Cold Sprayed Copper-Diamond Composites for Thermal Management of Semiconductor Packages

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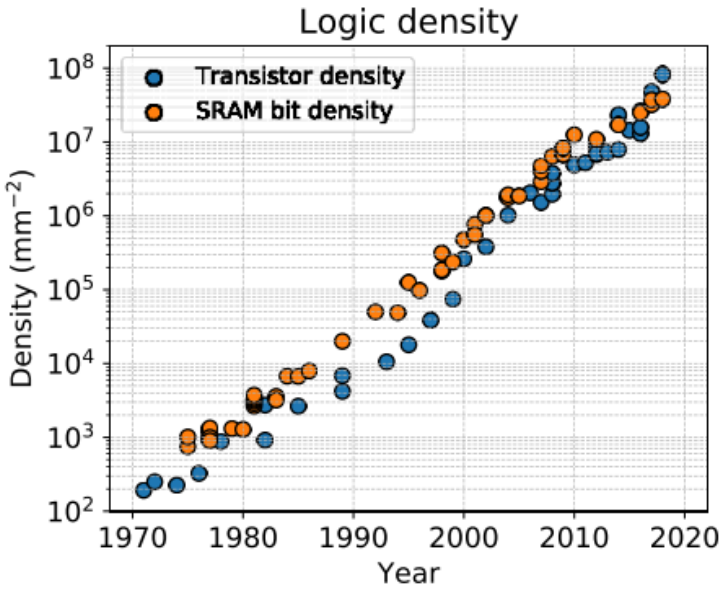
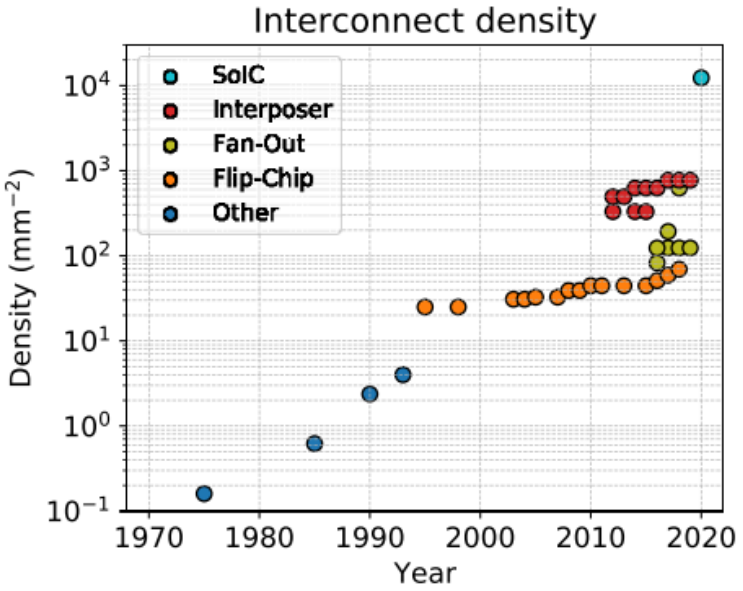
Outline

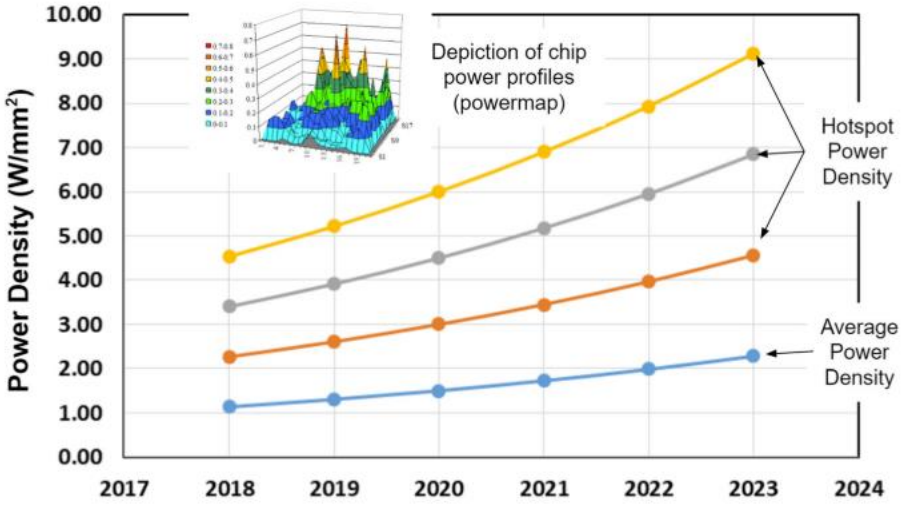
- Package thermal challenges and new solutions
- Diamond-Copper composite deposition
  - Cold spray technology overview
  - Material requirement
  - Composite thermal performance
  - Perspectives for new diamond development
- Conclusions

Increasingly powerful chips and thermal challenges





Proc. IEEE, 2020, vol.108, pp. 478-482

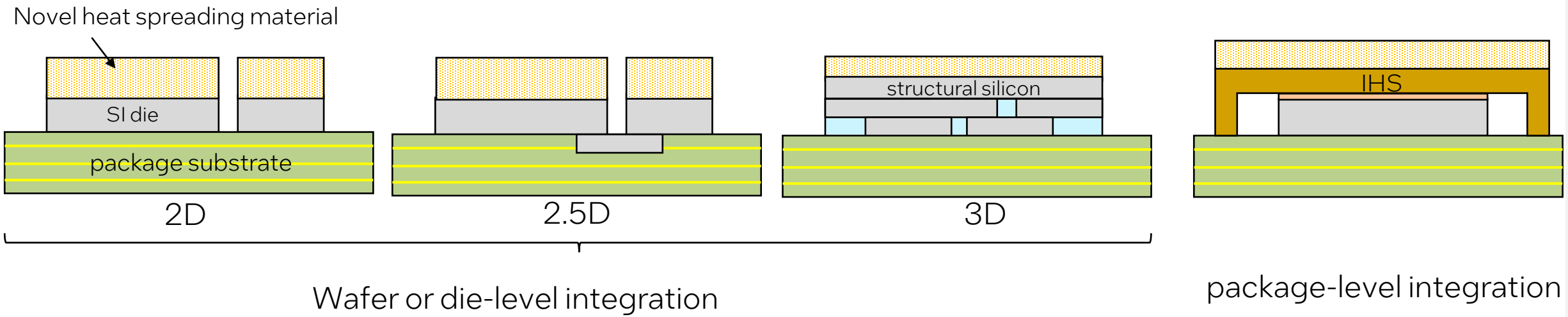


Heterogeneous Integration Roadmap 2023

- Thermal technologies should envelop the increasing thermal demand, i.e., higher TDP and hotspots.

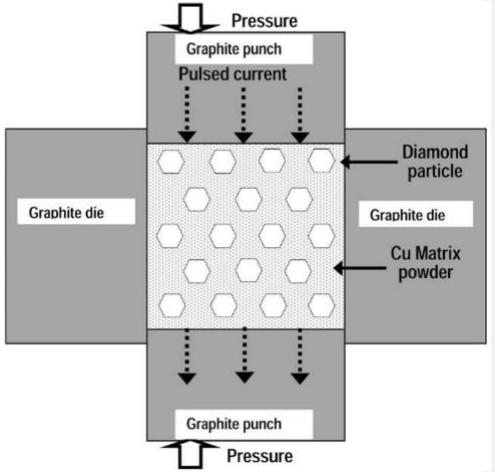
Heterogeneous integration requires new thermal solutions

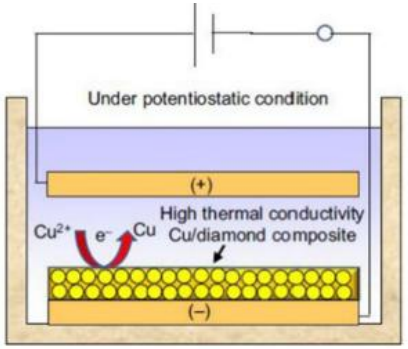
- The rise of integration and power density of package call for advanced thermal materials for heat spreading with:
  - Higher-than-silicon thermal conductivity
  - Compatibility with integration at different level of proximity to silicon
  - Reasonable (~10s um) thickness and high throughput



Cu-diamond composite for heat spreading

- Current manufacturing methods
  - Sintering technologies
    - Spark plasma, hot pressing, pressure infiltration, …
    - High thermal budget and requires appropriate bonding to silicon
  - Electroplating
    - Low throughput and requires unconventional plating configuration





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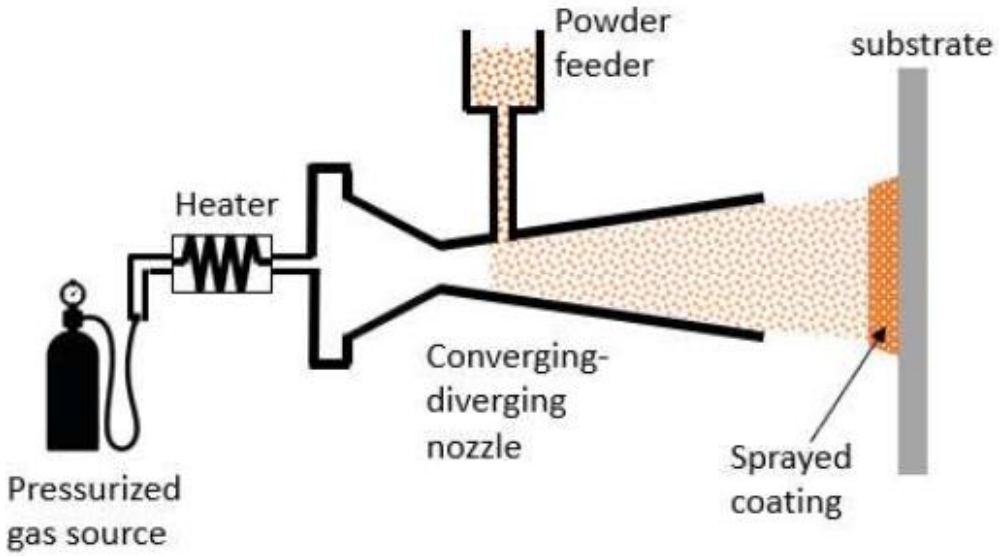
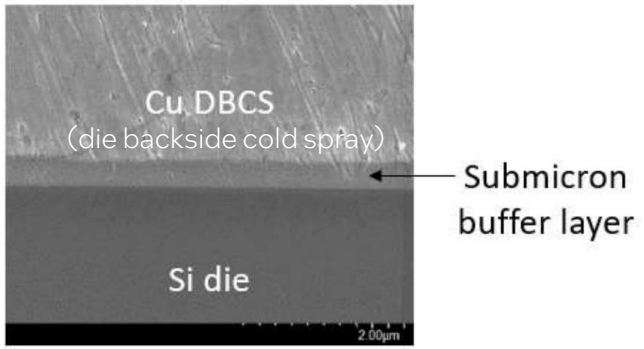
Cold spray technology overview

- Micron-sized particles accelerated in carrier gas through customized spray nozzle
- Particle bonding and film thickness growth depend on high-momentum impingement



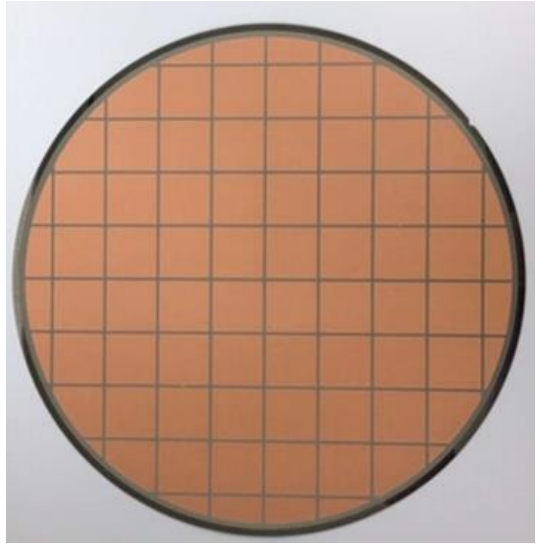


ECTC, 2021, pp. 1109-1114

Cold spray technology overview

- Additive manufacturing with high deposition rate
- Low thermal budget
  - Gas temperature << melting temperature
  - Substrate temperature < ~ 100°C
- Compatible with wafer- and unit-level deposition for different packaging architectures.

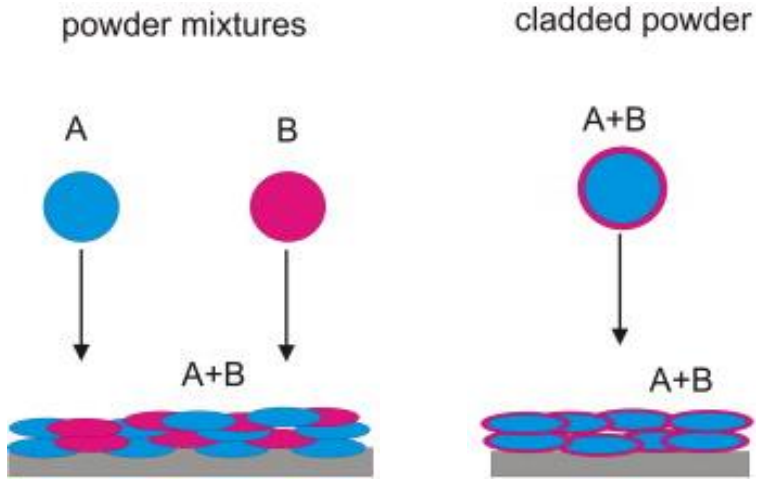
Cu on 300mm Si wafer



ECTC, 2021, pp. 1109-1114

Cold spray for rapid thick film deposition

- Strategies to include brittle particles, i.e., diamond, in the composite films:
  - Spray Cu and diamond powder mixture
    - Challenging to increase diamond volume fraction
  - <u>Use Cu cladded diamond powder</u>
    - Requires engineered powder

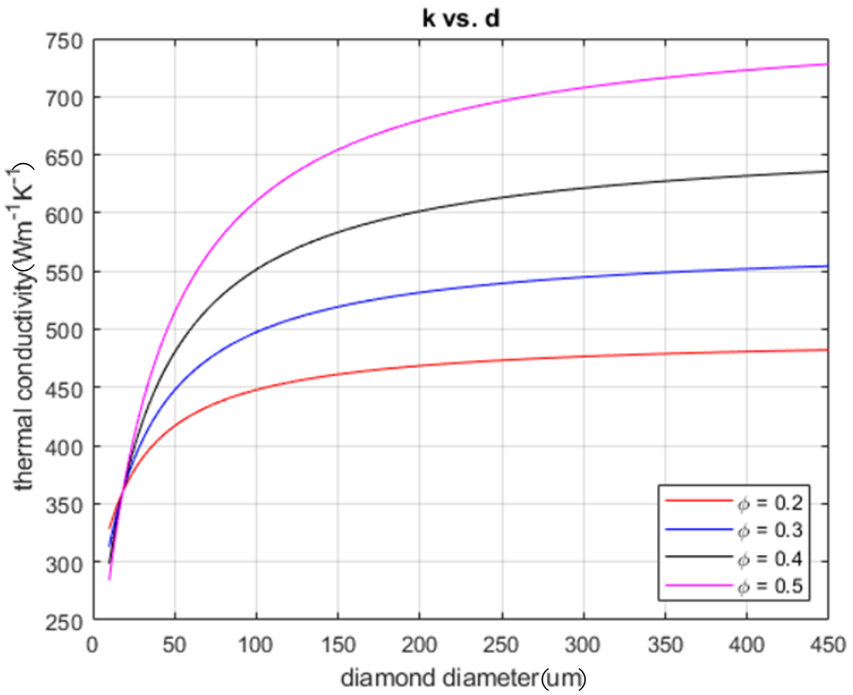


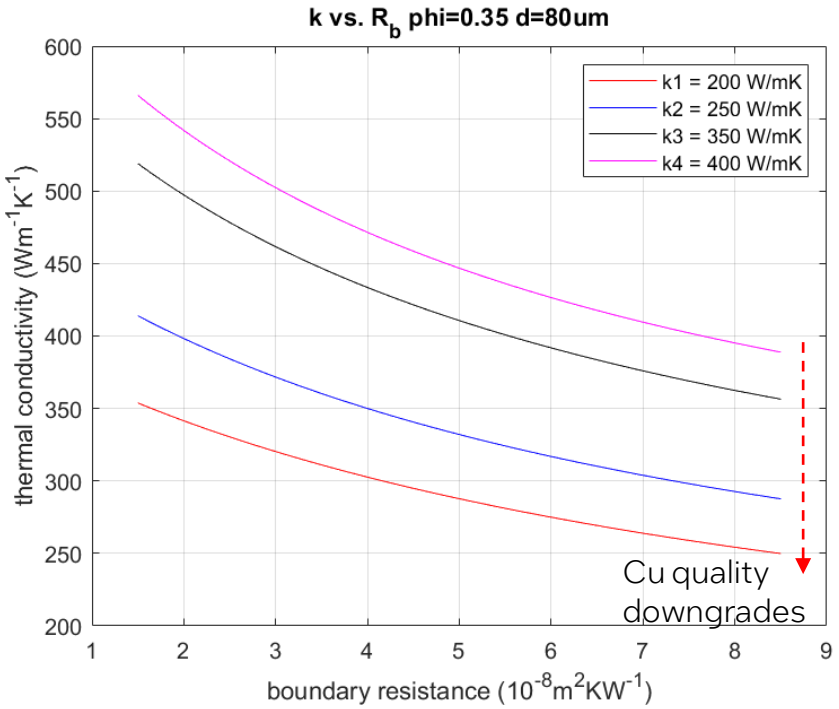
Design of composite materials

- Objective: determine the appropriate diamond size, copper cladding thickness and copper matrix quality

- Method:
  - Simulated composite thermal conductivity based on effective medium theory
  - Diamond impingement stress analysis with Ansys LS-Dyna

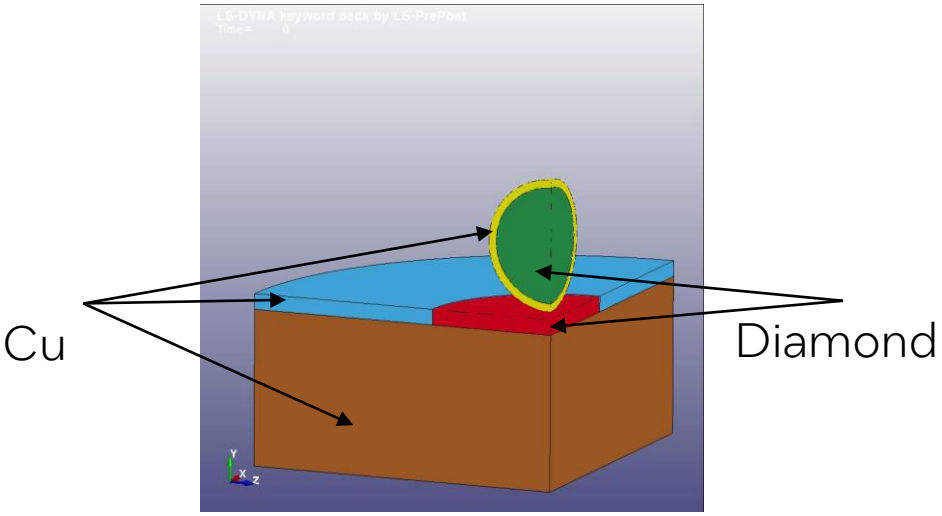
Design of composite materials

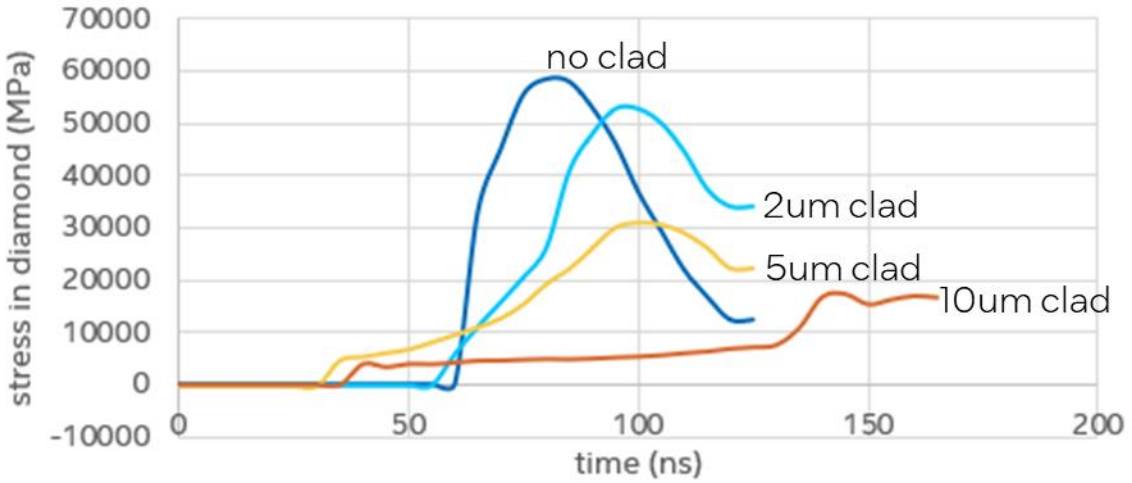




- Result:
  - Larger diamond powder, and Cu matrix with close-to-bulk thermal conductivity are desired .

Design of composite materials

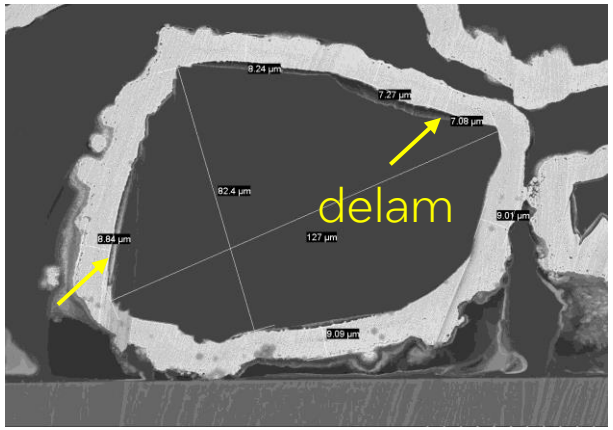




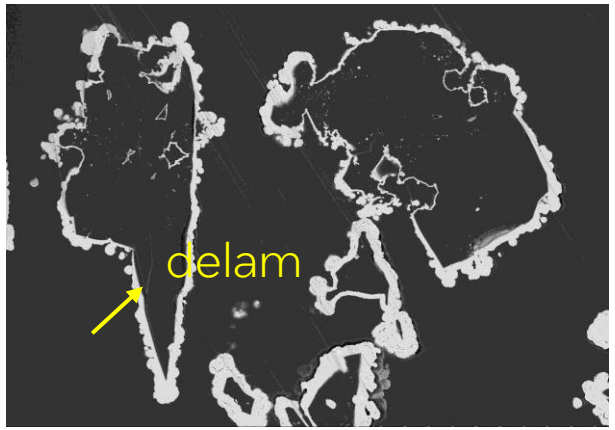
- Result:
  - Copper clad is crucial to reducing the maximum stress in diamond and avoiding diamond fracture .

Diamond powder feedstock evaluation

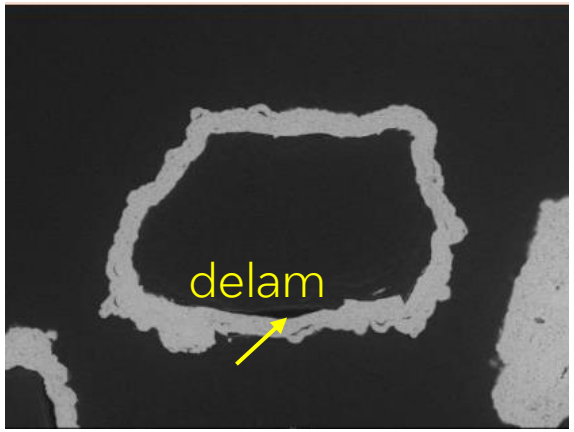
Type A



Type B



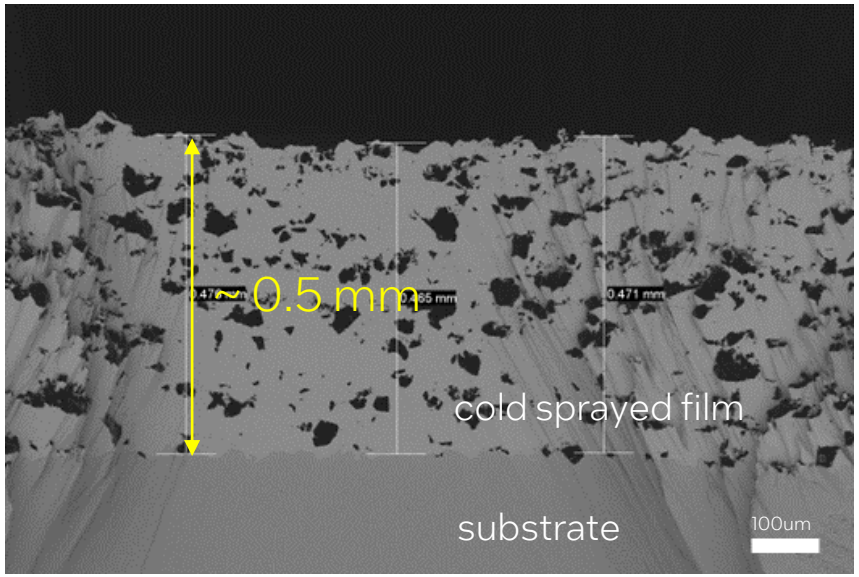
Type C

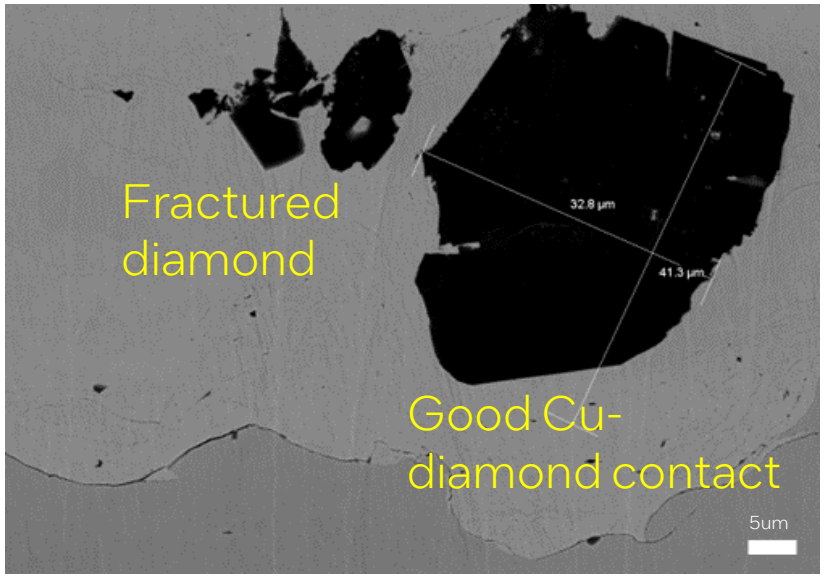


Diamond	[O] measured by IGA (instrumental gas analysis)	Nominal clad thickness (um)
Supplier 1, type A	6000 ppm	9, uniform
Supplier 2, type B	1000 ppm	2, non-uniform
Supplier 3, type C	750 ppm	9, uniform

- Result:
  - Two challenges identified in copper cladded diamond powders:
    - Cu clad was partially oxidized
    - Delamination was present at the Cu-diamond interface

Composite film spray and thermal properties

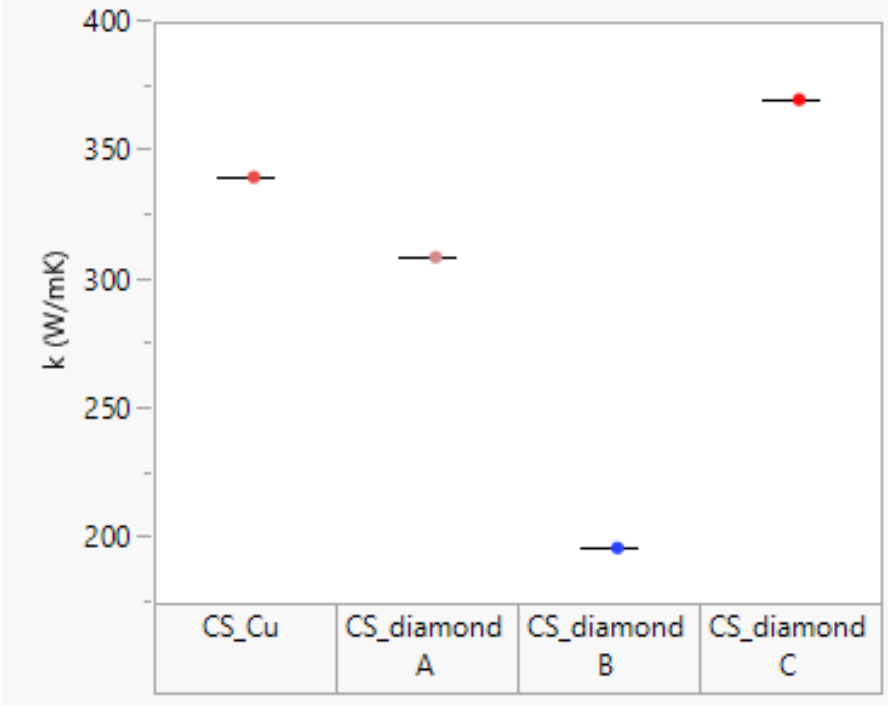




Zoom in on particles

- Results:
  - Millimeter-thick films were demonstrated on various substrates.
  - Cold spray enabled void-free, intimate contact between Cu-Cu and Cu-diamond despite presence of diamond fracture.

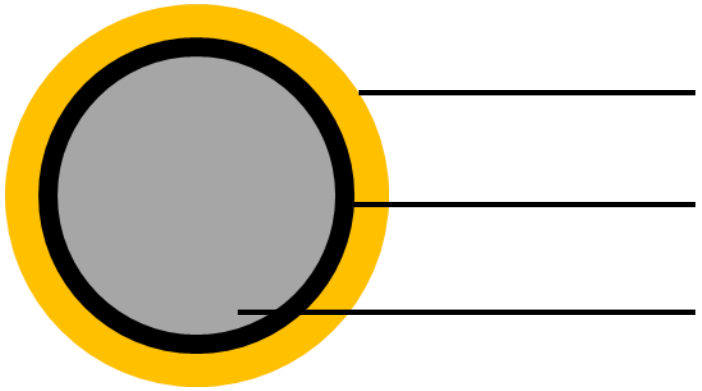
Composite film spray and thermal properties



- Result:
  - Composites made from different powder feedstock varied in thermal conductivity. Best sample showed 10% improvement.

Perspectives for new diamond materials

- Advances in diamond powder engineering will enable new paths to cold sprayed composites with high-thermal conductivities.



Copper clad: good adhesion and thick (~10 um), low [O]

Interlayer: conformal, good adhesion to diamond core and thin (<=0.1um)

Diamond: monocrystalline, low [N] and metal impurity

Conclusions

- Cold spray was demonstrated for high thermal conductivity composite deposition to address package thermal spreading.
- Diamond powder requirement was laid out regarding size, copper clad thickness and oxidation level.
- Proof-of-concept experiment showed mm-thick film on metal and organic substrates with thermal conductivity 10% higher than copper.
- Continued innovation in diamond powder materials should further improve the composite thermal properties.

Acknowledgement

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