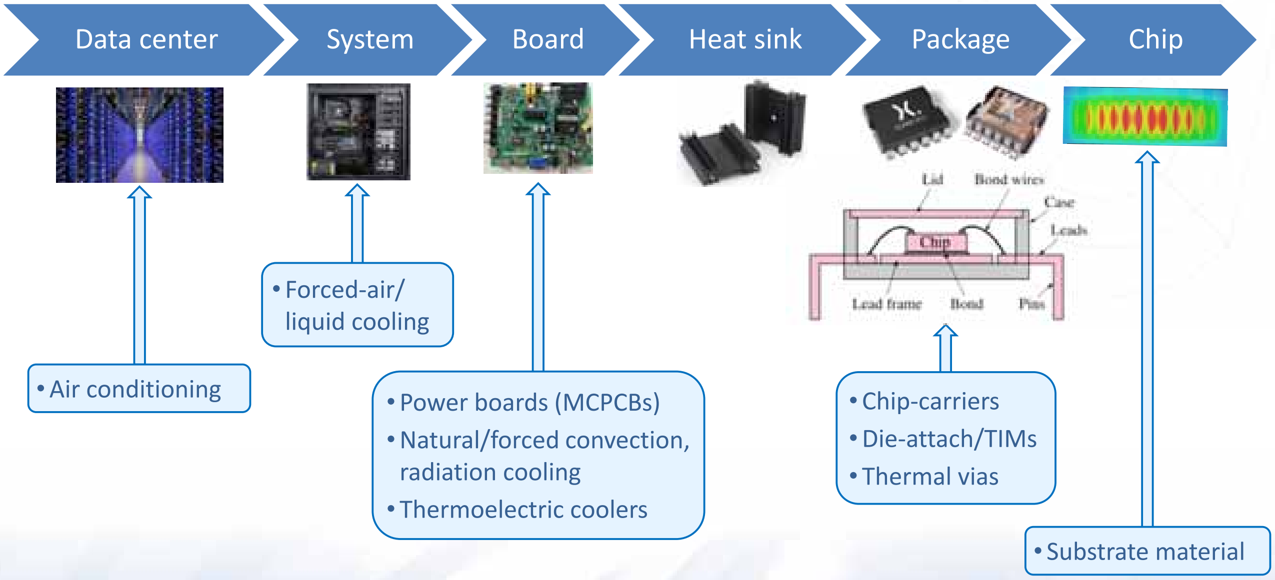


Data center → System → Board → Heat sink → Package → Chip

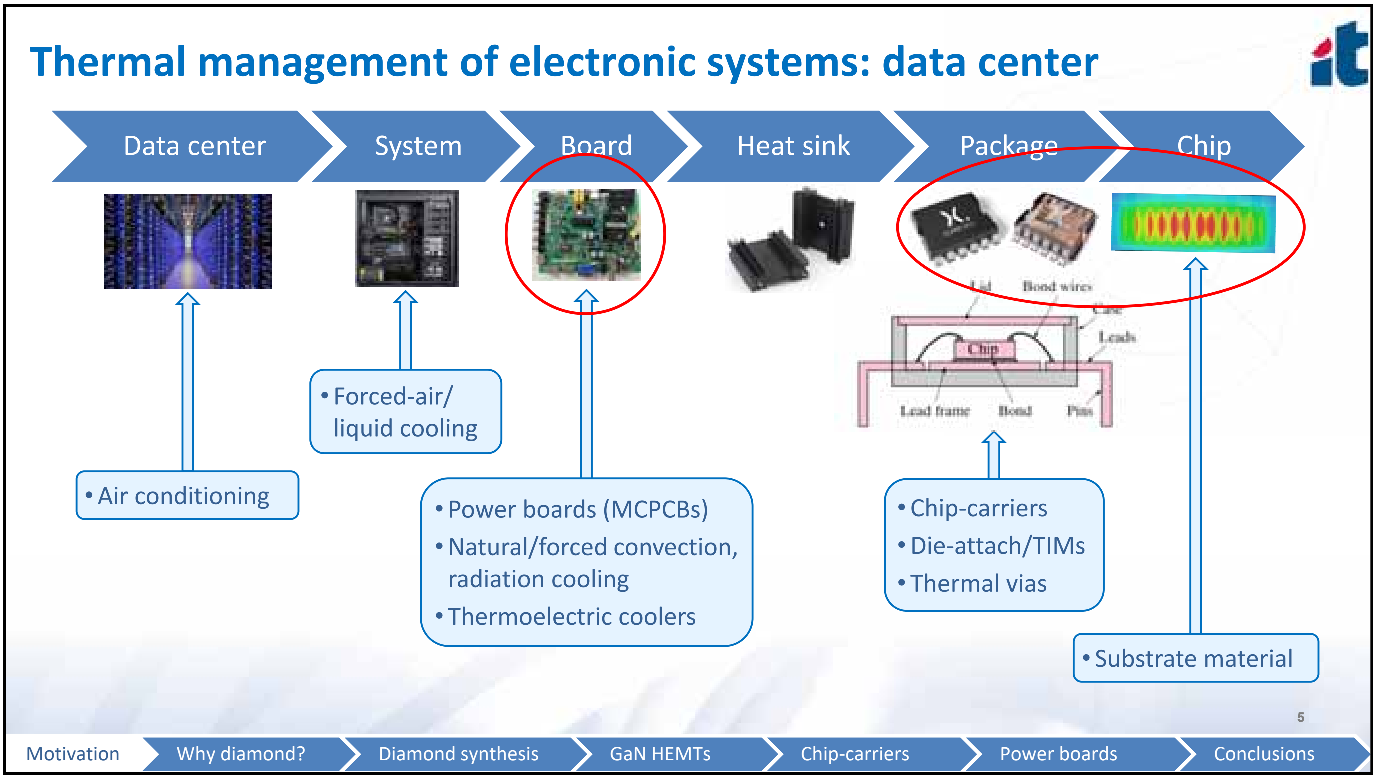
- Air conditioning

- Forced-air/ liquid cooling

- Power boards (MCPCBs)
- Natural/forced convection, radiation cooling
- Thermoelectric coolers

- Chip-carriers
- Die-attach/TIMs
- Thermal vias

- Substrate material



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Motivation | Why diamond? | Diamond synthesis | GaN HEMTs | Chip-carriers | Power boards | Conclusions

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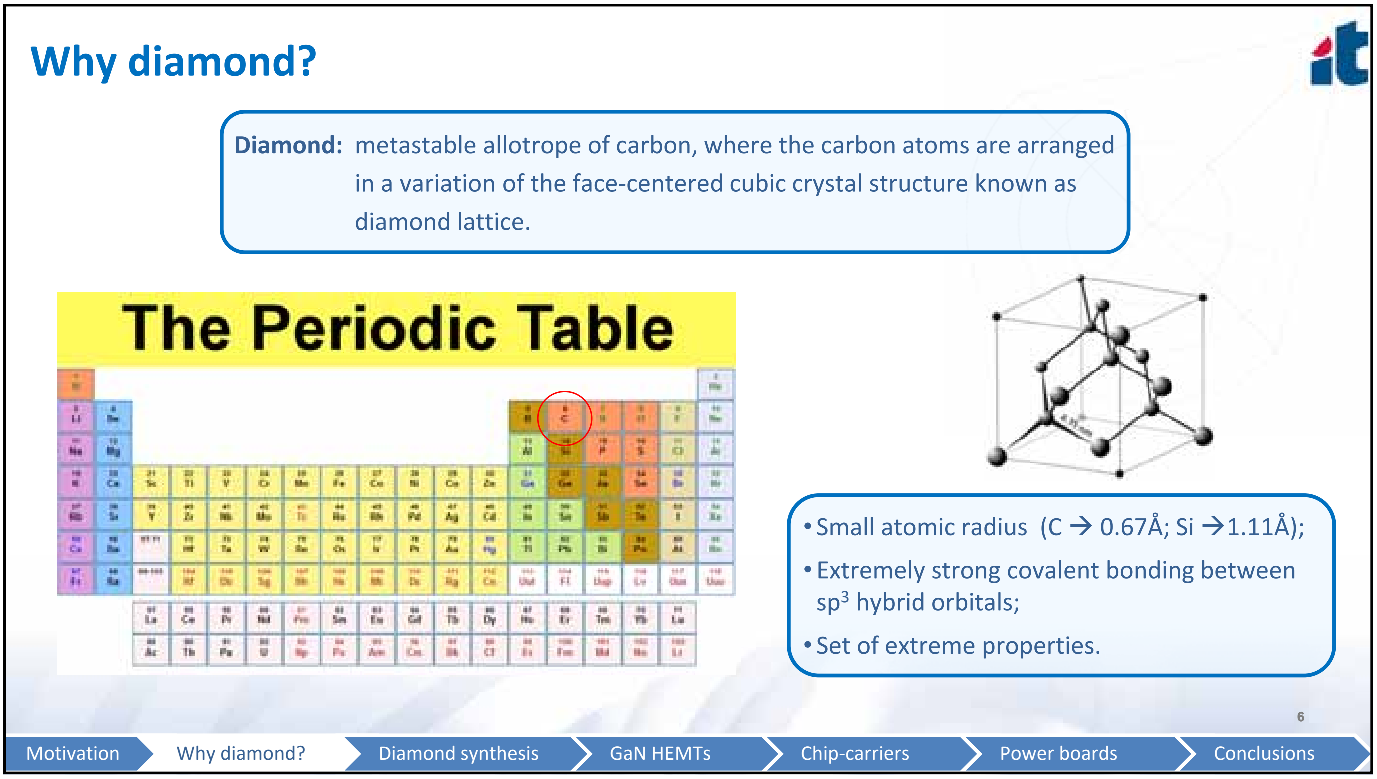

Why diamond?

Diamond: metastable allotrope of carbon, where the carbon atoms are arranged in a variation of the face-centered cubic crystal structure known as diamond lattice.

- Small atomic radius (C → 0.67Å; Si → 1.11Å);
- Extremely strong covalent bonding between sp^3 hybrid orbitals;
- Set of extreme properties.

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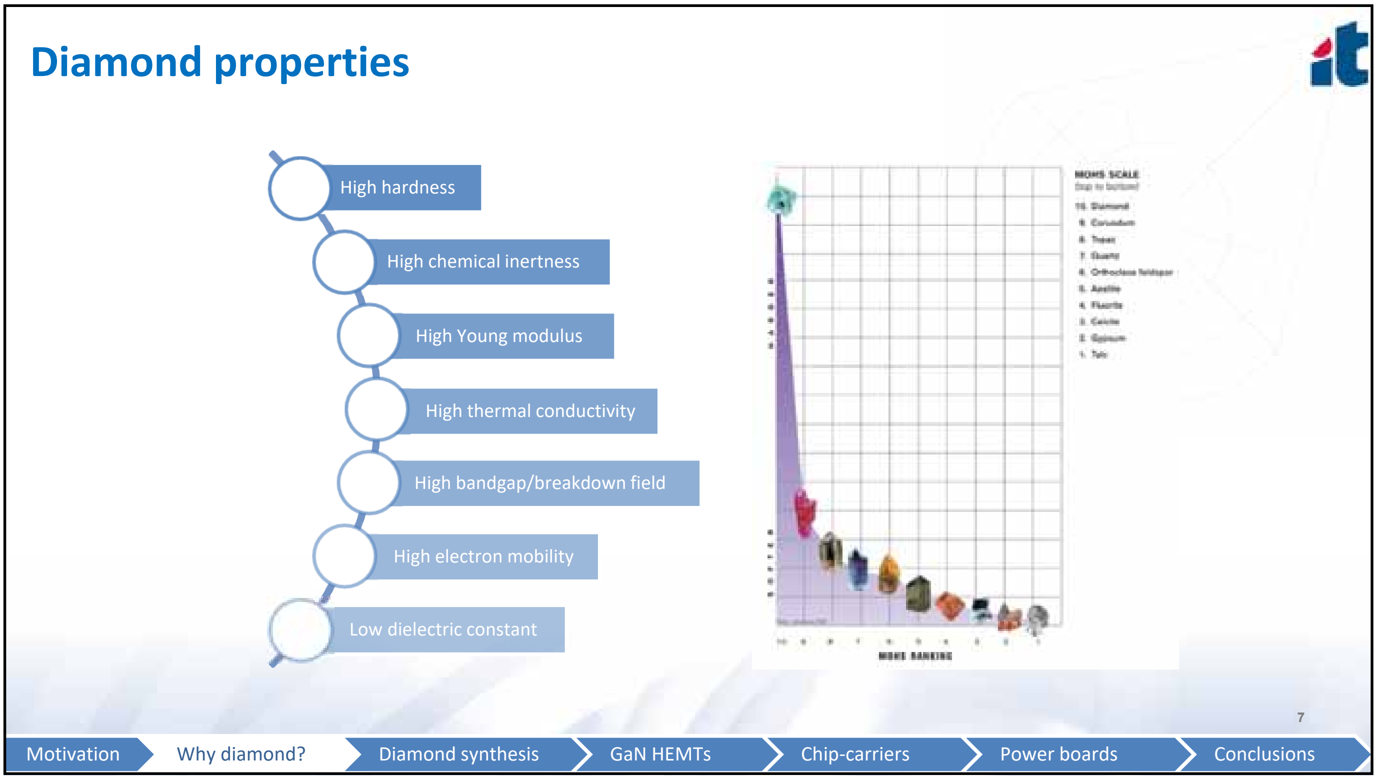
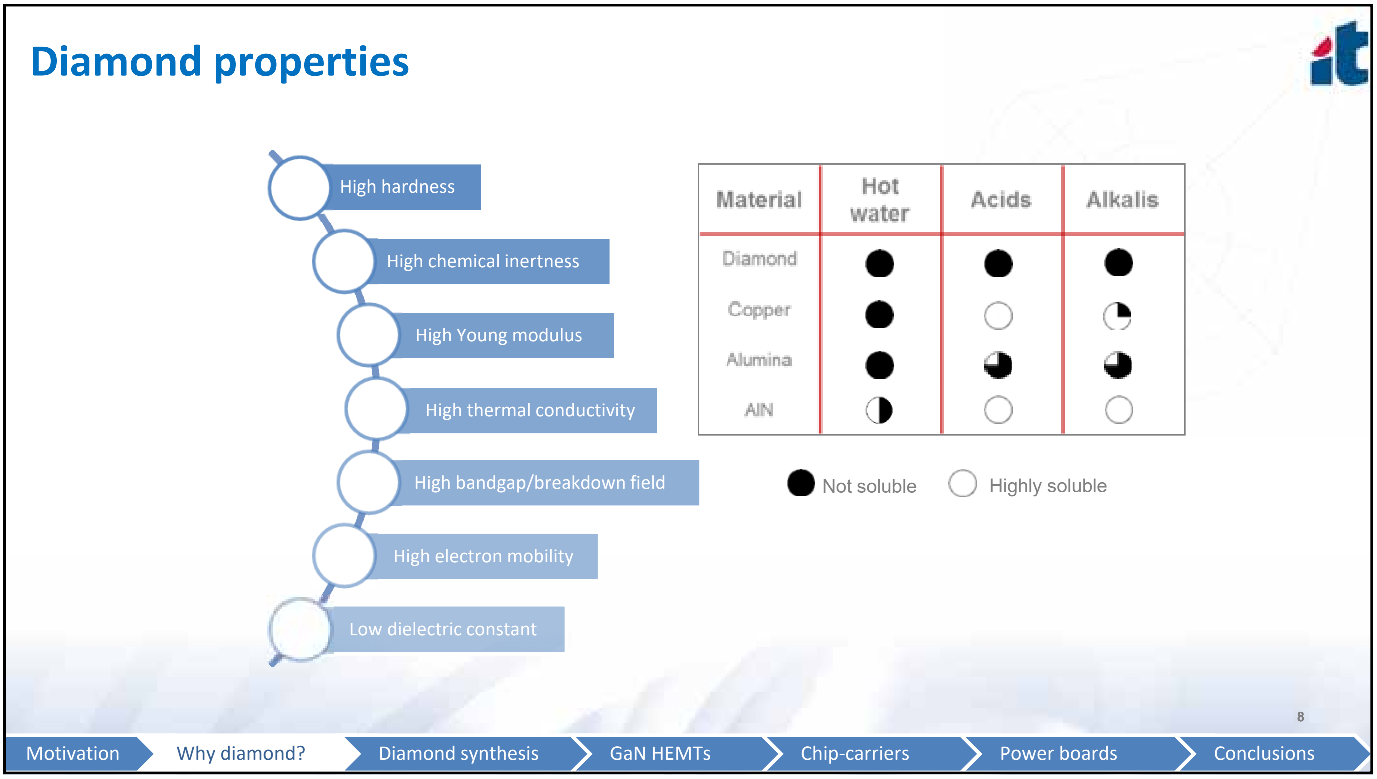


Diamond properties

- High hardness
- High chemical inertness
- High Young modulus
- High thermal conductivity
- High bandgap/breakdown field
- High electron mobility
- Low dielectric constant



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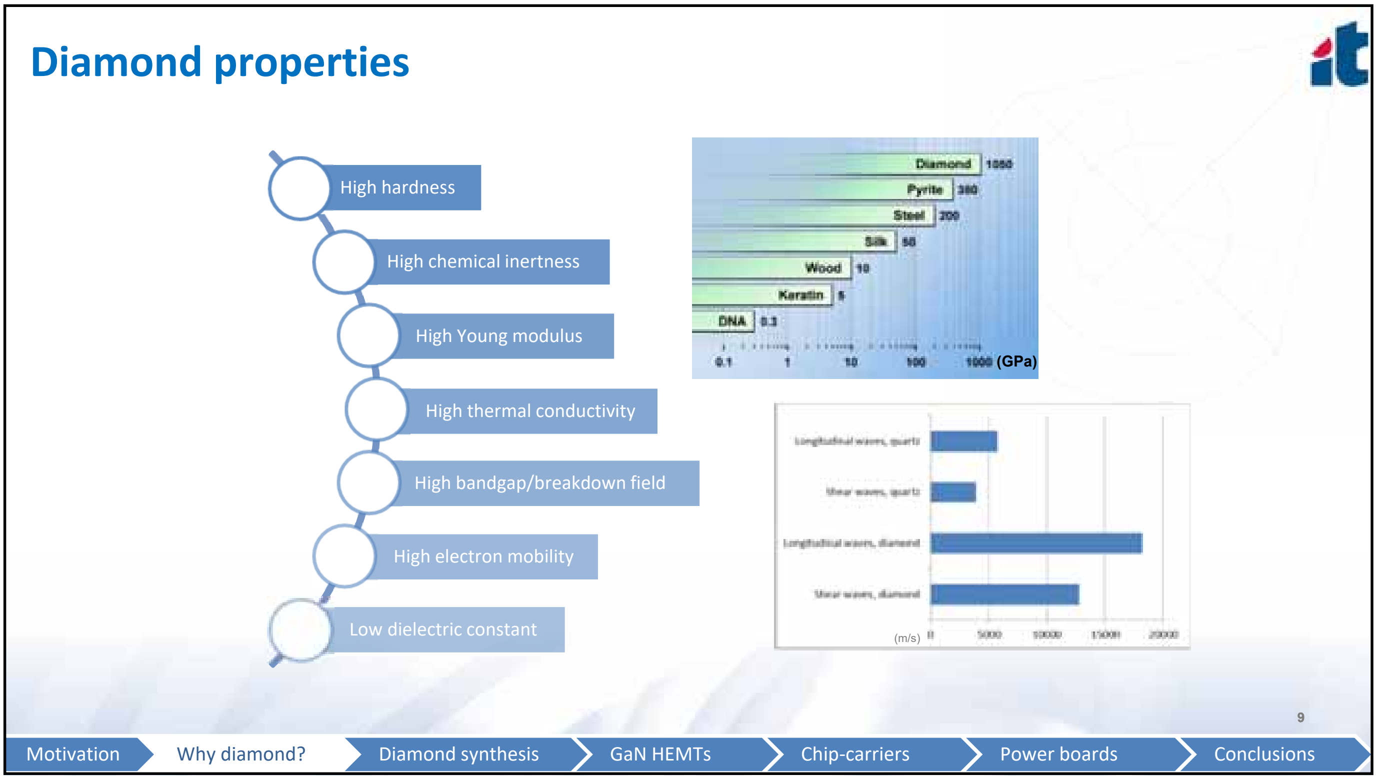
Material	Hot water	Acids	Alkalis
Diamond	●	●	●
Copper	●	○	◔
Alumina	●	◕	◕
AlN	◑	○	○

● Not soluble ○ Highly soluble



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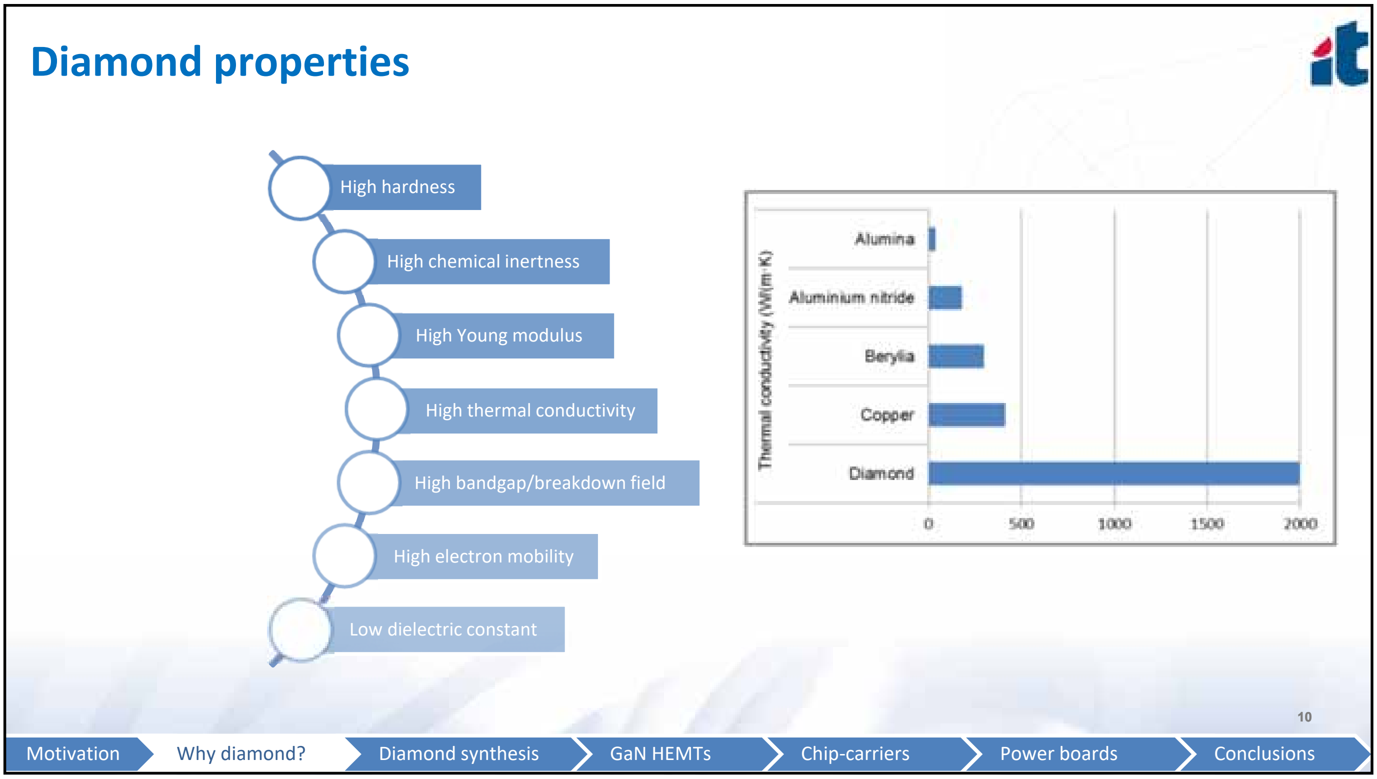

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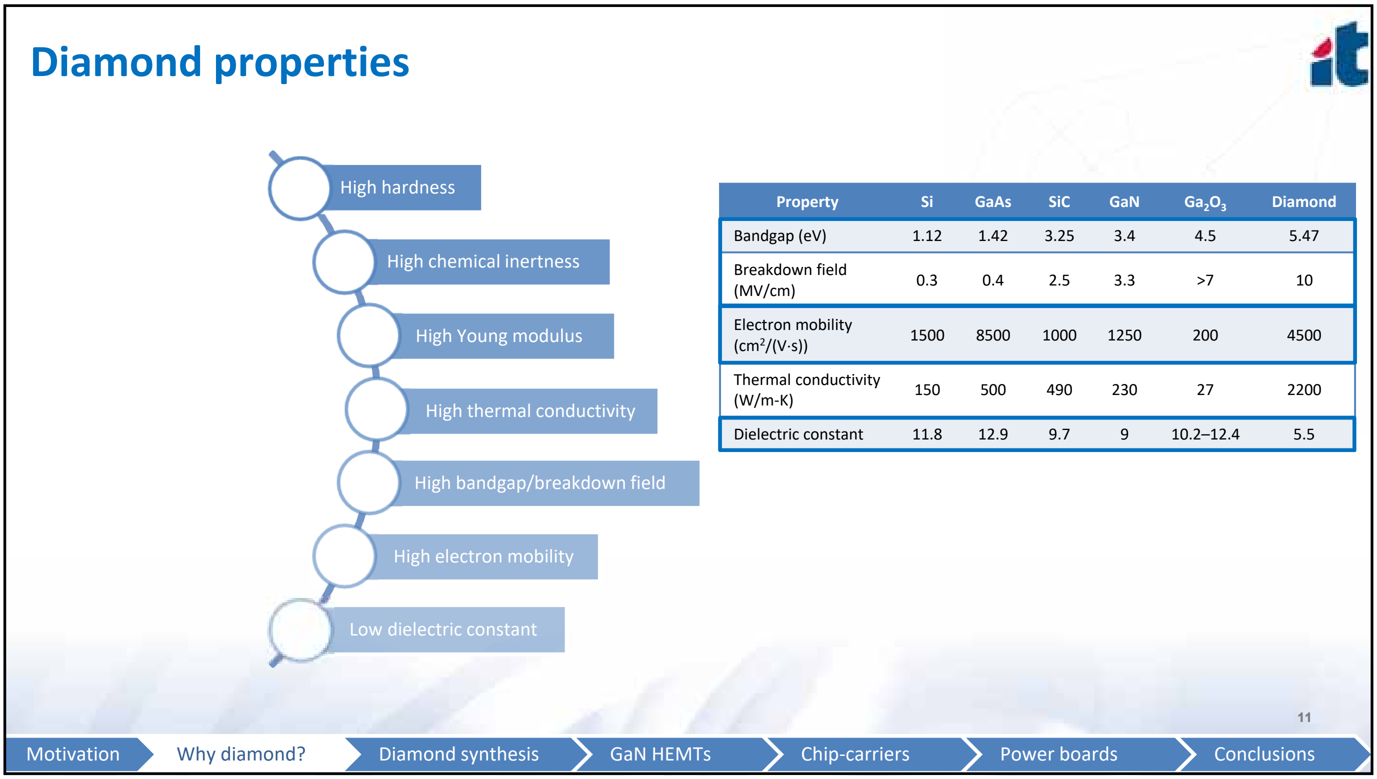

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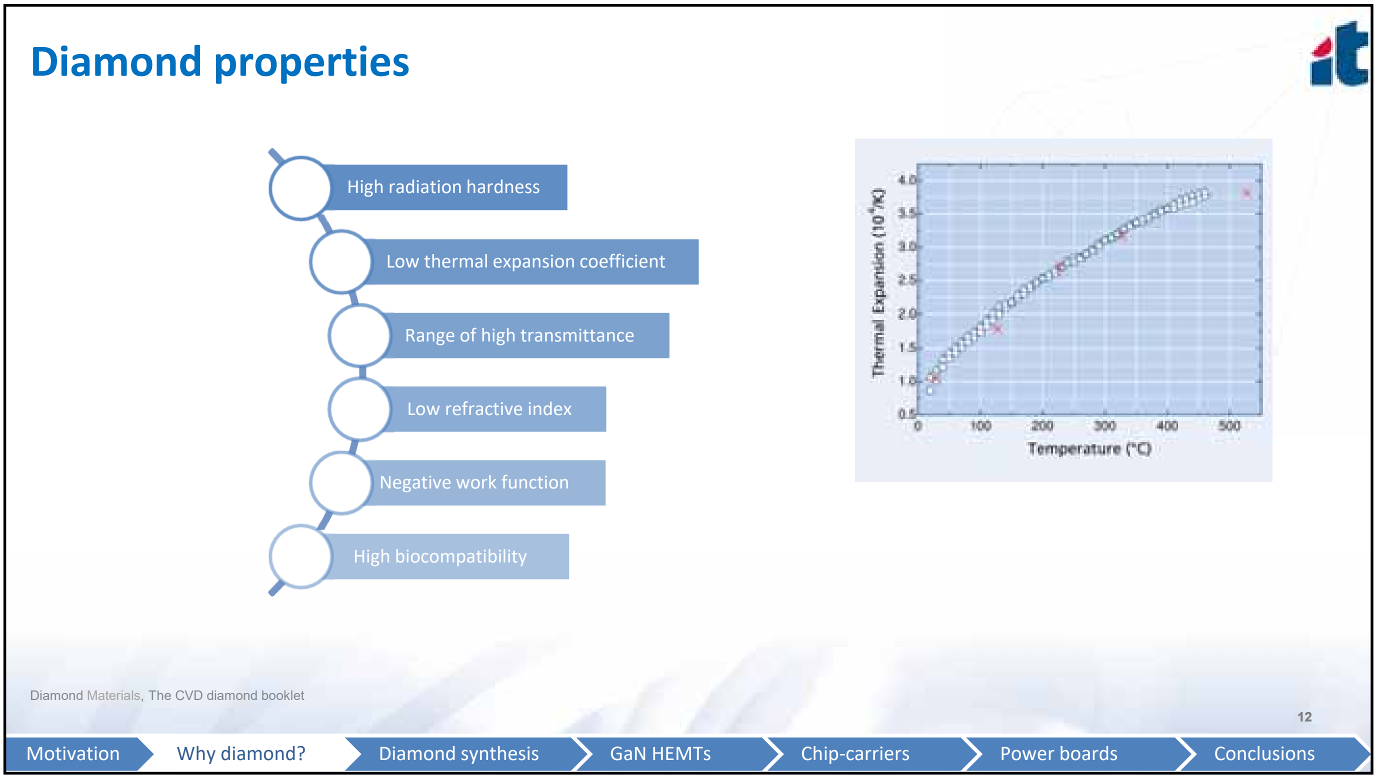
Property	Si	GaAs	SiC	GaN	Ga_2O_3	Diamond
Bandgap (eV)	1.12	1.42	3.25	3.4	4.5	5.47
Breakdown field (MV/cm)	0.3	0.4	2.5	3.3	>7	10
Electron mobility ($cm^2/(V{\cdot}s)$)	1500	8500	1000	1250	200	4500
Thermal conductivity (W/m-K)	150	500	490	230	27	2200
Dielectric constant	11.8	12.9	9.7	9	10.2–12.4	5.5



Diamond properties

- High radiation hardness
- Low thermal expansion coefficient
- Range of high transmittance
- Low refractive index
- Negative work function
- High biocompatibility

Diamond Materials, The CVD diamond booklet

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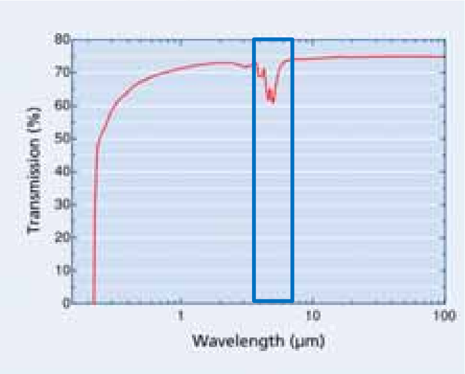

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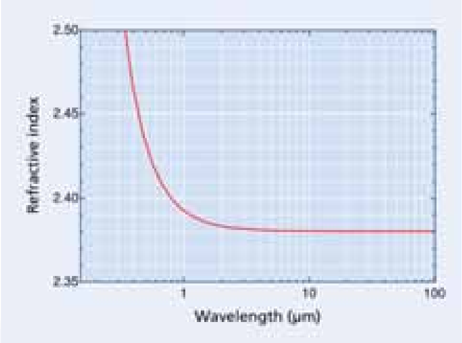
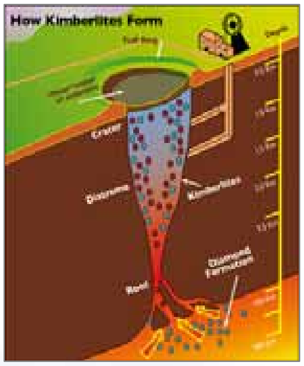


Diamond Materials, The CVD diamond booklet

Diamond synthesis

Natural diamond

Natural diamond forms 150–200 km inside the Earth mantle under extreme conditions: **4.5–6.5 GPa** and **900–1300 °C**

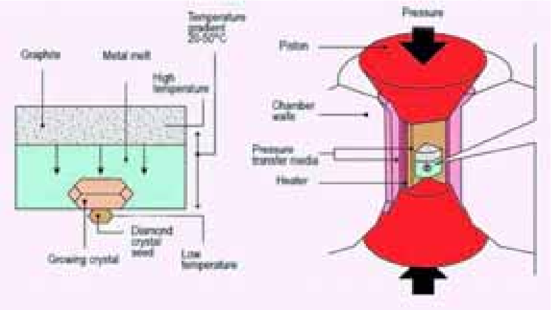


Ekati diamond mine, Canada

- Despite their high commercial value in jewelry, natural diamond crystals have too many defects and cannot be used for electronic applications.
- Their use is typically limited to tribological applications.

Artificial diamond – High Pressure High Temperature (HPHT)

- HPHT method reproduces diamond formation conditions inside the Earth mantle.
- Diamond seeds are placed at the bottom of a press at 5 GPa.
- The internal part of the press is heated above 1400 °C and melts the solvent metal.
- The molten metal dissolves and drags atoms from the high purity carbon source, which precipitate on the diamond seed.

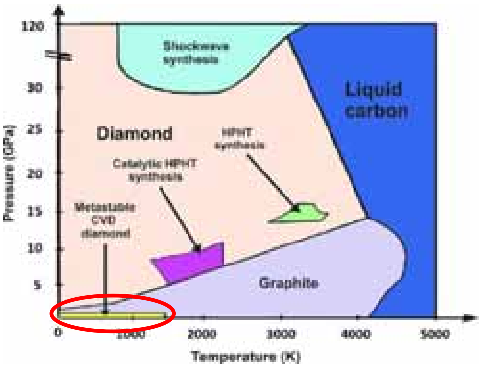


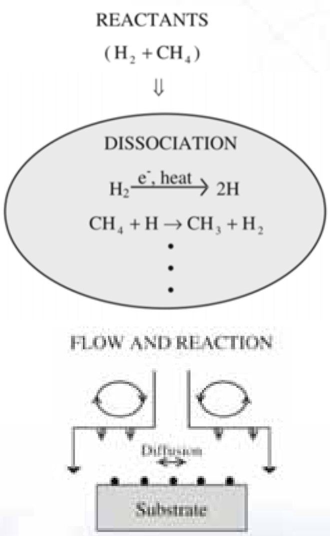
- High perfection of the crystal structure;
- Thermal conductivity up to 2200 W/m-K;
- Range of optical transparency from 225 nm to 25 µm.

- Size up to 10×10 mm^2.

https://blog.javda.com/wp-content/uploads/2021/04/HPHT-diamonds-method-1.jpg

Artificial diamond – Chemical vapor deposition (CVD)





- CH_4 and H_2 as typical input gases;
- Input gases are dissociated and activated;
- The activated radicals flow and react with the C atoms on a substrate;
- Atomic H etches away non-sp^3 C bonds.

Artificial diamond – Chemical vapor deposition (CVD)

- Energy source
  - Hot filament
  - MW, waveguide
  - MW, linear antennas array

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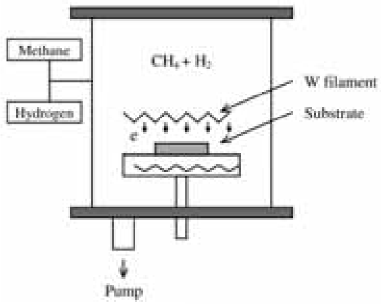
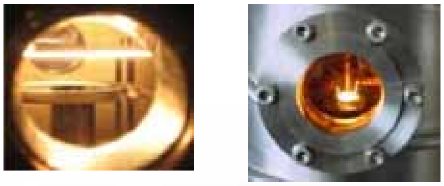




Artificial diamond – Chemical vapor deposition (CVD)

Energy source

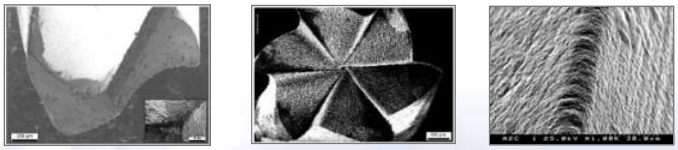
Hot filament

MW, waveguide

MW, linear antennas array

- Conceptually simple and low cost system;
- Can be easily scaled up;
- Coating of complex 3D substrates and internal surfaces possible by smart filament arrangement.

- Filament melting temperature sets upper limit of 2200 °C;
- Low production of atomic H and C radicals → low deposition rates;
- Contamination with atoms from filament;
- Extremely high energy consumption.



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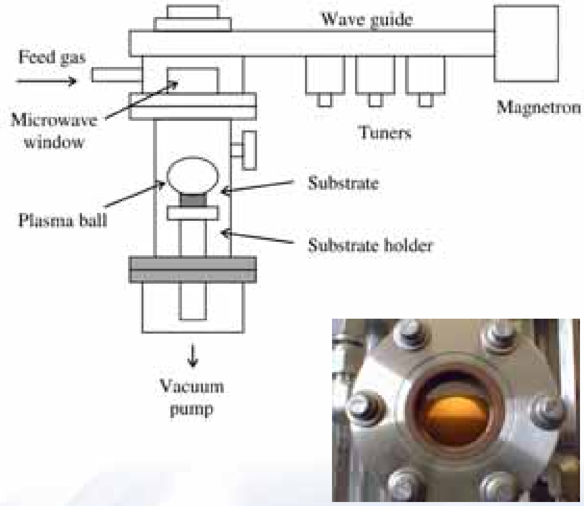
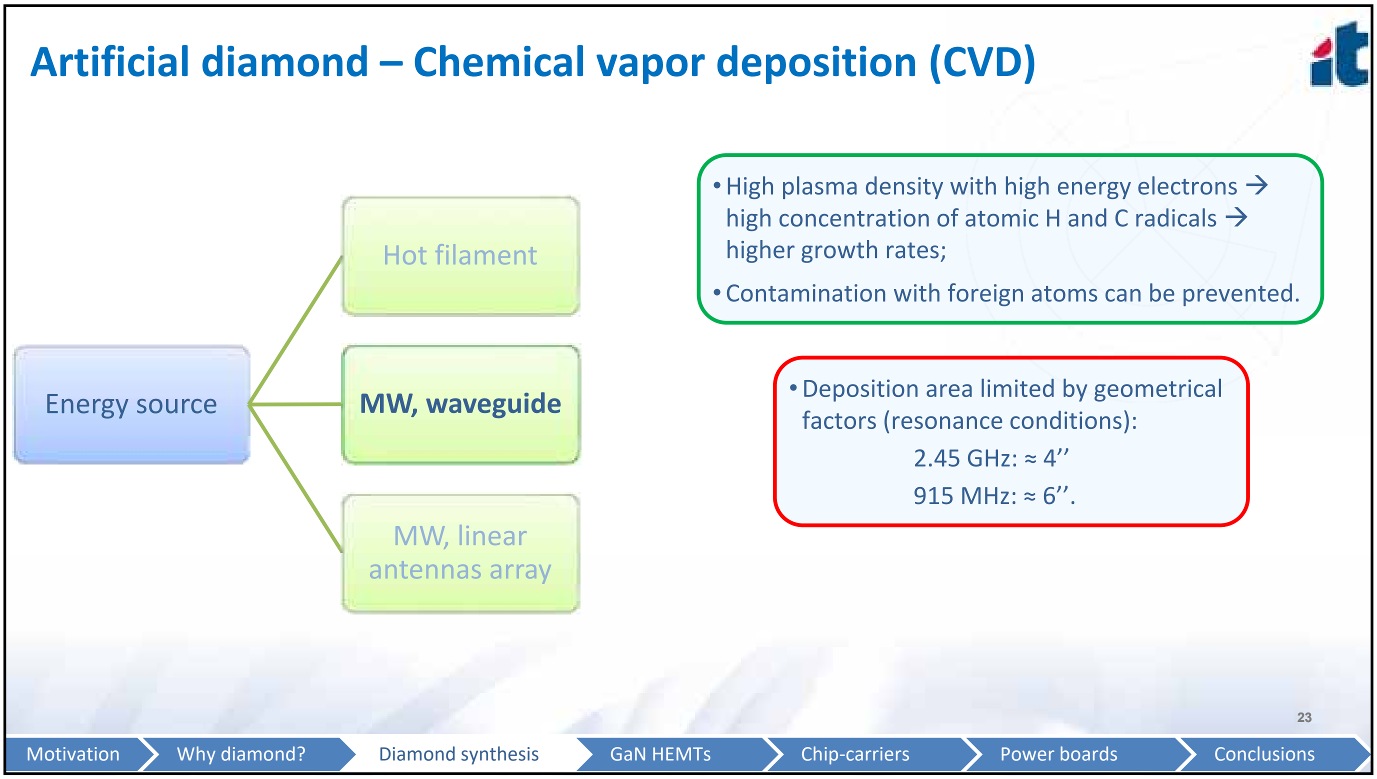




Artificial diamond – Chemical vapor deposition (CVD)

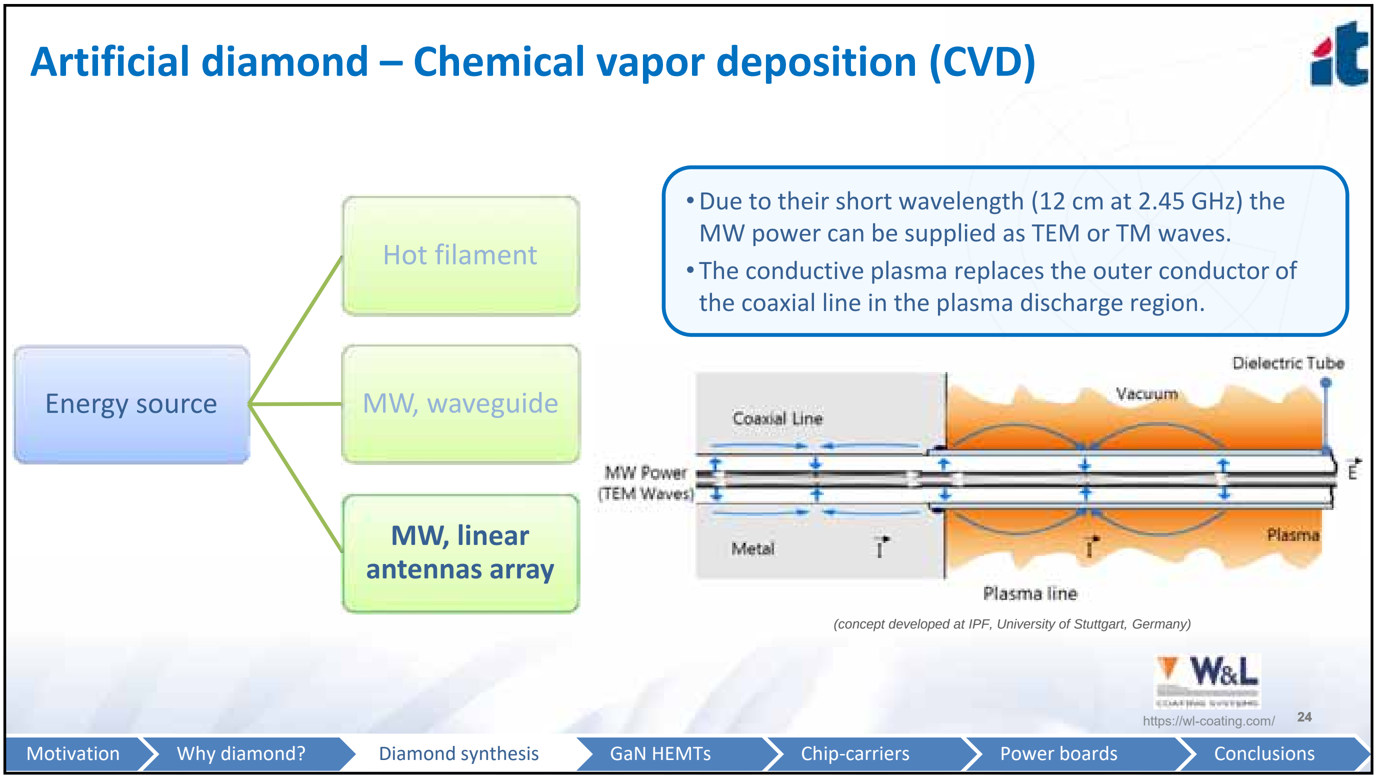
Energy source
- Hot filament
- **MW, waveguide**
- MW, linear antennas array

- High plasma density with high energy electrons → high concentration of atomic H and C radicals → higher growth rates;
- Contamination with foreign atoms can be prevented.

- Deposition area limited by geometrical factors (resonance conditions):

  2.45 GHz: ≈ 4’’

  915 MHz: ≈ 6’’.



Artificial diamond – Chemical vapor deposition (CVD)

Energy source
- Hot filament
- MW, waveguide
- **MW, linear antennas array**

- Due to their short wavelength (12 cm at 2.45 GHz) the MW power can be supplied as TEM or TM waves.
- The conductive plasma replaces the outer conductor of the coaxial line in the plasma discharge region.

(concept developed at IPF, University of Stuttgart, Germany)

W&L
COATING SYSTEMS
https://wl-coating.com/

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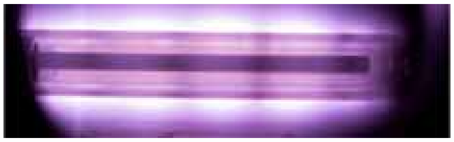

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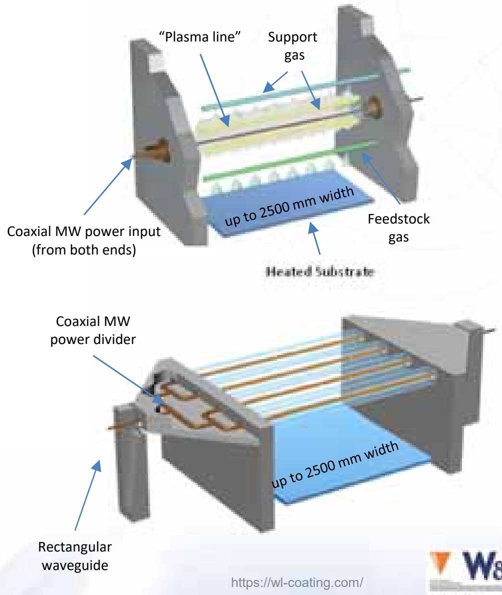

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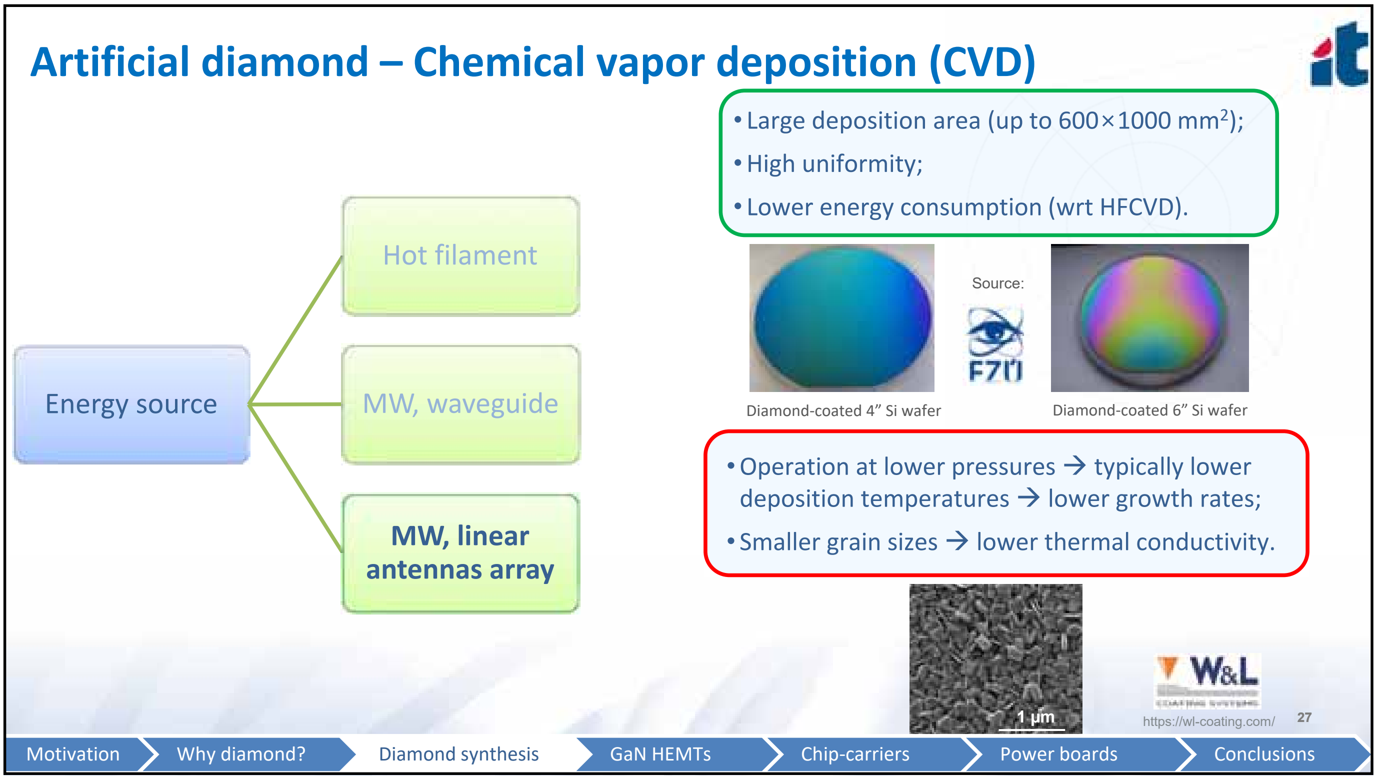


Artificial diamond – Chemical vapor deposition (CVD)

Energy source

- Hot filament
- MW, waveguide
- **MW, linear antennas array**

- Large deposition area (up to 600×1000 mm^2);
- High uniformity;
- Lower energy consumption (wrt HFCVD).

Diamond-coated 4” Si wafer

Source:

Diamond-coated 6” Si wafer

- Operation at lower pressures → typically lower deposition temperatures → lower growth rates;
- Smaller grain sizes → lower thermal conductivity.

https://wl-coating.com/

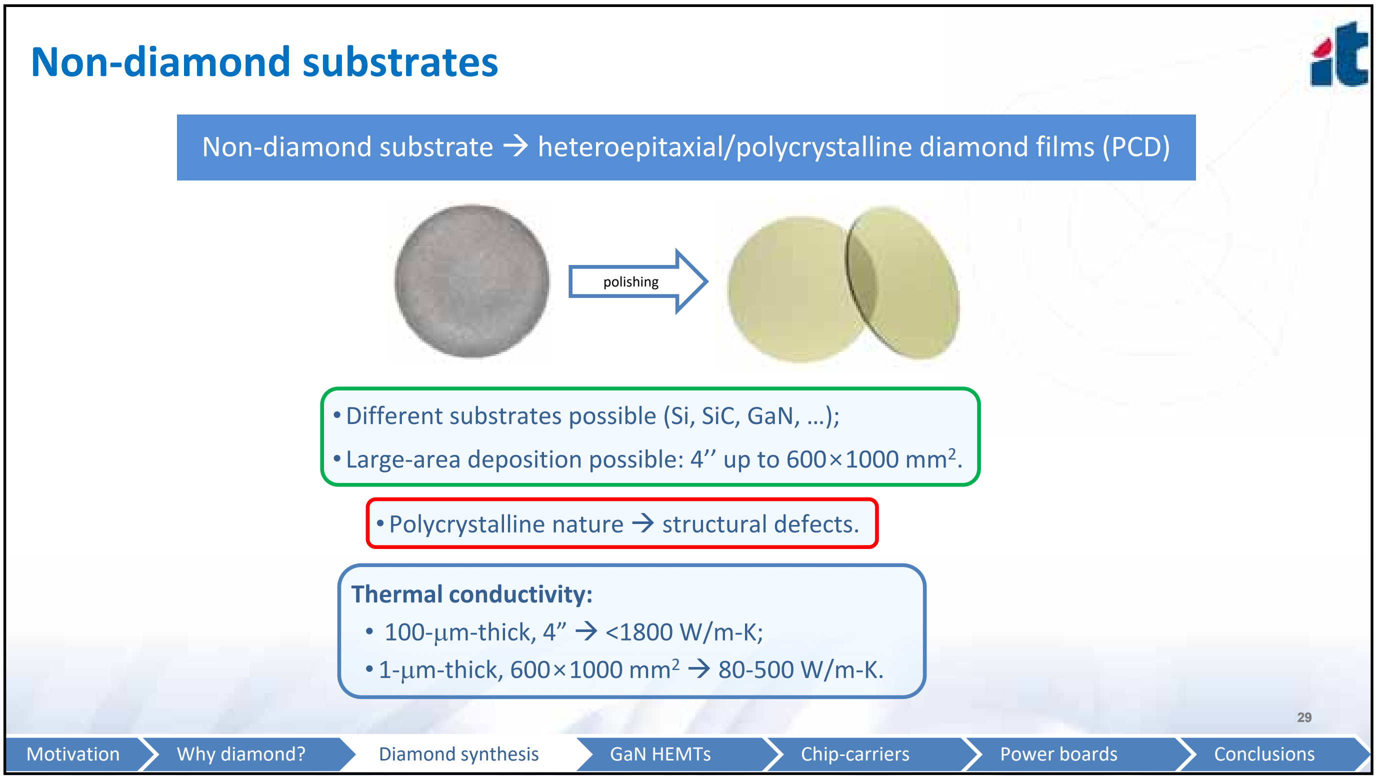
Single crystal diamond substrates

Single crystal diamond (SCD) substrate → homoepitaxial diamond films

- Films with highest thermal conductivity (2400 W/m-K);
- Ideal for electronic devices and thermal management applications.

- Most expensive films;
- Low area (between 2×2 mm^2 up to 10×10 mm^2).

https://www.diamond-materials.com/



Non-diamond substrates

Non-diamond substrate → heteroepitaxial/polycrystalline diamond films (PCD)

- Different substrates possible (Si, SiC, GaN, …);
- Large-area deposition possible: 4’’ up to 600×1000 mm^2.

- Polycrystalline nature → structural defects.

Thermal conductivity:
- 100-µm-thick, 4” → <1800 W/m-K;
- 1-µm-thick, 600×1000 mm^2 → 80-500 W/m-K.

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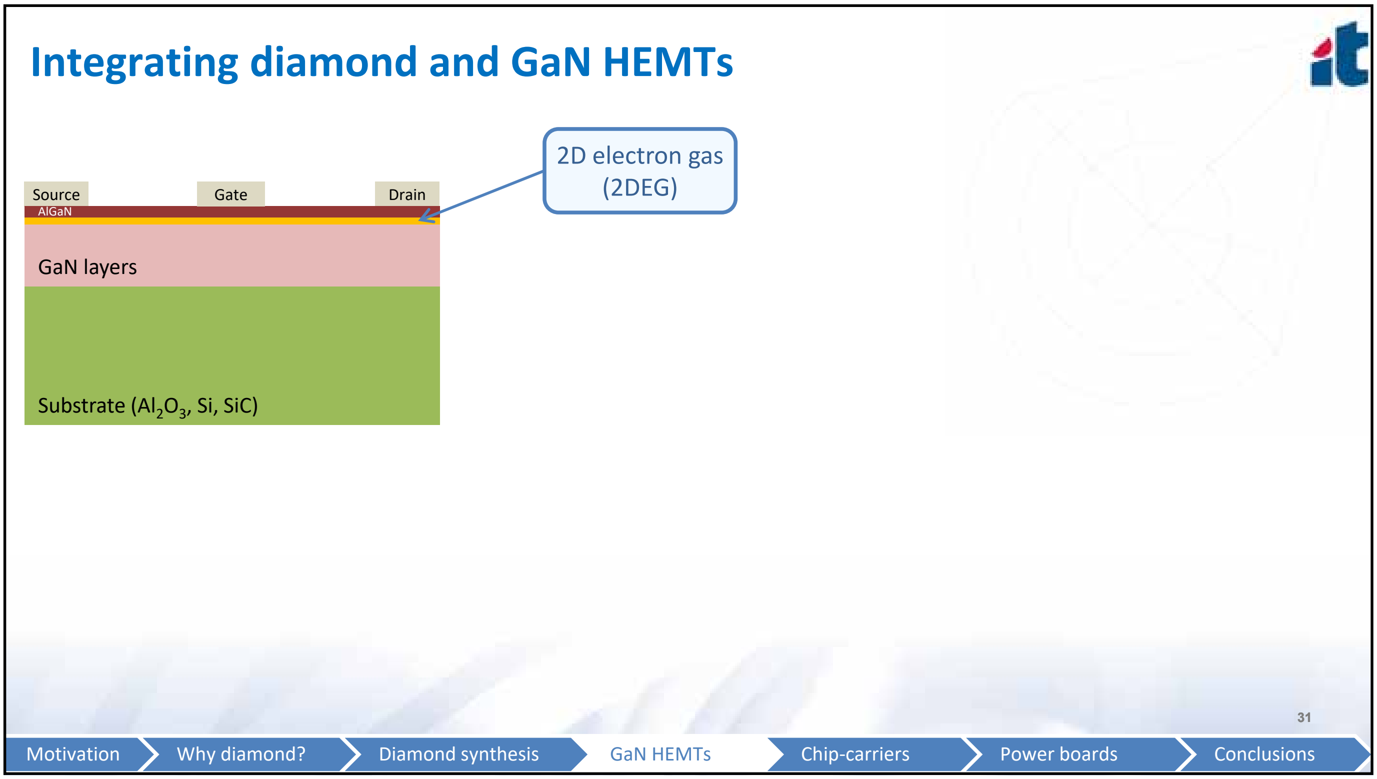

Integrating diamond and GaN HEMTs

2D electron gas (2DEG)

Source
Gate
Drain
AlGaN
GaN layers
Substrate (Al_2O_3, Si, SiC)

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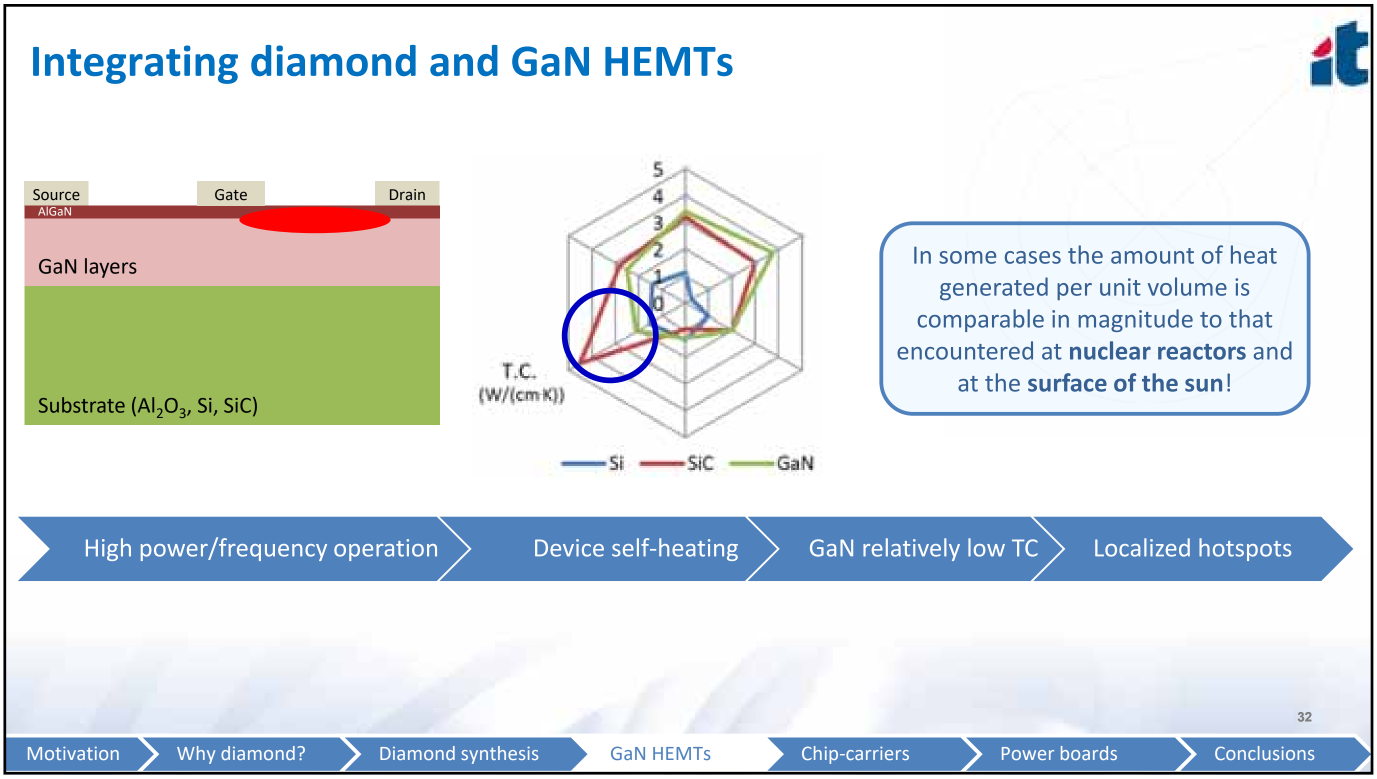
Motivation | Why diamond? | Diamond synthesis | GaN HEMTs | Chip-carriers | Power boards | Conclusions



Integrating diamond and GaN HEMTs

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In some cases the amount of heat generated per unit volume is comparable in magnitude to that encountered at **nuclear reactors** and at the **surface of the sun**!

High power/frequency operation → Device self-heating → GaN relatively low TC → Localized hotspots

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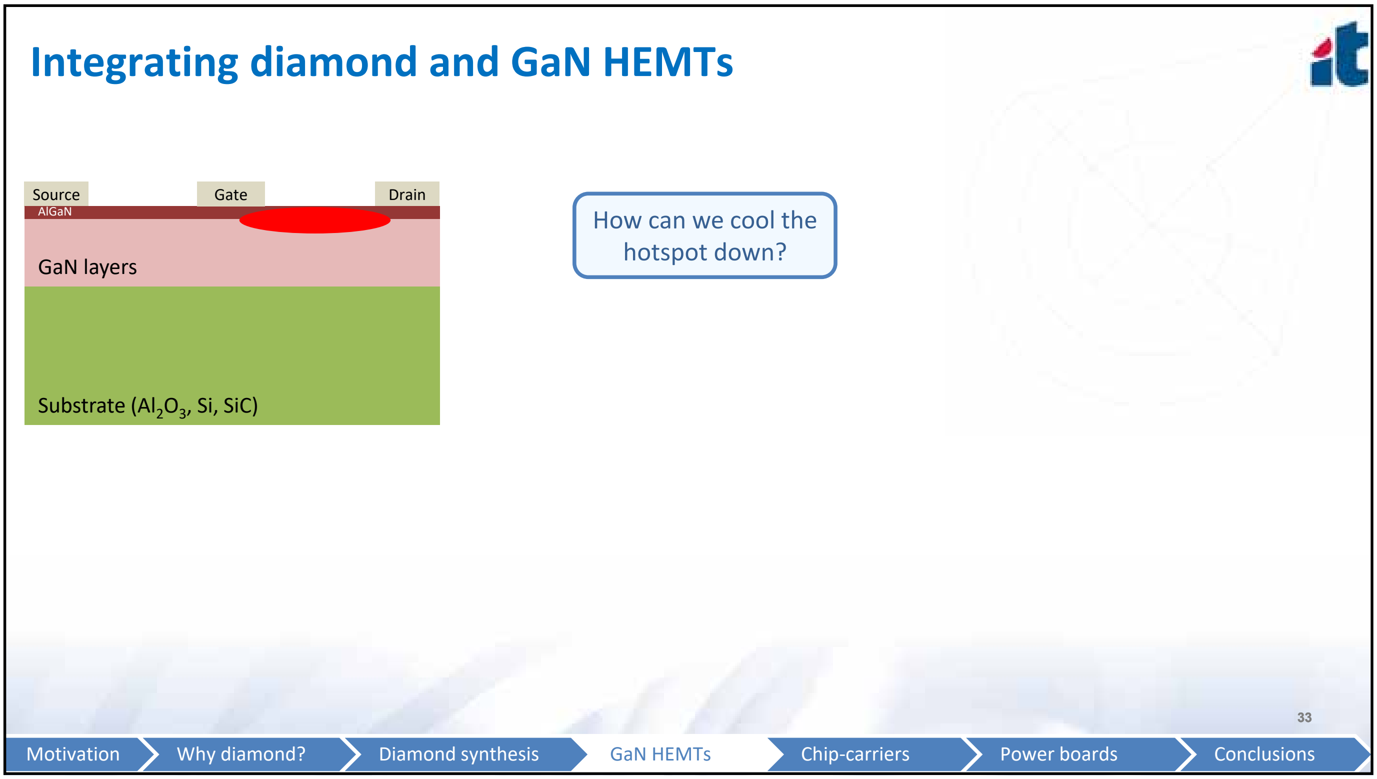
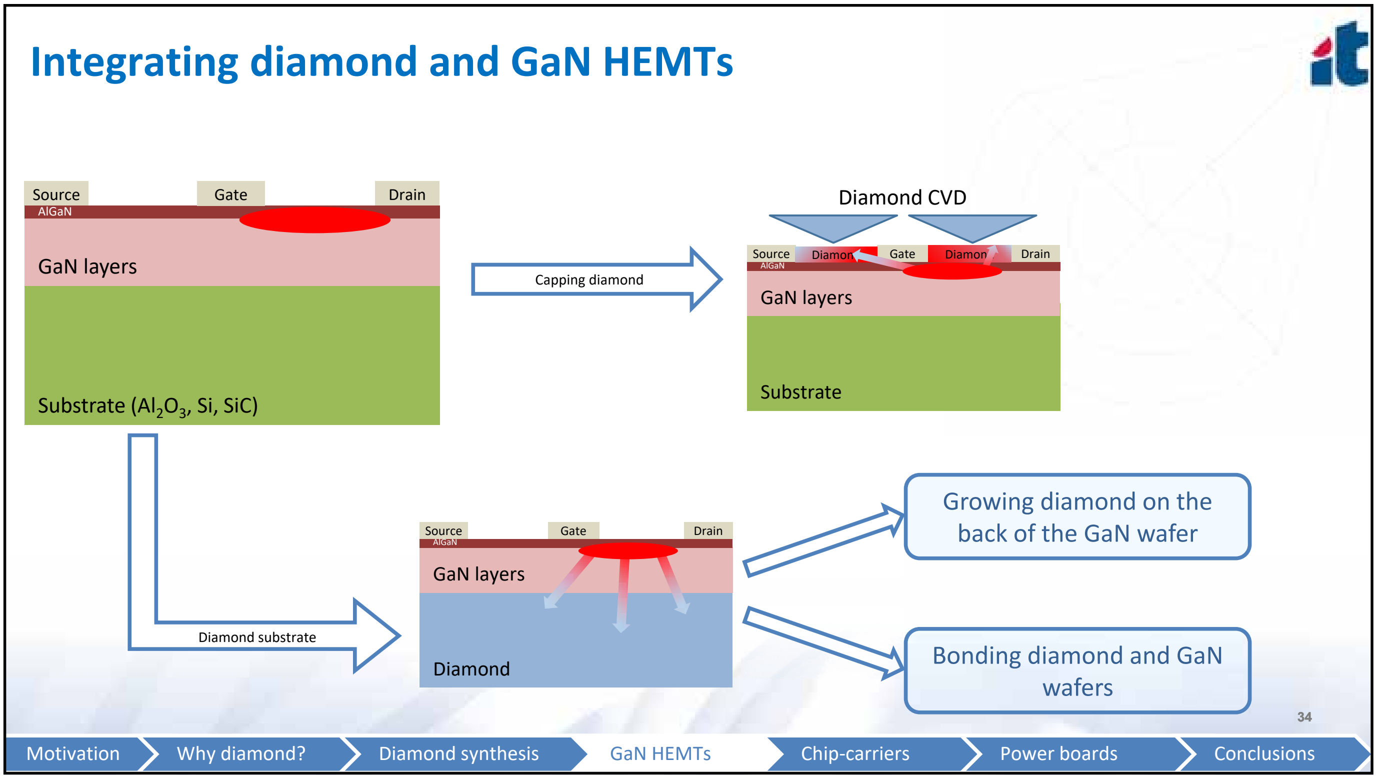


Integrating diamond and GaN HEMTs

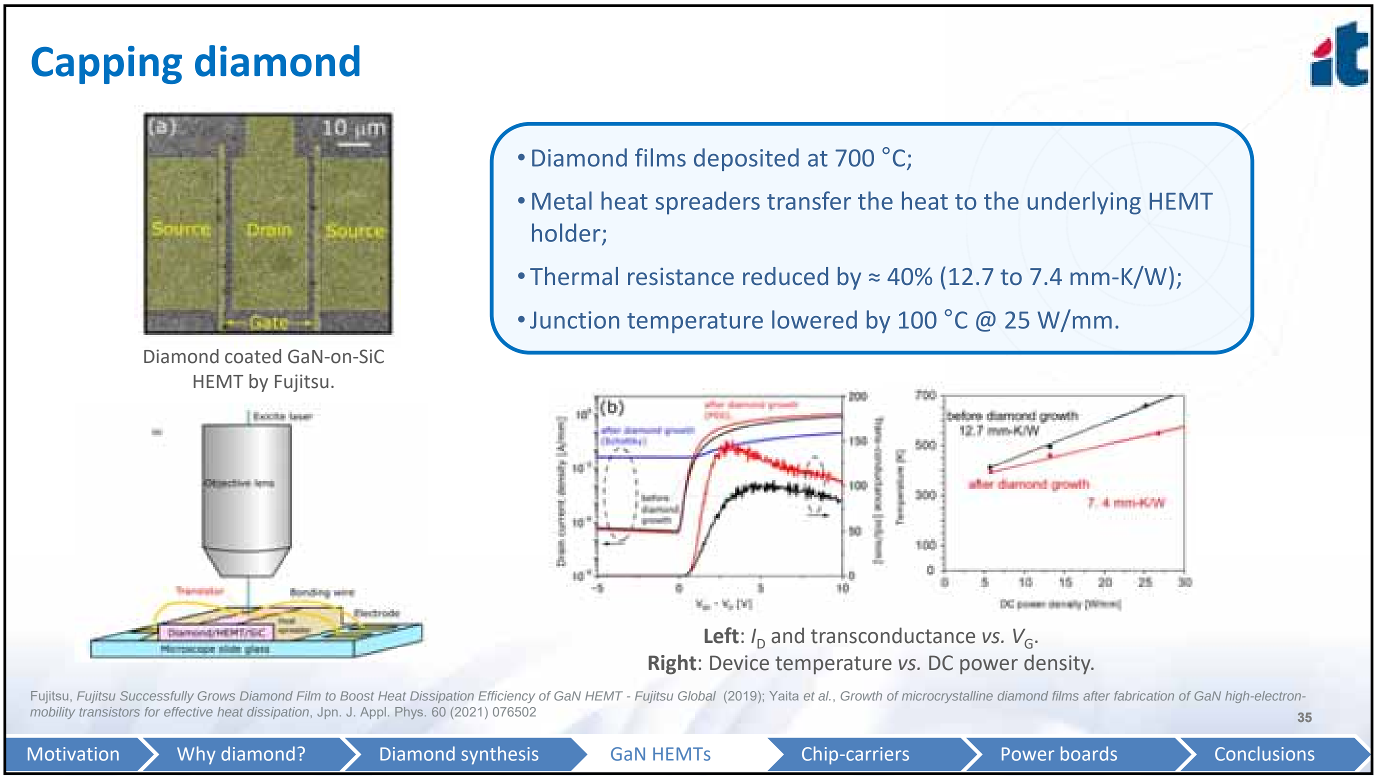
How can we cool the hotspot down?



Integrating diamond and GaN HEMTs

Growing diamond on the back of the GaN wafer

Bonding diamond and GaN wafers



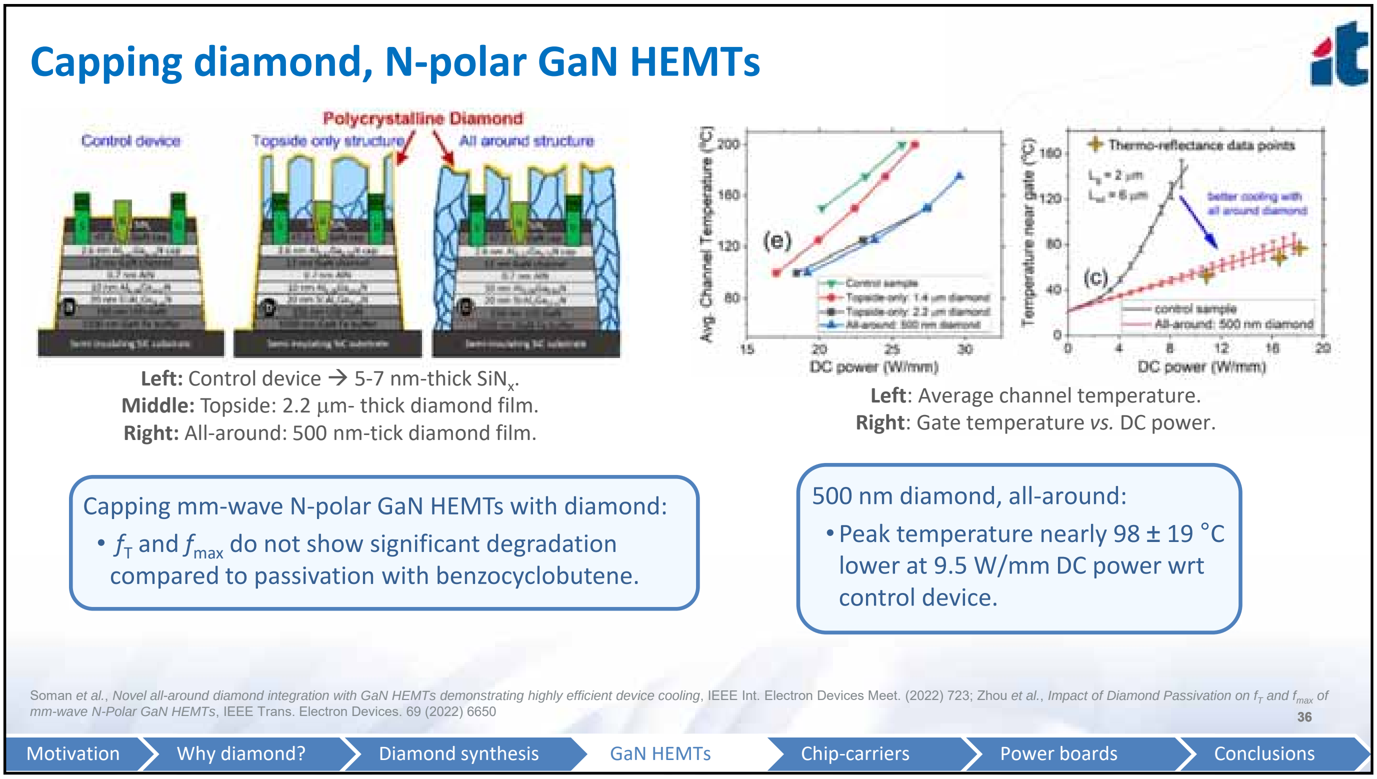
Capping diamond

Diamond coated GaN-on-SiC HEMT by Fujitsu.

- Diamond films deposited at 700 °C;
- Metal heat spreaders transfer the heat to the underlying HEMT holder;
- Thermal resistance reduced by ≈ 40% (12.7 to 7.4 mm-K/W);
- Junction temperature lowered by 100 °C @ 25 W/mm.

Left: I_D and transconductance *vs.* V_G.
Right: Device temperature *vs.* DC power density.

Fujitsu, *Fujitsu Successfully Grows Diamond Film to Boost Heat Dissipation Efficiency of GaN HEMT - Fujitsu Global* (2019); Yaita *et al.*, *Growth of microcrystalline diamond films after fabrication of GaN high-electron-mobility transistors for effective heat dissipation*, Jpn. J. Appl. Phys. 60 (2021) 076502



Capping diamond, N-polar GaN HEMTs

Left: Control device → 5-7 nm-thick SiN_x.
Middle: Topside: 2.2 μm- thick diamond film.
Right: All-around: 500 nm-tick diamond film.

Left: Average channel temperature.
Right: Gate temperature *vs.* DC power.

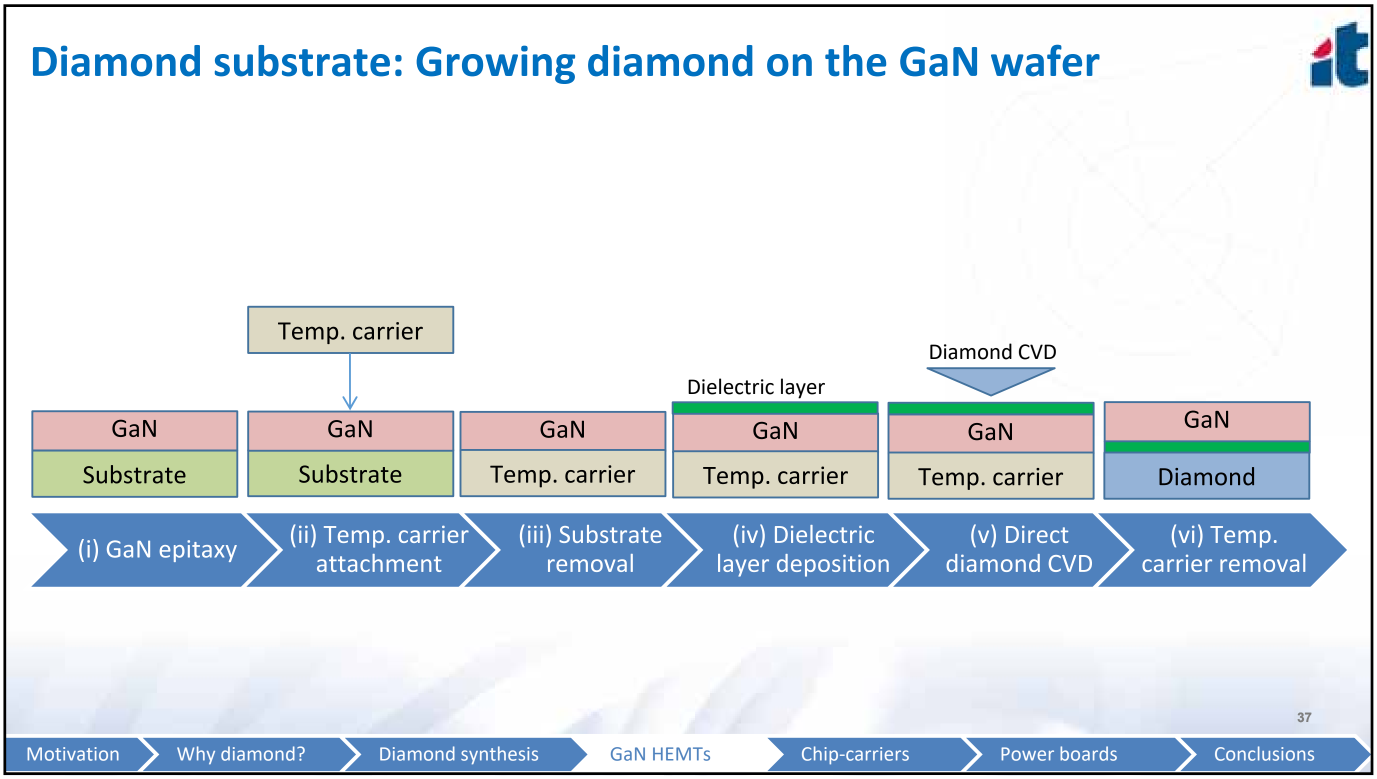
Capping mm-wave N-polar GaN HEMTs with diamond:

- f_T and f_{max} do not show significant degradation compared to passivation with benzocyclobutene.

500 nm diamond, all-around:

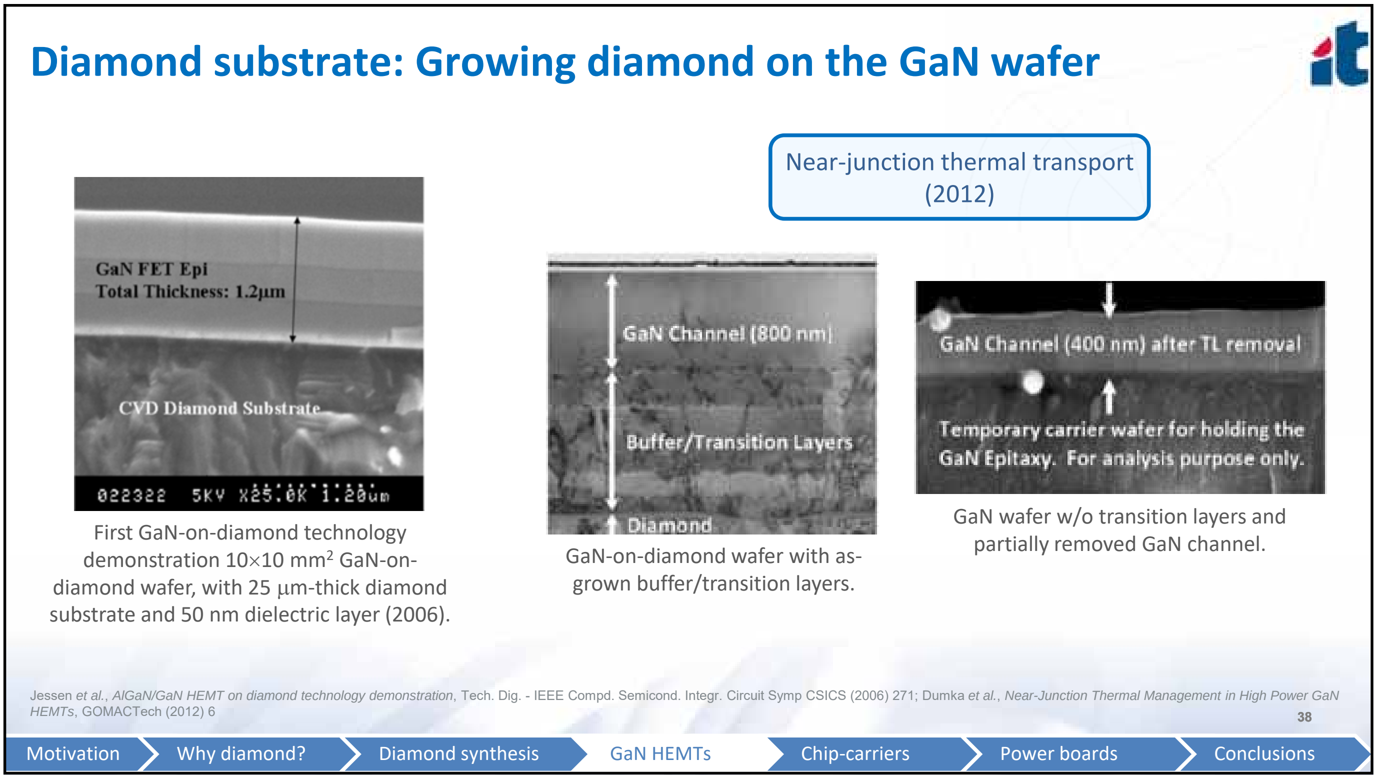
- Peak temperature nearly 98 ± 19 °C lower at 9.5 W/mm DC power wrt control device.

Soman *et al.*, *Novel all-around diamond integration with GaN HEMTs demonstrating highly efficient device cooling*, IEEE Int. Electron Devices Meet. (2022) 723; Zhou *et al.*, *Impact of Diamond Passivation on f_T and f_{max} of mm-wave N-Polar GaN HEMTs*, IEEE Trans. Electron Devices. 69 (2022) 6650



Diamond substrate: Growing diamond on the GaN wafer

- (i) GaN epitaxy
- (ii) Temp. carrier attachment
- (iii) Substrate removal
- (iv) Dielectric layer deposition
- (v) Direct diamond CVD
- (vi) Temp. carrier removal



Diamond substrate: Growing diamond on the GaN wafer

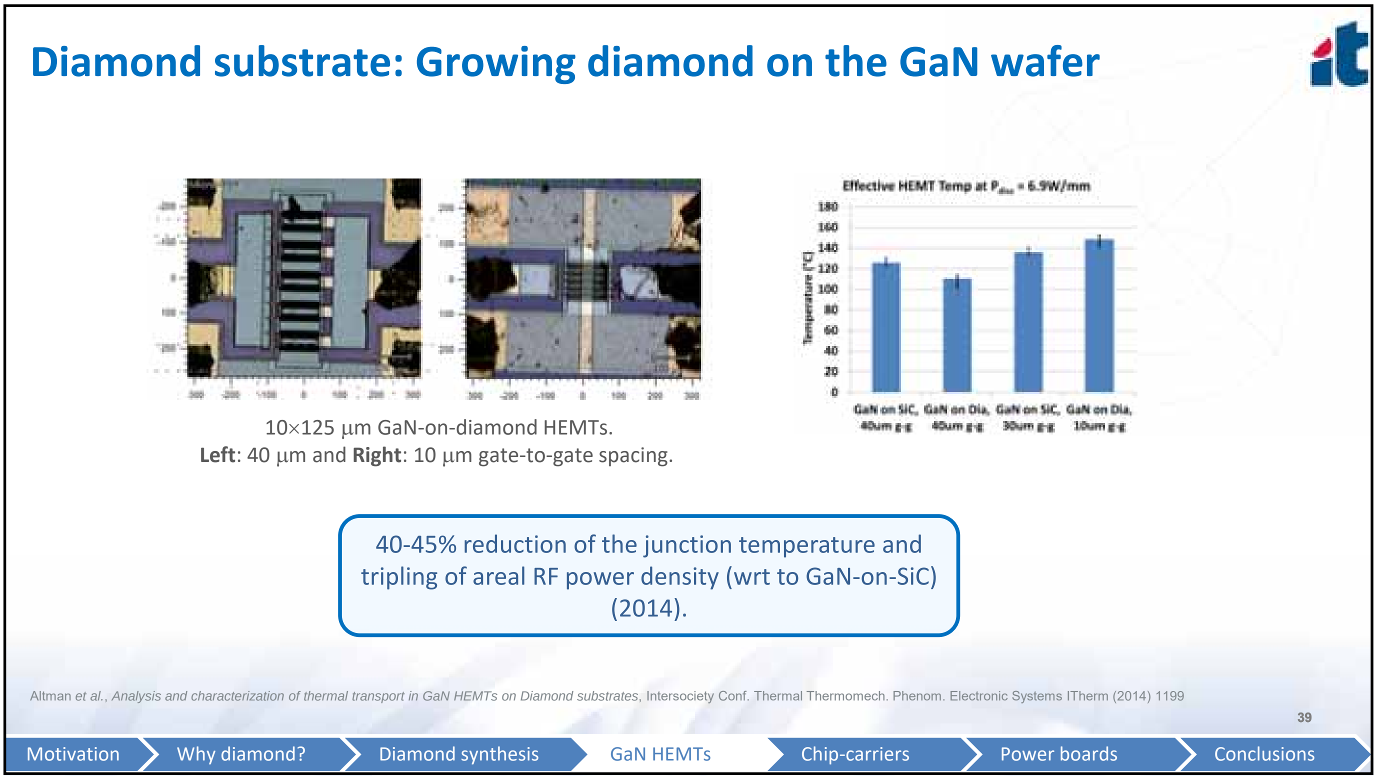
Near-junction thermal transport (2012)

First GaN-on-diamond technology demonstration 10×10 mm^2 GaN-on-diamond wafer, with 25 µm-thick diamond substrate and 50 nm dielectric layer (2006).

GaN-on-diamond wafer with as-grown buffer/transition layers.

GaN wafer w/o transition layers and partially removed GaN channel.

Jessen *et al.*, *AlGaN/GaN HEMT on diamond technology demonstration*, Tech. Dig. - IEEE Compd. Semicond. Integr. Circuit Symp CSICS (2006) 271; Dumka *et al.*, *Near-Junction Thermal Management in High Power GaN HEMTs*, GOMACTech (2012) 6

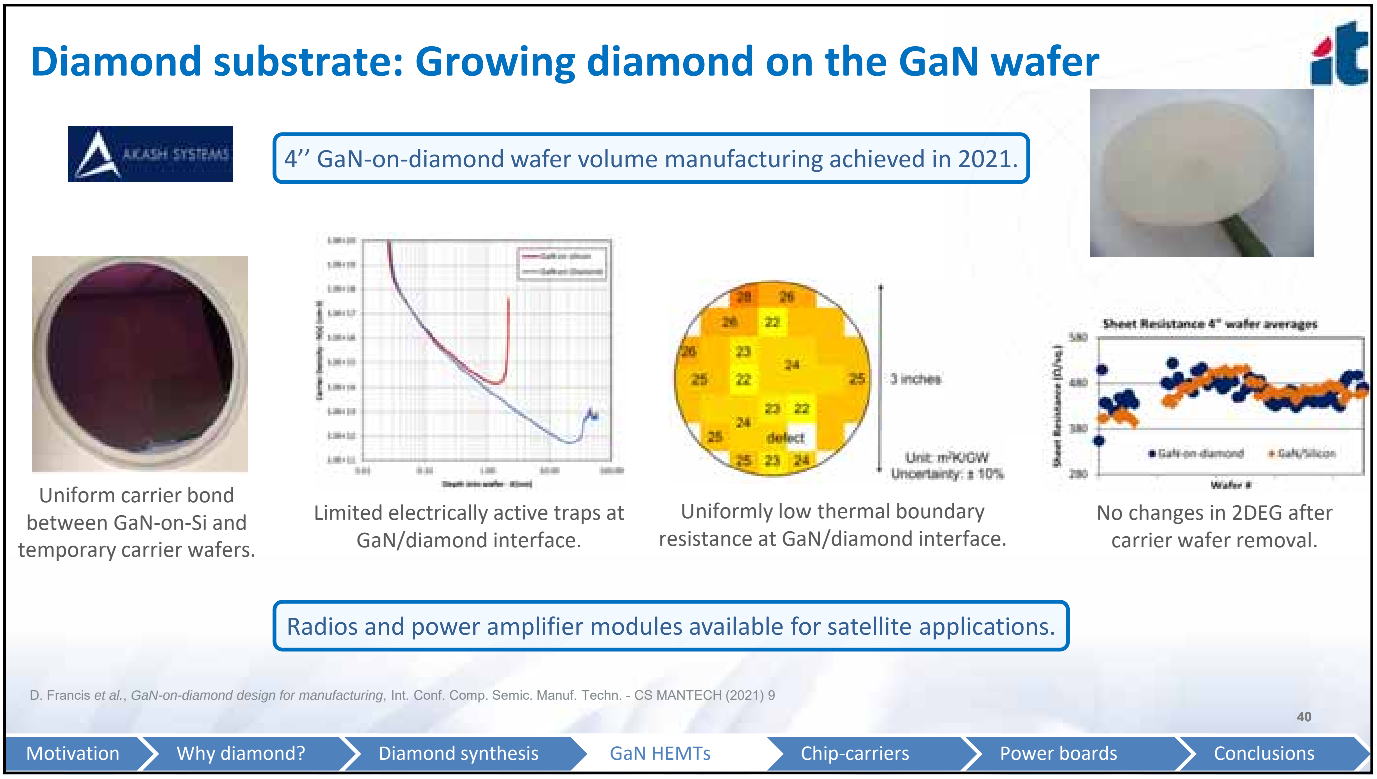


Diamond substrate: Growing diamond on the GaN wafer

10×125 μm GaN-on-diamond HEMTs.
Left: 40 μm and **Right**: 10 μm gate-to-gate spacing.

40-45% reduction of the junction temperature and tripling of areal RF power density (wrt to GaN-on-SiC) (2014).

Altman *et al.*, *Analysis and characterization of thermal transport in GaN HEMTs on Diamond substrates*, Intersociety Conf. Thermal Thermomech. Phenom. Electronic Systems ITherm (2014) 1199



Diamond substrate: Growing diamond on the GaN wafer

4’’ GaN-on-diamond wafer volume manufacturing achieved in 2021.

Uniform carrier bond between GaN-on-Si and temporary carrier wafers.

Limited electrically active traps at GaN/diamond interface.

Uniformly low thermal boundary resistance at GaN/diamond interface.

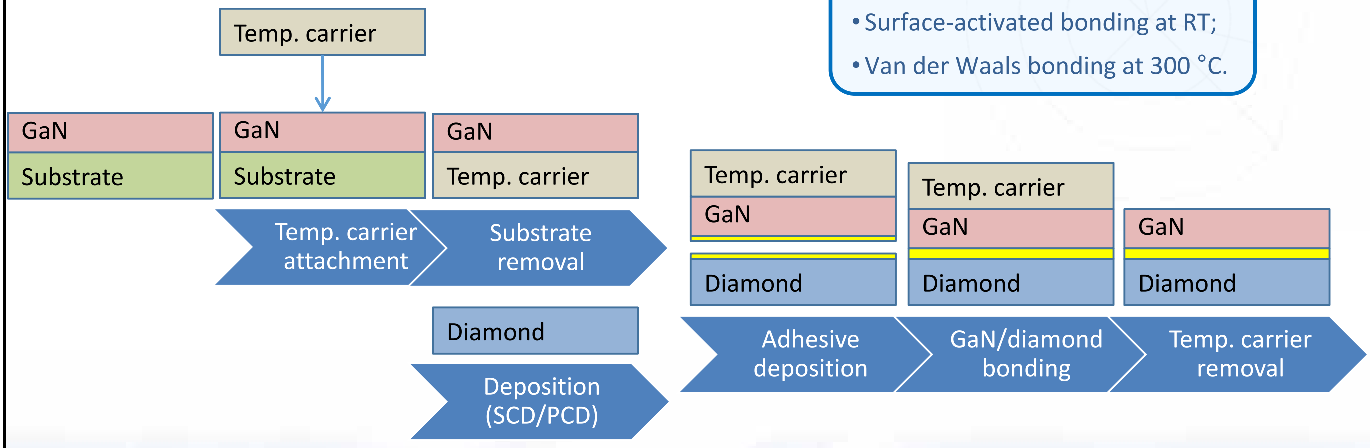
No changes in 2DEG after carrier wafer removal.

Radios and power amplifier modules available for satellite applications.

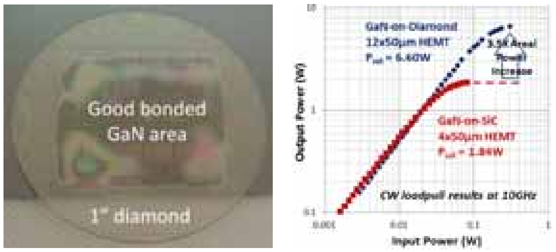
D. Francis *et al.*, *GaN-on-diamond design for manufacturing*, Int. Conf. Comp. Semic. Manuf. Techn. - CS MANTECH (2021) 9

Diamond substrate: GaN/diamond wafer bonding

- Adhesive layer, 150-200 °C;
- Surface-activated bonding at RT;
- Van der Waals bonding at 300 °C.

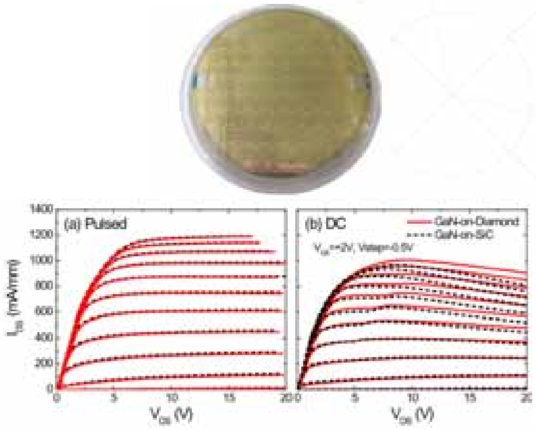


Diamond substrate: Thermocompression using adhesive layer



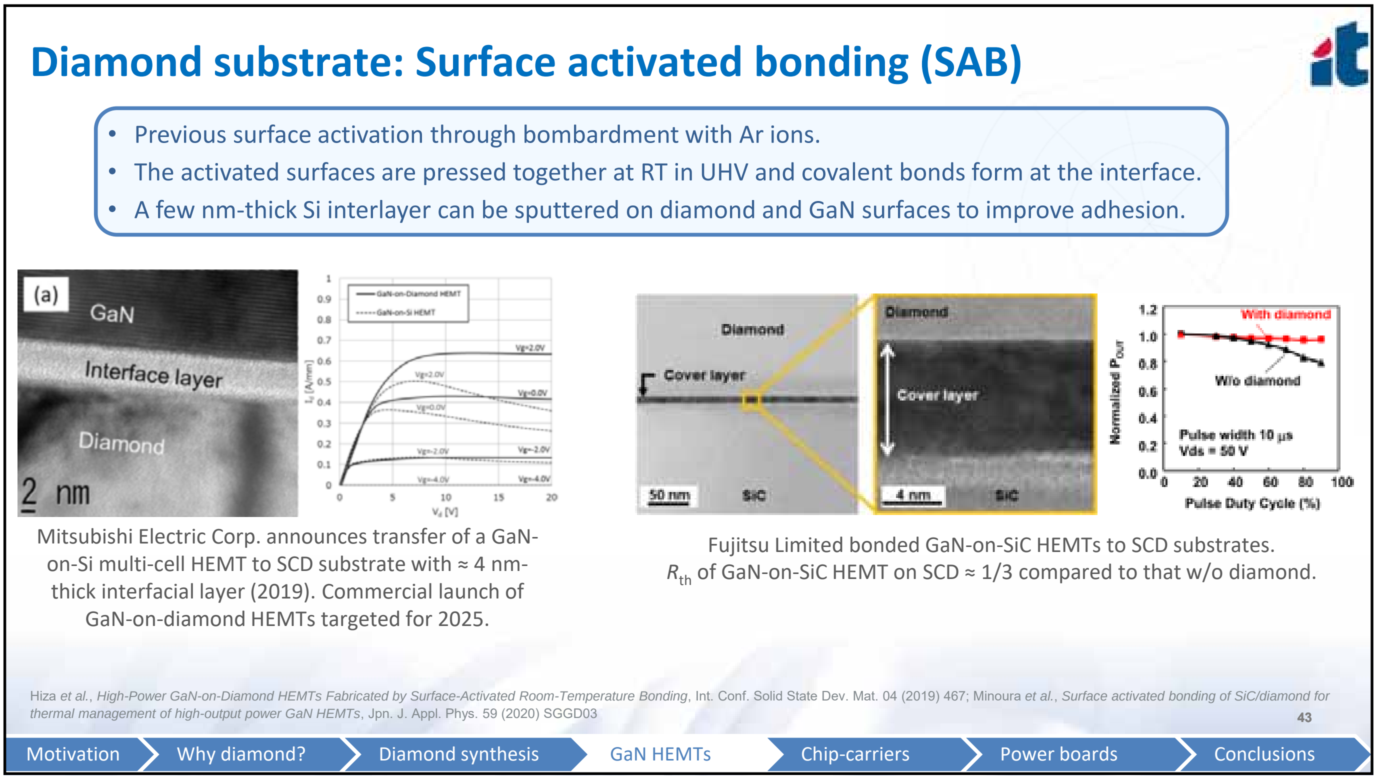
Left: GaN HEMTs bonded to 1'' PCD substrate.

Right: CW load-pull measurements: 3.5× areal power increase wrt GaN-on-SiC.



Top: 3" GaN-on-diamond wafer; functional device yield over 80%.
Bottom: Reduced self-heating of GaN-on-diamond wrt GaN-on-SiC.

Chu *et al.*, *S2-T4: Low-temperature substrate bonding technology for high power GaN-on-diamond HEMTs*. Proc. Lester Eastman Conf.– LEC (2014) 1; Chu *et al.*, *High-Performance GaN-on-Diamond HEMTs Fabricated by Low-Temperature Device Transfer Process*, IEEE Comp. Sem. Int. Circ. Symp. CSICS (2015) 7; Liu *et al.*, *3-inch GaN-on-Diamond HEMTs with Device-First Transfer Technology*, IEEE Electron Device Lett. 38 (2017) 1417



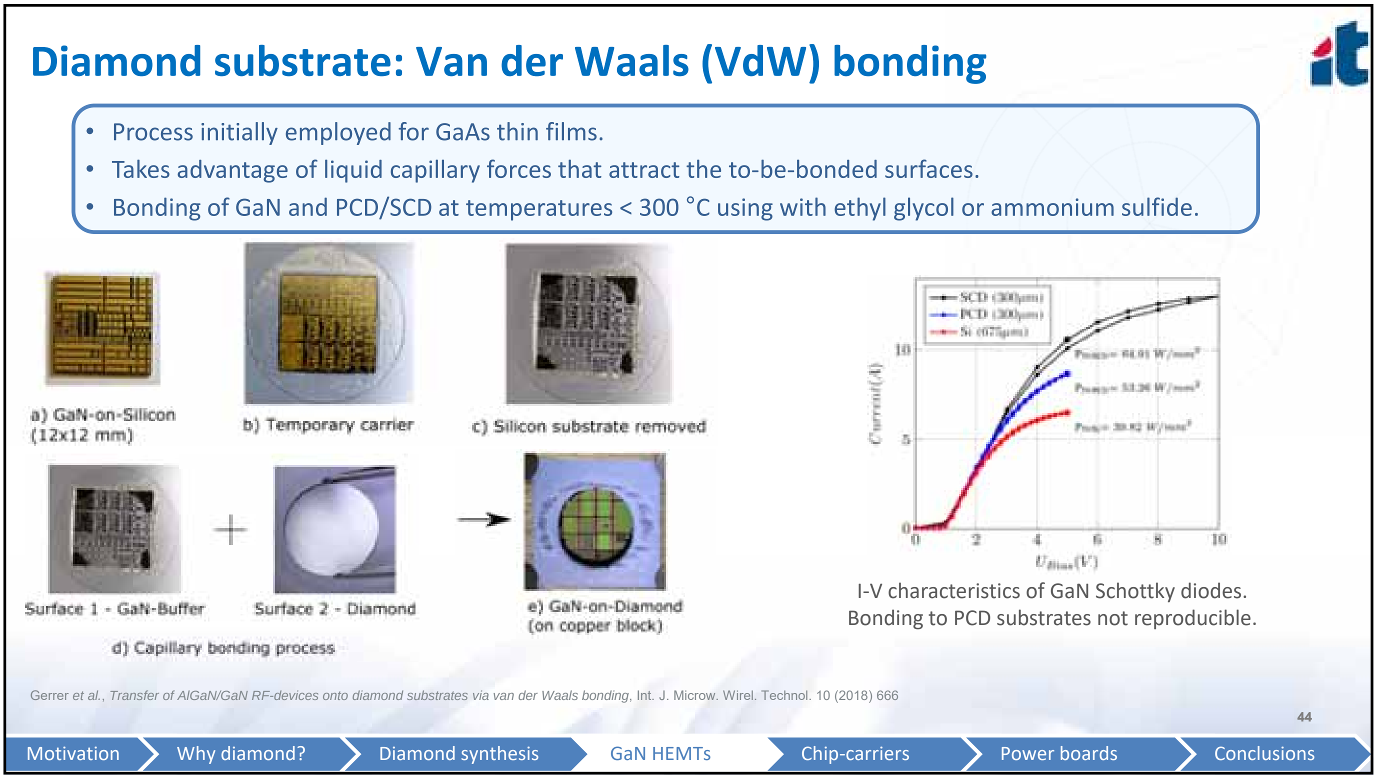
Diamond substrate: Surface activated bonding (SAB)

- Previous surface activation through bombardment with Ar ions.
- The activated surfaces are pressed together at RT in UHV and covalent bonds form at the interface.
- A few nm-thick Si interlayer can be sputtered on diamond and GaN surfaces to improve adhesion.

Mitsubishi Electric Corp. announces transfer of a GaN-on-Si multi-cell HEMT to SCD substrate with ≈ 4 nm-thick interfacial layer (2019). Commercial launch of GaN-on-diamond HEMTs targeted for 2025.

Fujitsu Limited bonded GaN-on-SiC HEMTs to SCD substrates.
R_{th} of GaN-on-SiC HEMT on SCD ≈ 1/3 compared to that w/o diamond.

Hiza *et al.*, *High-Power GaN-on-Diamond HEMTs Fabricated by Surface-Activated Room-Temperature Bonding*, Int. Conf. Solid State Dev. Mat. 04 (2019) 467; Minoura *et al.*, *Surface activated bonding of SiC/diamond for thermal management of high-output power GaN HEMTs*, Jpn. J. Appl. Phys. 59 (2020) SGGD03



Diamond substrate: Van der Waals (VdW) bonding

- Process initially employed for GaAs thin films.
- Takes advantage of liquid capillary forces that attract the to-be-bonded surfaces.
- Bonding of GaN and PCD/SCD at temperatures < 300 °C using with ethyl glycol or ammonium sulfide.

I-V characteristics of GaN Schottky diodes.
Bonding to PCD substrates not reproducible.

Gerrer *et al.*, *Transfer of AlGaN/GaN RF-devices onto diamond substrates via van der Waals bonding*, Int. J. Microw. Wirel. Technol. 10 (2018) 666

Diamond as chip-carrier

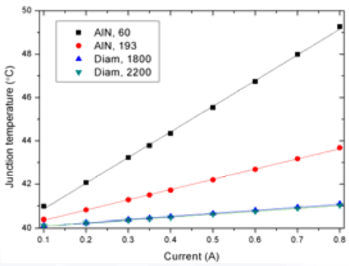
Diamond as chip-carrier of power LEDs

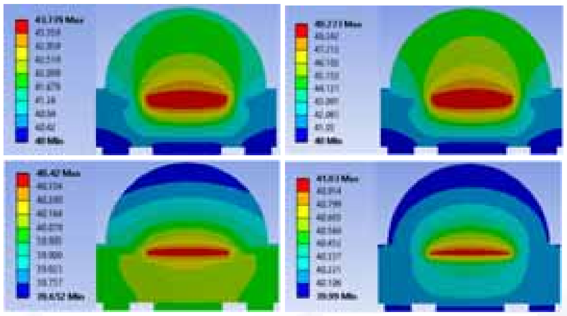
Impact on device characteristics

Cree® white Xlamp® XB-D LEDs
2.45×2.45 mm^2 foot print

AlN (60-193 W/m-K)
SCD (2200 W/m-K)
PCD (1800 W/m-K)

+ Ansys





350 mA, (top) AlN, (bottom) diamond

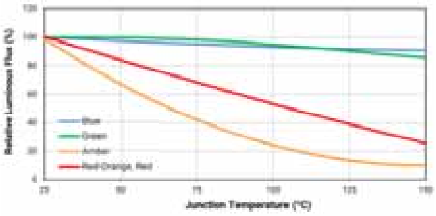
800 mA, (top) AlN, (bottom) diamond

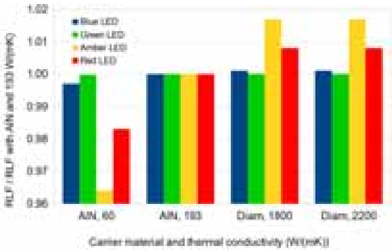
SCD and PCD carriers have the same impact on the junction temperature.

Kyatam *et al.*, *Impact of Die Carrier on Reliability of Power LEDs*, J. Elect. Dev. Soc. 9 (2021) 854

Diamond carriers for high power LED dice

Luminous flux



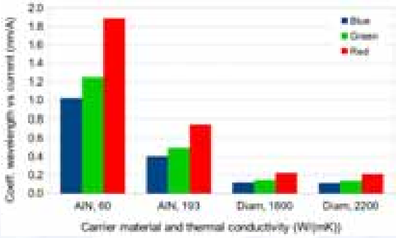


Replacing AlN with diamond has no meaningful impact on the luminous flux.

Stability of wavelength with level of current

$$\nu = E_g/h \qquad \lambda = \frac{c \cdot h}{E_g}$$

$$E_g(T) = E_g(0) - \frac{\alpha \cdot T^2}{T + \beta}$$



Diamond decreases the dependence of the wavelength on the current level.

Kyatam *et al.*, *Impact of Die Carrier on Reliability of Power LEDs*, J. Elect. Dev. Soc. 9 (2021) 854

Motivation | Why diamond? | Diamond synthesis | GaN HEMTs | Chip-carriers | Power boards | Conclusions

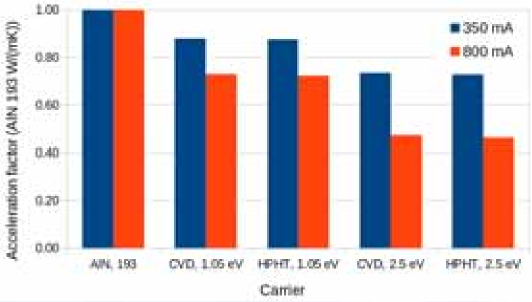
Diamond carriers for high power LED dice

Acceleration factor / lifetime

$$TTF = I_0 \cdot J^{-n} \cdot \exp\left(\frac{q \cdot E_a}{k_B \cdot T}\right)$$

$$AF_{\mathrm{AlN}} = \frac{TTF_{\mathrm{AlN}}}{TTF_{\mathrm{car}}} = \exp\left[\frac{q \cdot E_a}{k_B} \cdot \left(\frac{1}{T_{\mathrm{J,AlN}}} - \frac{1}{T_{\mathrm{J,car}}}\right)\right]$$

1.05 eV < E_a < 2.5 eV



AlN 193 W/m-K

E_a = 1.05 eV: diamond slows the aging of the LED by ≈**10%** (@350 mA) and ≈**30%** (@800 mA);

E_a = 2.5 eV: Diamond slows the aging of the LED by ≈**25%** (@350 mA) and ≈**50%** (@800 mA).

Kyatam *et al.*, *Impact of Die Carrier on Reliability of Power LEDs*, J. Elect. Dev. Soc. 9 (2021) 854

Motivation | Why diamond? | Diamond synthesis | GaN HEMTs | Chip-carriers | Power boards | Conclusions

Diamond carriers for high power LED dice

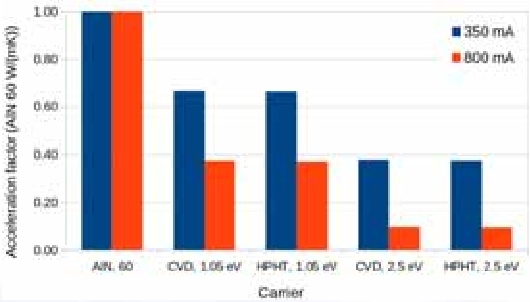
Acceleration factor / lifetime

$$TTF = I_0 \cdot J^{-n} \cdot \exp\left(\frac{q \cdot E_a}{k_B \cdot T}\right)$$

$$AF_{\mathrm{AlN}} = \frac{TTF_{\mathrm{AlN}}}{TTF_{\mathrm{car}}} = \exp\left[\frac{q \cdot E_a}{k_B} \cdot \left(\frac{1}{T_{J,\mathrm{AlN}}} - \frac{1}{T_{J,\mathrm{car}}}\right)\right]$$

1.05 eV < E_a < 2.5 eV

Simulations considered a perfect contact between chip and carrier.



AlN 60 W/m-K

E_a = 1.05 eV:	diamond slows the aging of the LED by **≈35%** (@350 mA) and **≈60%** (@800 mA);
E_a = 2.5 eV:	Diamond slows the aging of the LED by **≈60%** (@350 mA) and **≈90%** (@800 mA).

Kyatam *et al.*, *Impact of Die Carrier on Reliability of Power LEDs*, J. Elect. Dev. Soc. 9 (2021) 854

Diamond as power board

Diamond as power board

Cree® white Xlamp® XB-D LEDs
2.45×2.45 mm² foot print

10×10 mm² boards

Board	Layer (top to bottom)	Thickness (μm)	Thermal conductivity (W/m-K)
MCPCB	Cu metallization	70	400
	Dielectric	100	2.2
	Al core	1588	150
Diamond	Ti/W/Au metallization	1 (Au)	318
	Diamond	300	1800

Datasheet
Stock No: 186-3600

ENGLISH

RS Pro Bottle of Silver Conductive Adhesive Paint

Product Details:

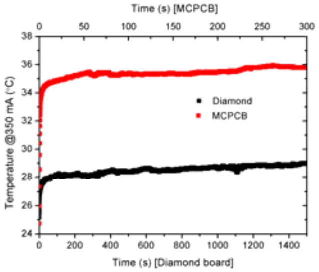
Key Features

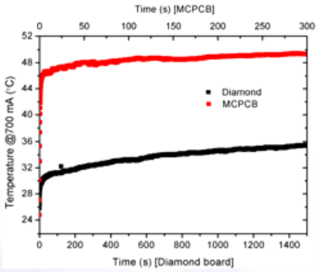
LEDs were mounted on the MCPCB using lead-free solder and on the diamond board using silver conductive paint.

Kyatam *et al.*, *Impact of board on the reliability of power LEDs*, Diam. Rel. Mater. 127 (2022) 109144

Diamond as power board

Case temperature

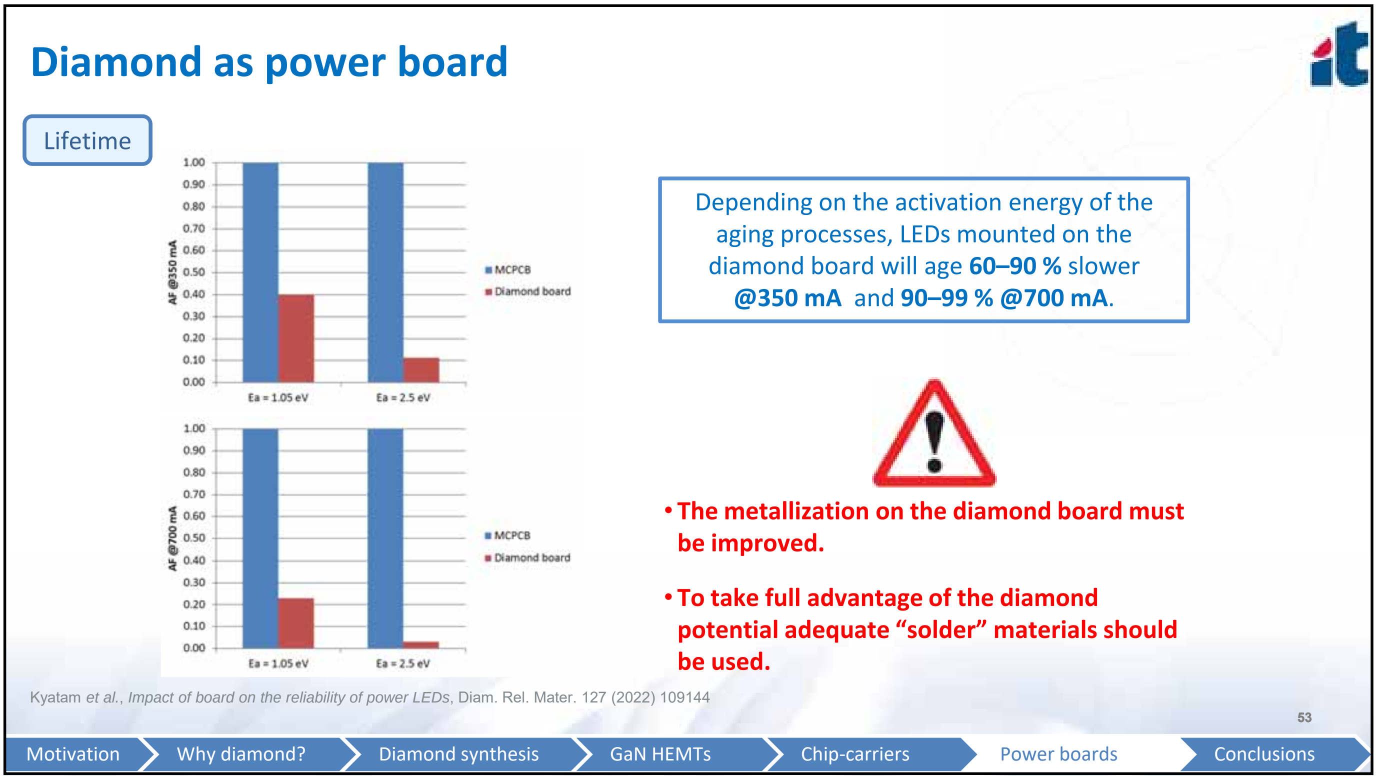




350 mA	MCPCB	Diamond	Temp. diff. (°C)
Case temperature (°C)	36.5	29.3	7.2
Junction temperature (°C)	41.8	34.5	7.3

700 mA	MCPCB	Diamond	Temp. diff. (°C)
Case temperature (°C)	49.3	36.1	13.2
Junction temperature (°C)	60.4	47.4	13

Kyatam *et al.*, *Impact of board on the reliability of power LEDs*, Diam. Rel. Mater. 127 (2022) 109144



Diamond as power board

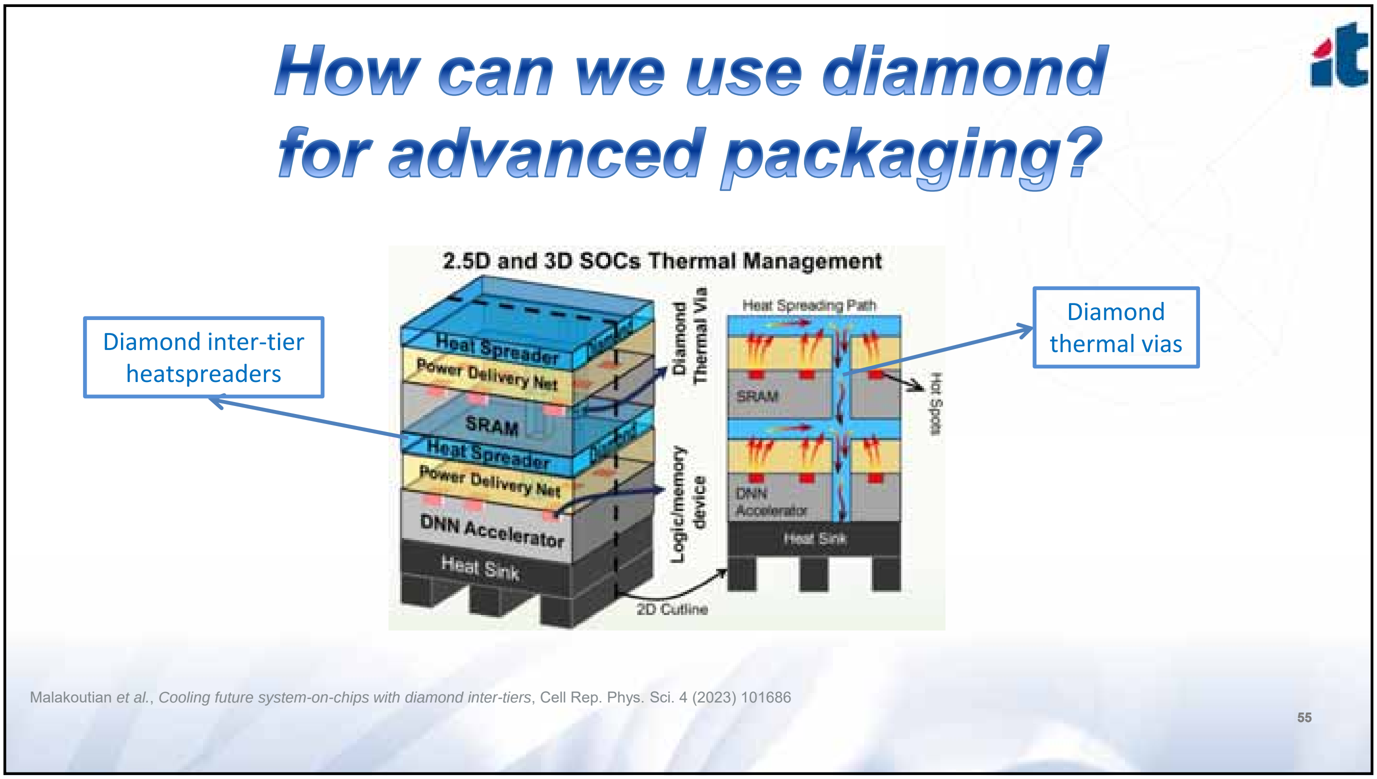
Depending on the activation energy of the aging processes, LEDs mounted on the diamond board will age **60–90 %** slower **@350 mA** and **90–99 % @700 mA**.

- **The metallization on the diamond board must be improved.**
- **To take full advantage of the diamond potential adequate “solder” materials should be used.**

Kyatam *et al.*, *Impact of board on the reliability of power LEDs*, Diam. Rel. Mater. 127 (2022) 109144

Conclusions

- Diamond has been successfully used to improve the thermal management of different devices.
- **GaN HEMTs:**
  - Diamond-capping of passivated HEMTs;
  - Direct growth of diamond on the back of GaN wafers;
  - Bonding of GaN wafers/HEMTs and diamond substrates;
  - Commercial GaN-on-diamond-based RF power amplifiers available for satellite communications;
  - Companies such as Mitsubishi Electric Corp. and Fujitsu Limited involved in research.
- **Diamond as chip-carrier:**
  - Similar impact of PCD and SCD carriers on LED characteristics;
  - Improves the stability of the wavelength with the current;
  - Increases LED lifetime significantly.
- **Diamond as power board:**
  - Increases LED lifetime considerably when compared to standard MCPCBs.
- Results can be extrapolated to other devices.

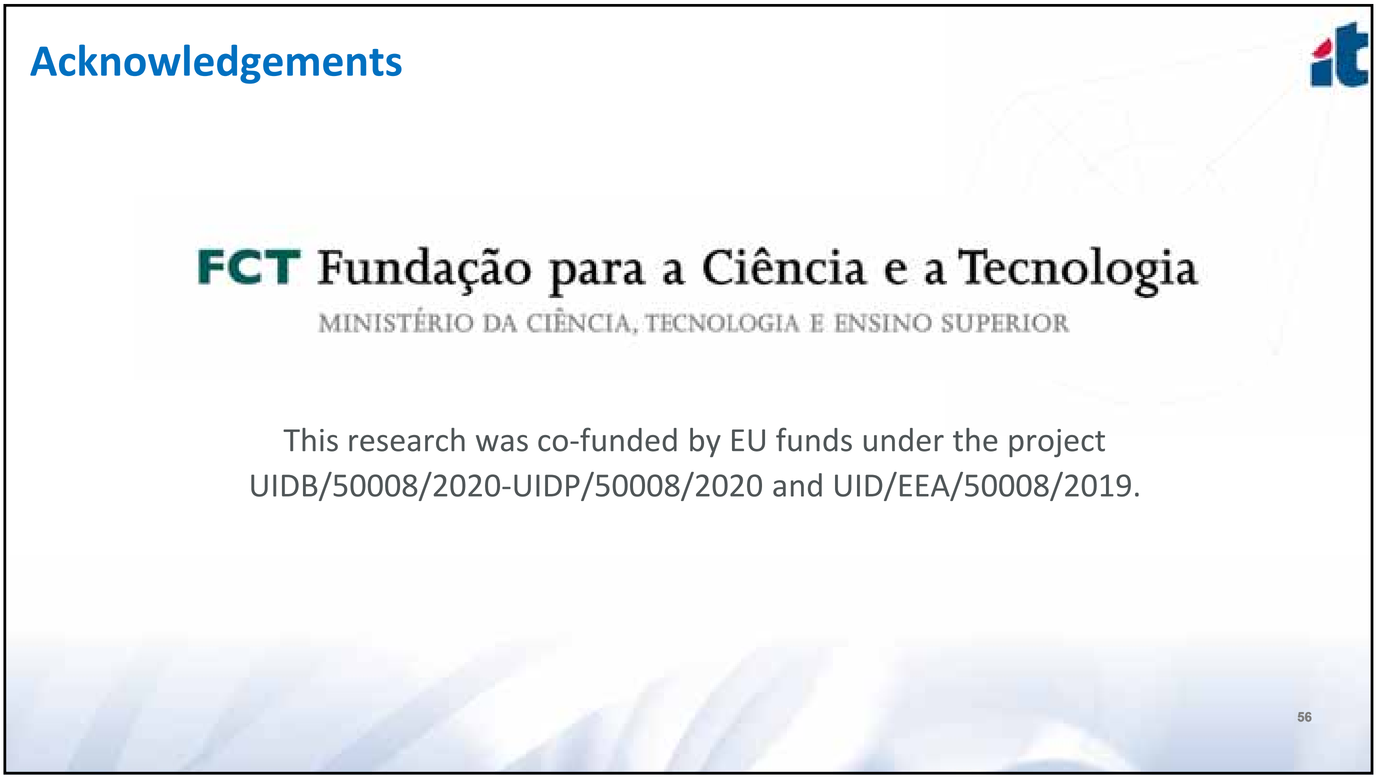


How can we use diamond for advanced packaging?

Diamond inter-tier heatspreaders

Diamond thermal vias

Malakoutian *et al.*, *Cooling future system-on-chips with diamond inter-tiers*, Cell Rep. Phys. Sci. 4 (2023) 101686



Acknowledgements

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Thank you for your attention!

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