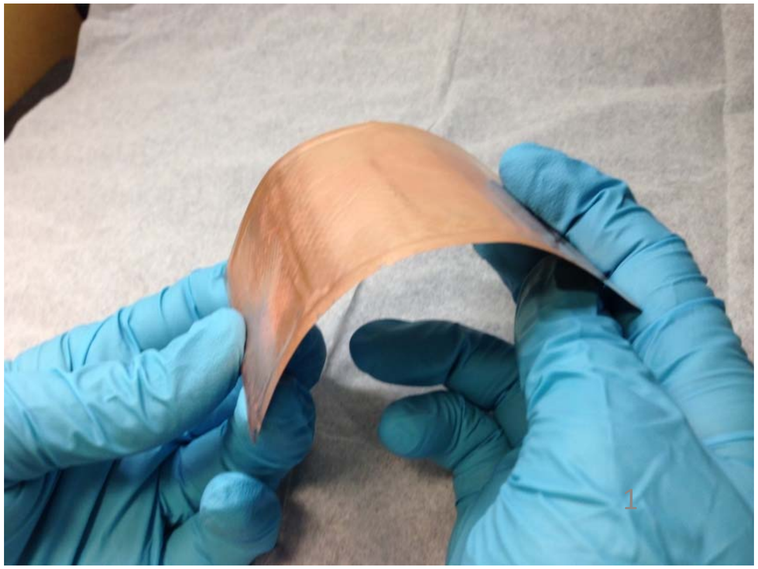
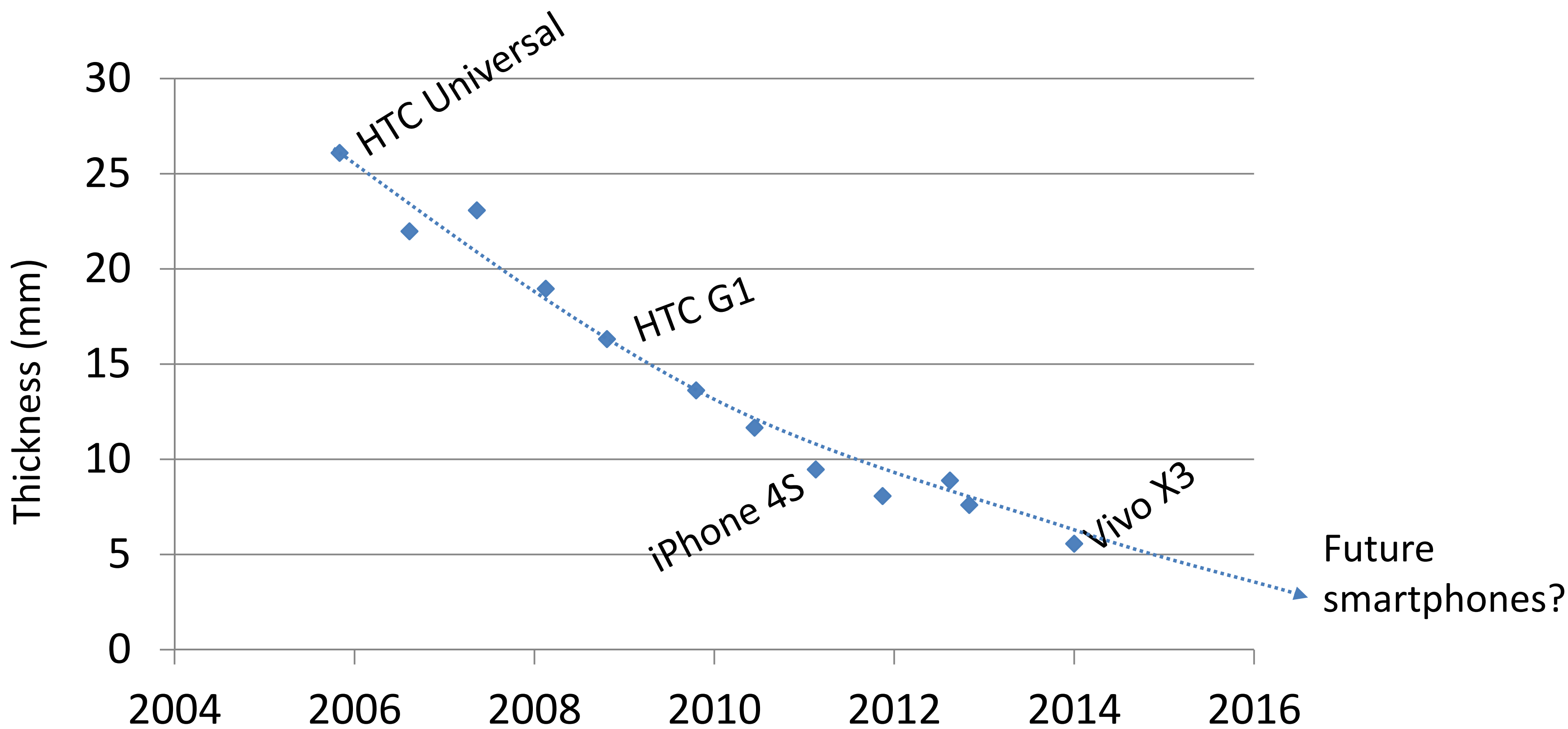
Flexible Thermal Ground Planes with Thicknesses Below Quarter-mm

Ryan Lewis, Ph.D.
Shanshan Xu, Y.C. Lee, Ronggui Yang, Li-Anne Liew
University of Colorado at Boulder
rjlewis@colorado.edu

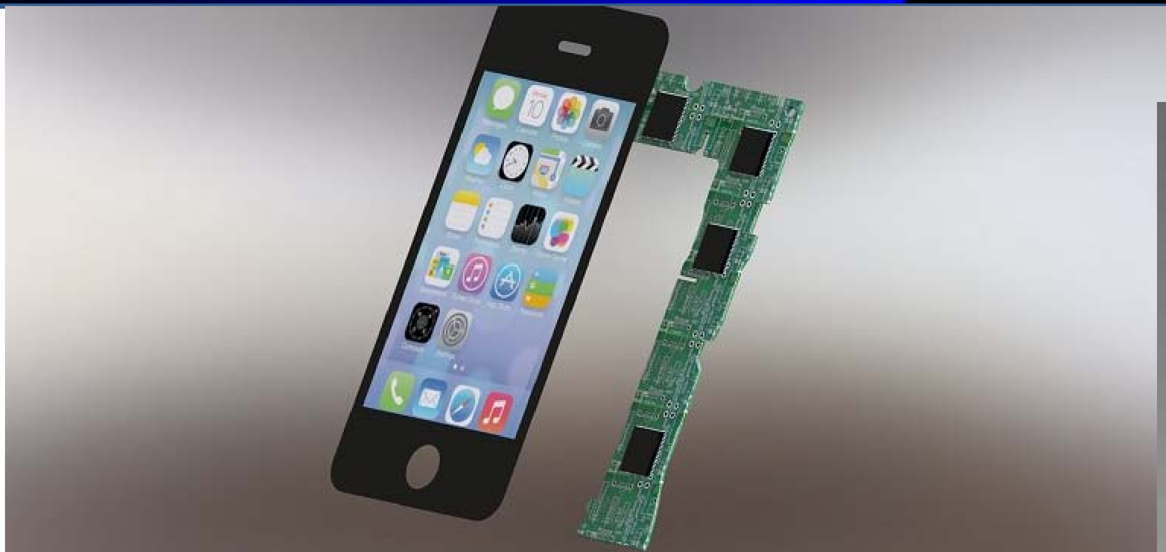


Future smart phones are thin



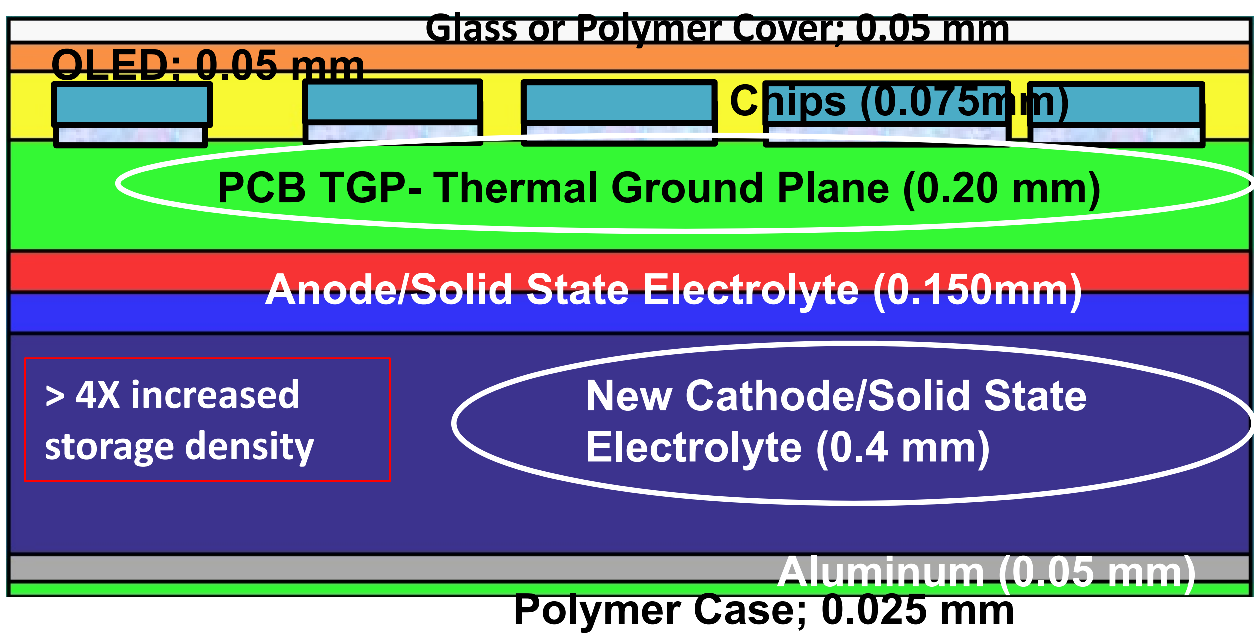
http://pocketnow.com/2012/05/16/remember-how-thick-phones-used-to-be

3mm **flexible** smartphone



http://www.consumerreports.org/cro/news/2014/09/consumer-reports-tests-iphone-6-bendgate/index.htm

Flexible 1-mm smartphone as future microsystem

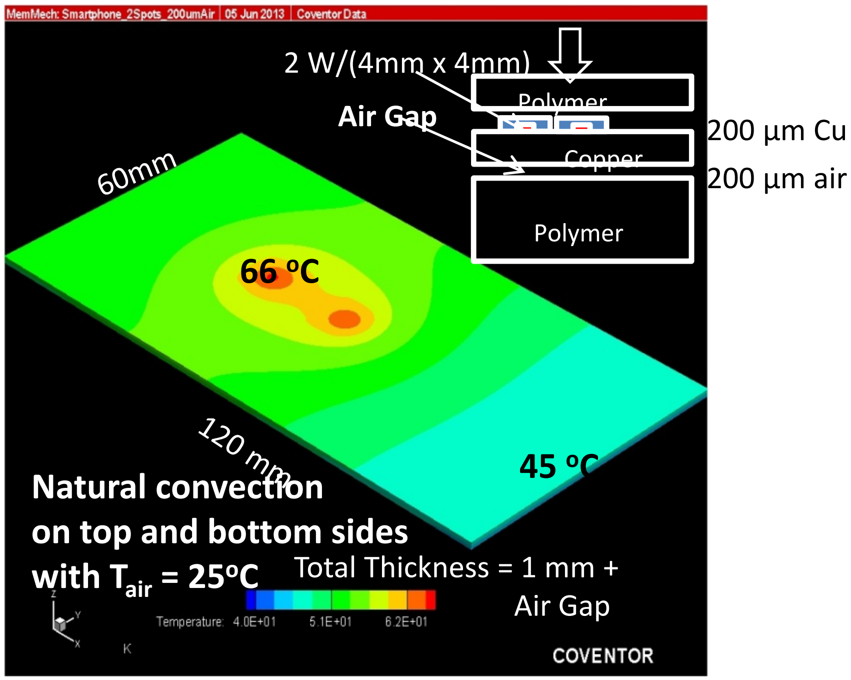


Three enabling technologies being developed at CU-Boulder

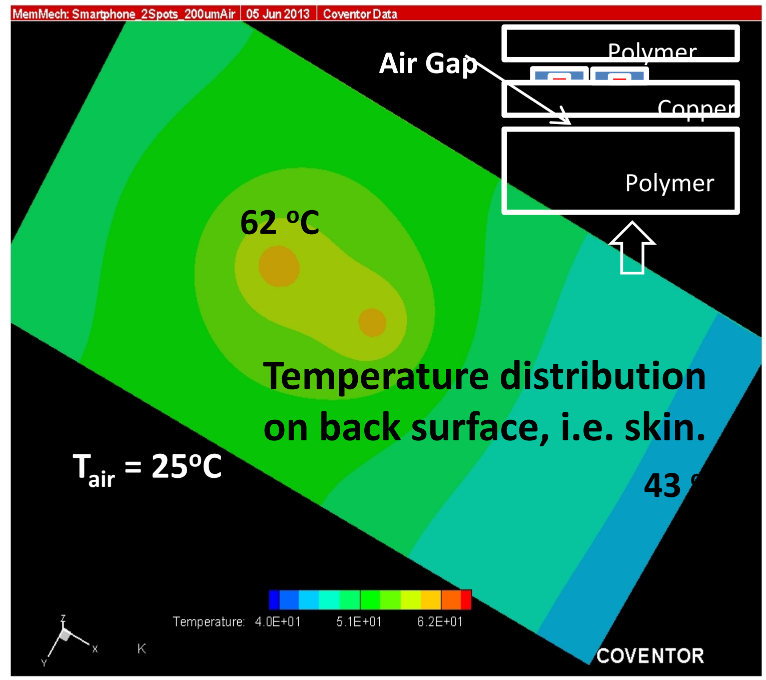
- Flexible thermal ground planes
- All solid state battery
- Atomic layer deposition

Air Gap? Alternative Needed!

chip-side



Back-side (i.e. skin surface)

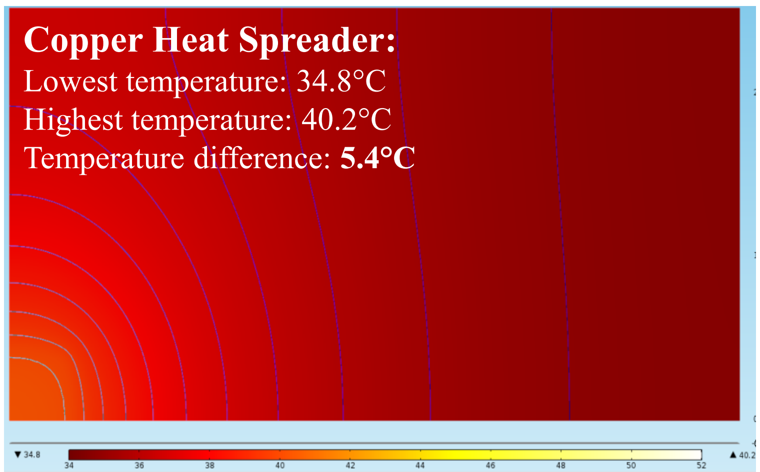


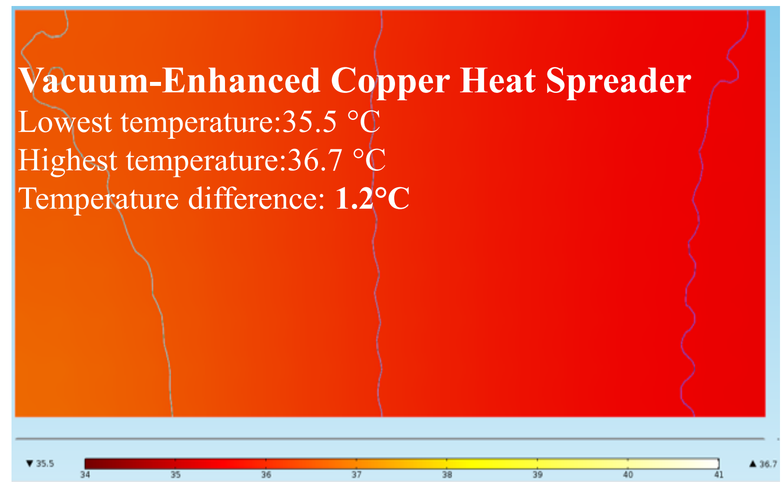
For thin electronics:

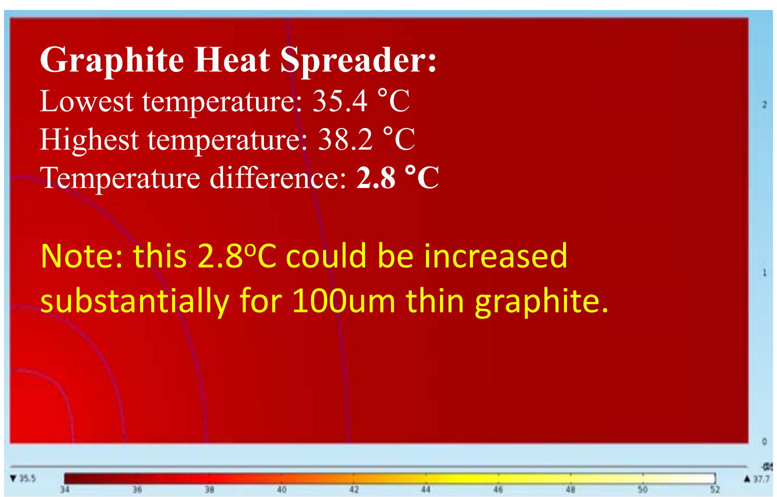
•**Copper and Graphite + Air-gap not good enough**!

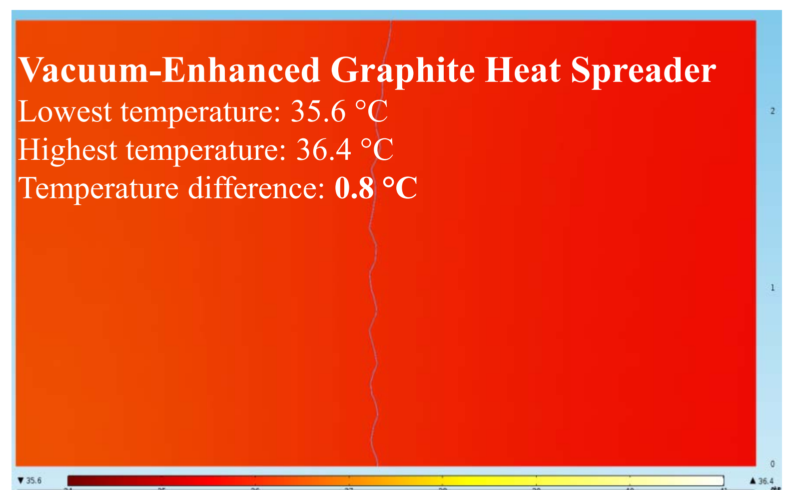
Vacuum-Enhanced Heat Spreader: Skin Temperatures Reduced

Copper or Graphite vs. Vacuum-Enhanced Heat Spreader

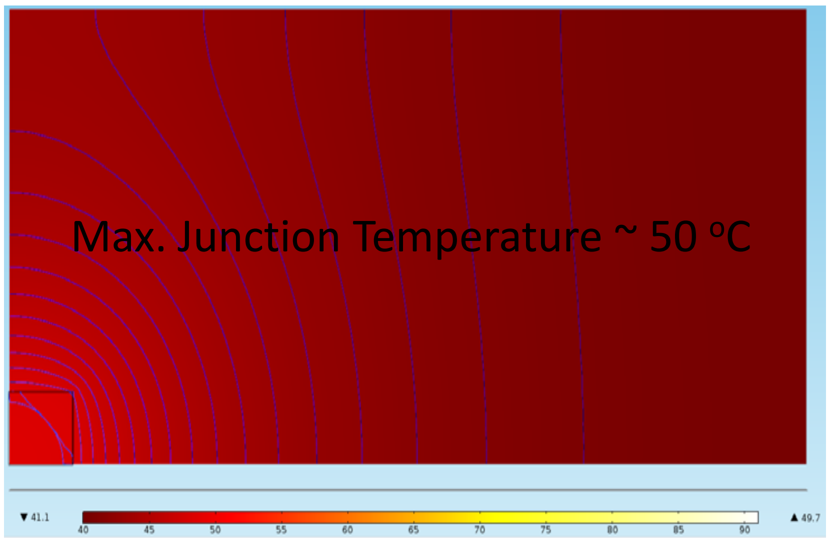




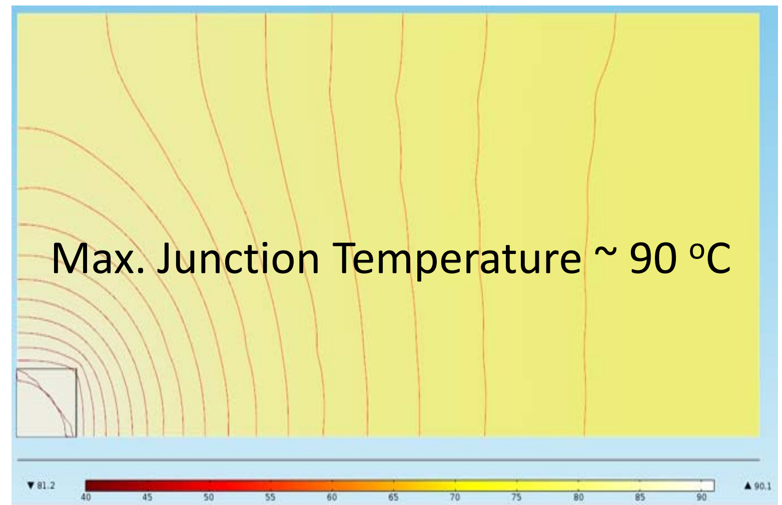




Vacuum-Enhanced Heat Spreader: Junction Temperatures?



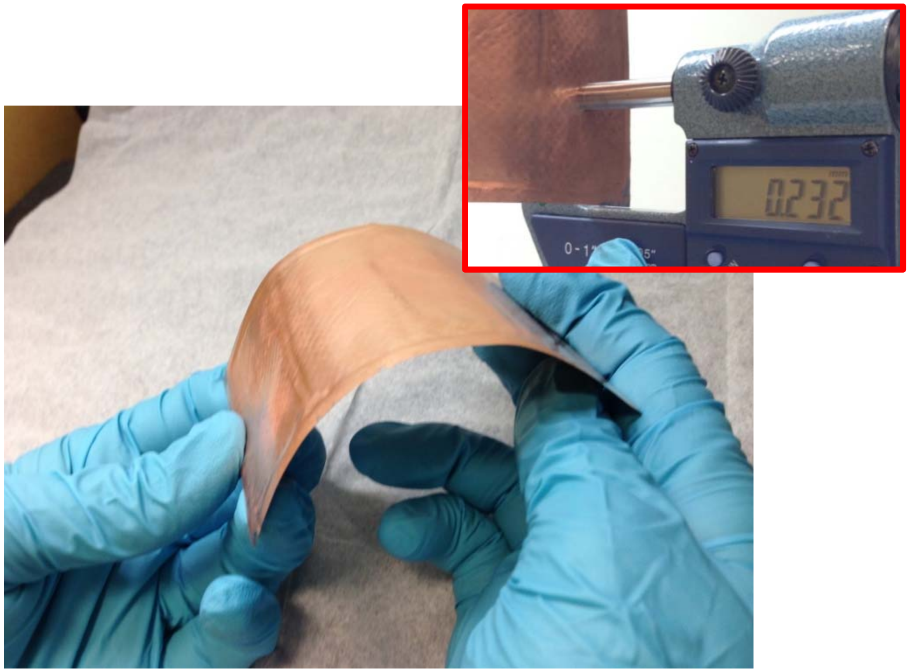
Vacuum-Enhanced Heat Spreader – Design A



Vacuum-Enhanced Heat Spreader – Design B

- Vacuum-enhanced heat spreading: a short term solution that is always better than copper/graphite + air gap.
- Trade-off analysis for an optimum design required.
- **Best solution: flexible thermal ground planes.**

Thermal Ground Plane

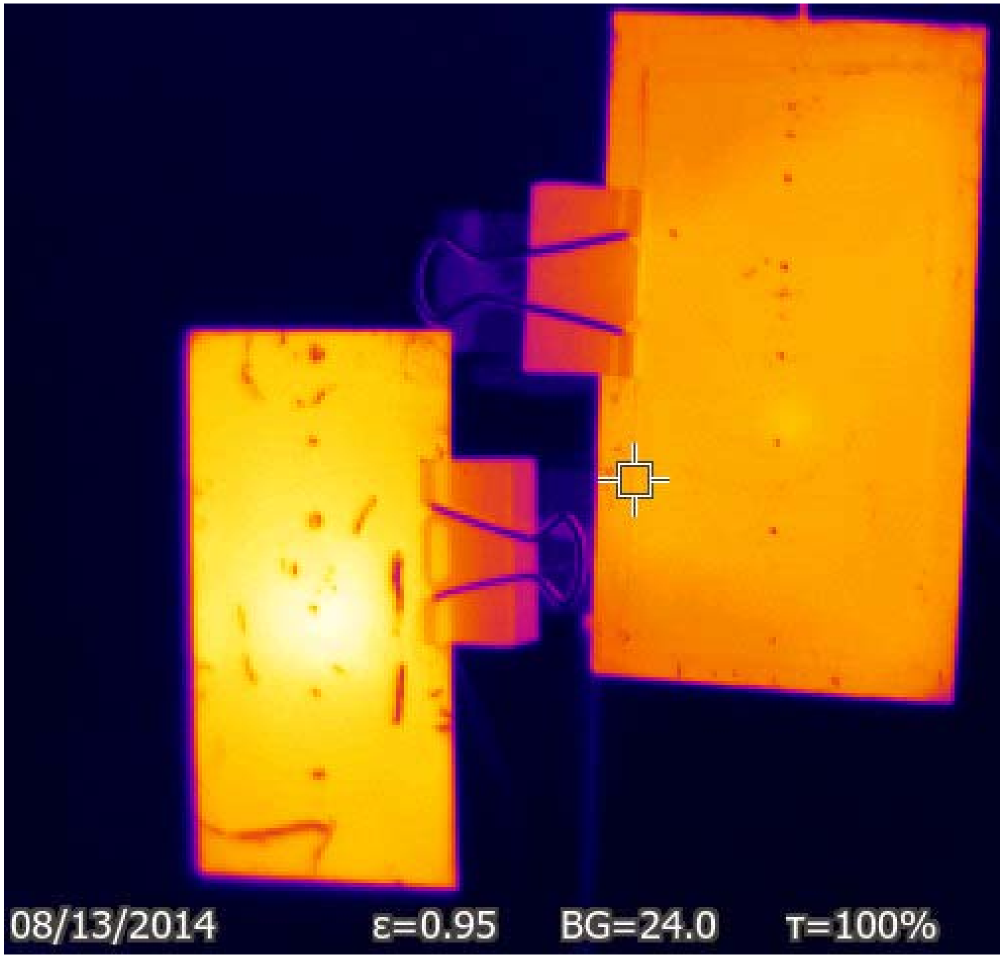


10 cm x 6 cm total area

- Printed Circuit Board substrate
- Built-in “vacuum” insulator
- Latent heat of phase-change for heat removal

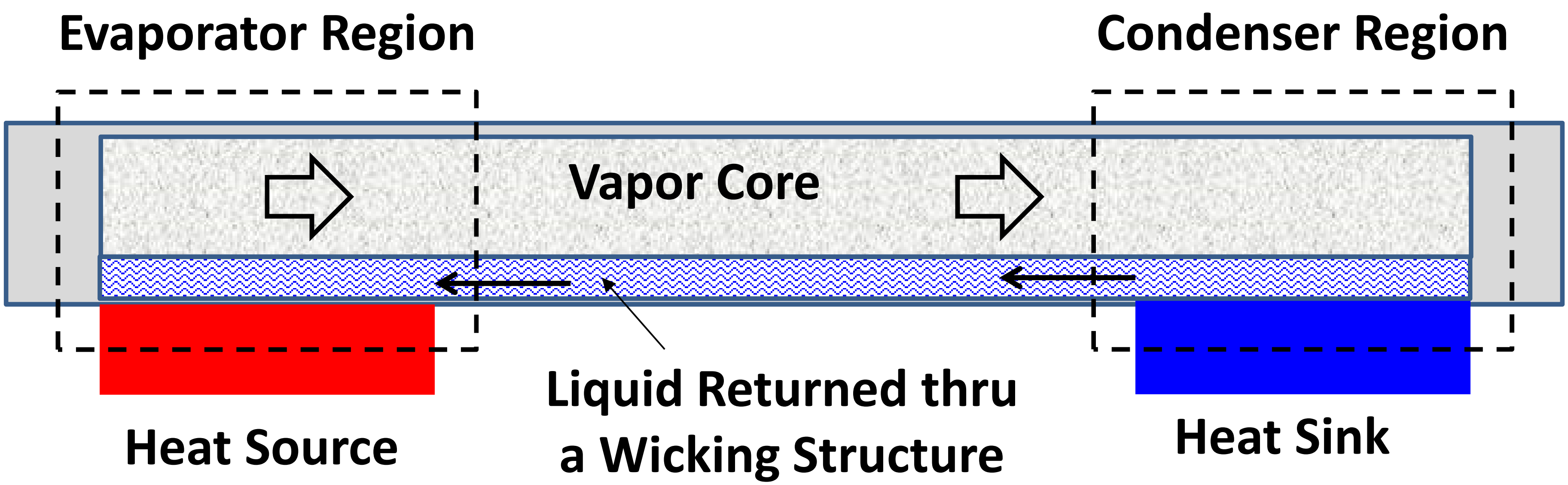
Video

TGP and Copper

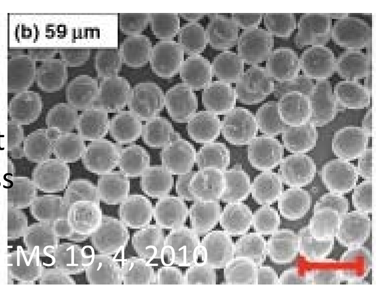


TGP working physics

(2-D Heat Pipe or Vapor Chamber)

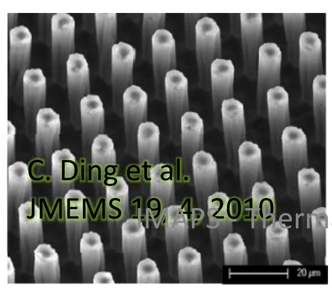


Sintered powder

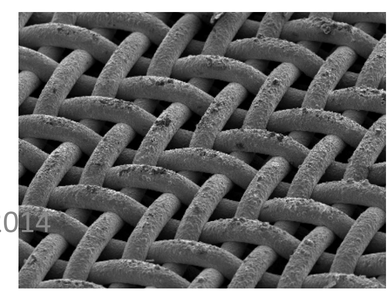


Y. Sungtaek Ju et al. I. J. Heat Mass Transfer, 60, 2013, 163-169

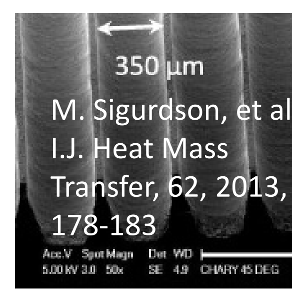
Micro-pillars



Woven mesh

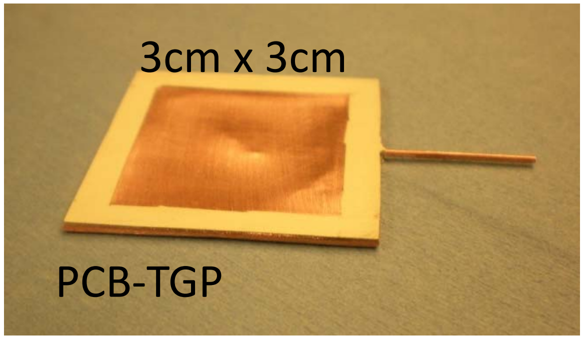


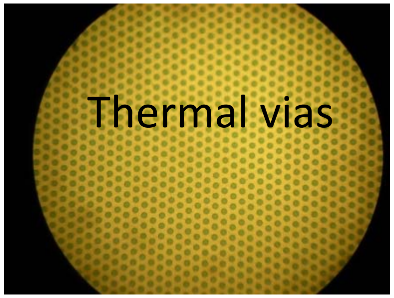
Grooved Channels

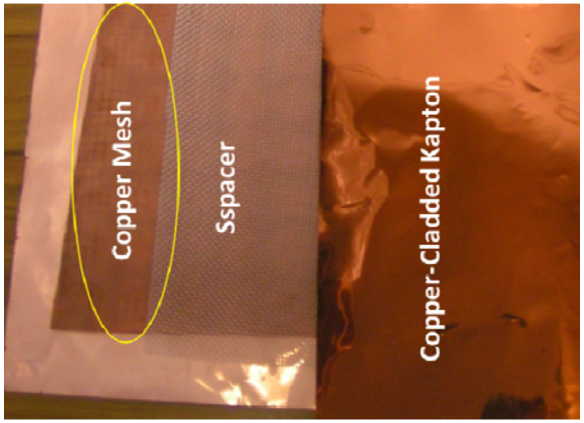


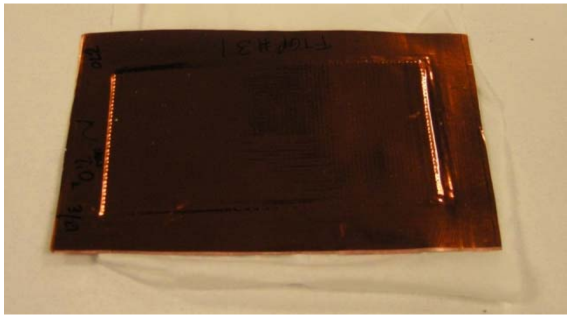
TGP and Graphite

	Flexible TGP	Graphite
In-plane thermal conductivity	1,000 – **4,000** W/m-K	400 - 1,500 W/m-K
Through-plane thermal conductivity	**<0.03**-100 W/m-K	3 – 15 W/m-K
Integration with PCB	**Can be part of PCB interconnects and vias**	Separate piece.





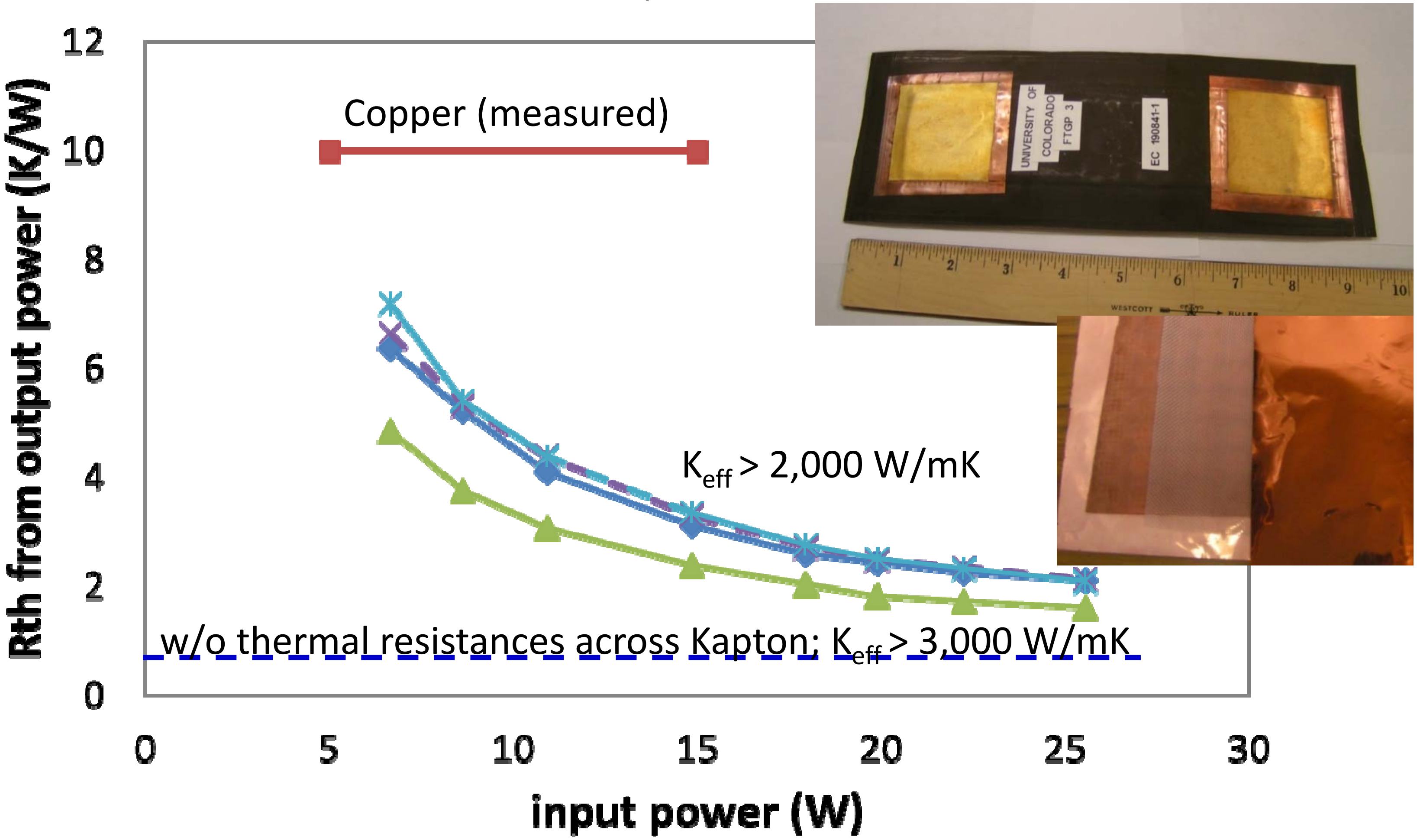




9.5 cm X 5 cm X 0.1cm

TGP Background at Colorado

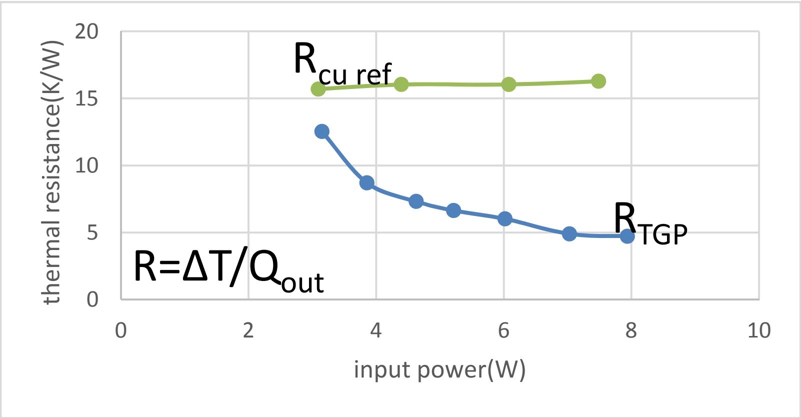
1-mm thick, 20 cm x 5 cm footprint

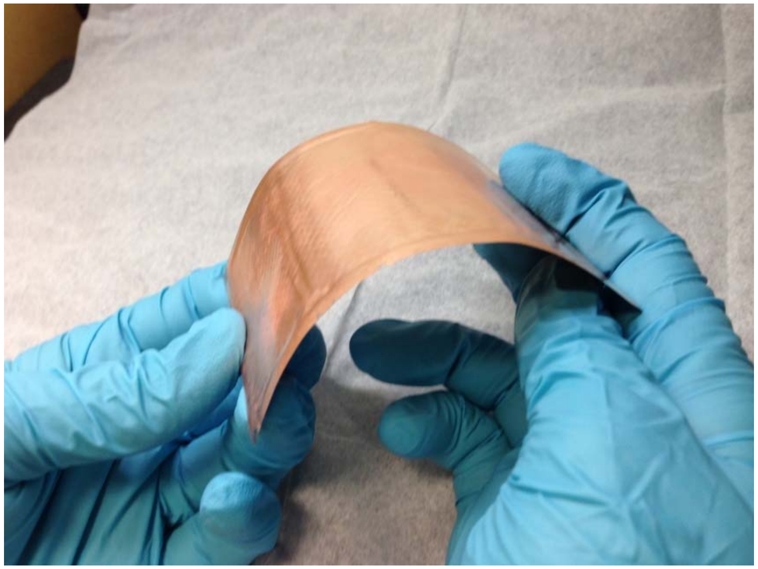


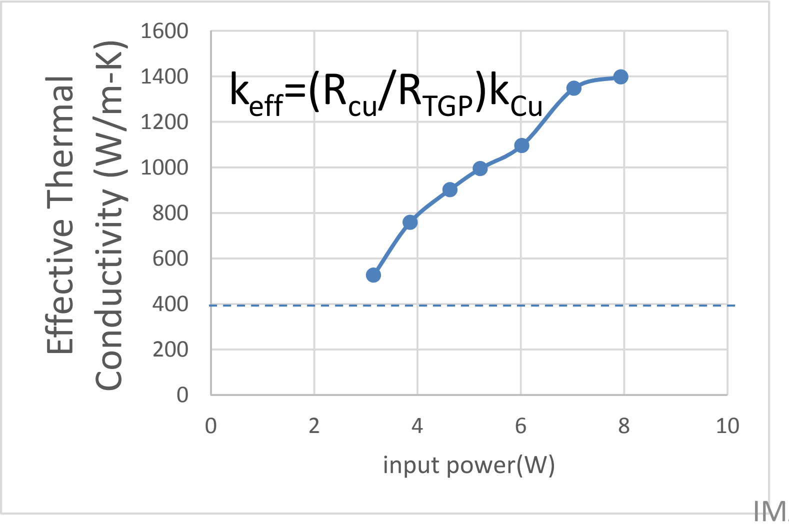
•Flexible, manufacturable, but too thick, too high power

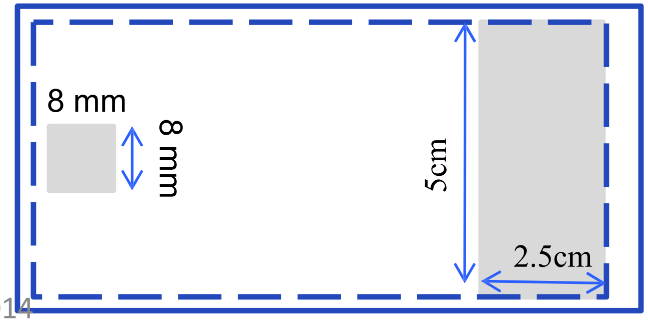
Quarter-mm TGP Results

- Carrying Heat (heat-pipe)



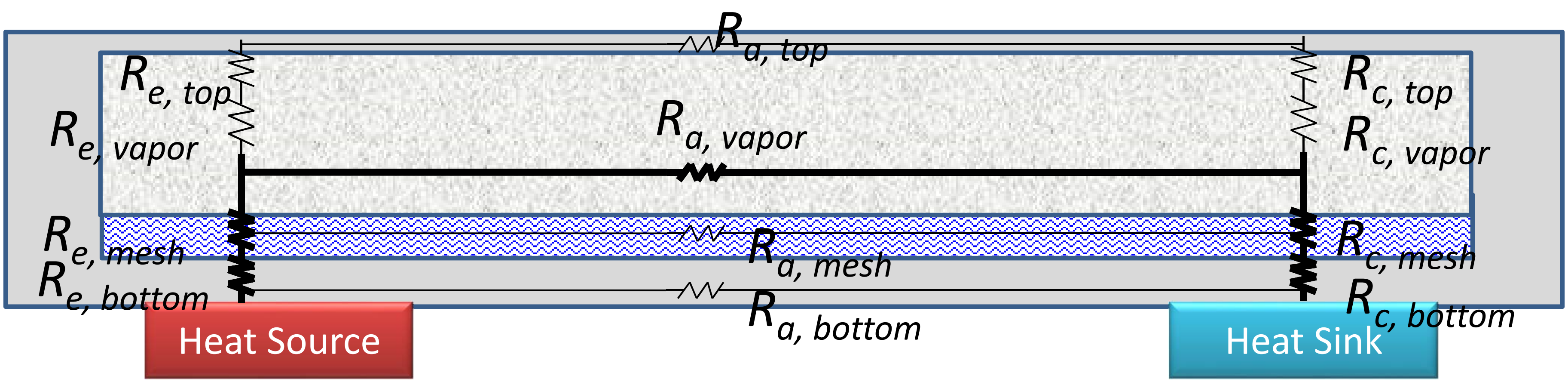






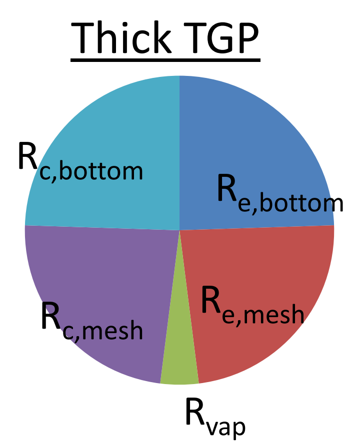
Vapor Core Design: Critical to Thin TGP

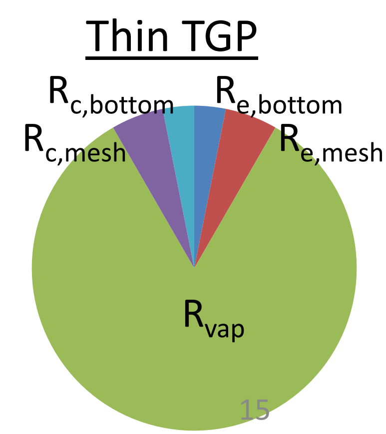
- Thermal resistance



$$\frac{dR_{vap}}{dx} = \frac{1}{Q}\frac{dT}{dx} = \frac{1}{Q}\frac{dT_{sat}}{dP}\frac{dP}{dx}$$

$$\frac{dP}{dx} = \frac{fRe}{2}\frac{\mu_v}{\rho_v}\frac{\dot{m}}{\delta_v^3 w}$$





TGP Limited by 50um Vapor Core?

- Vapor Core Effective Thermal Conductivity:

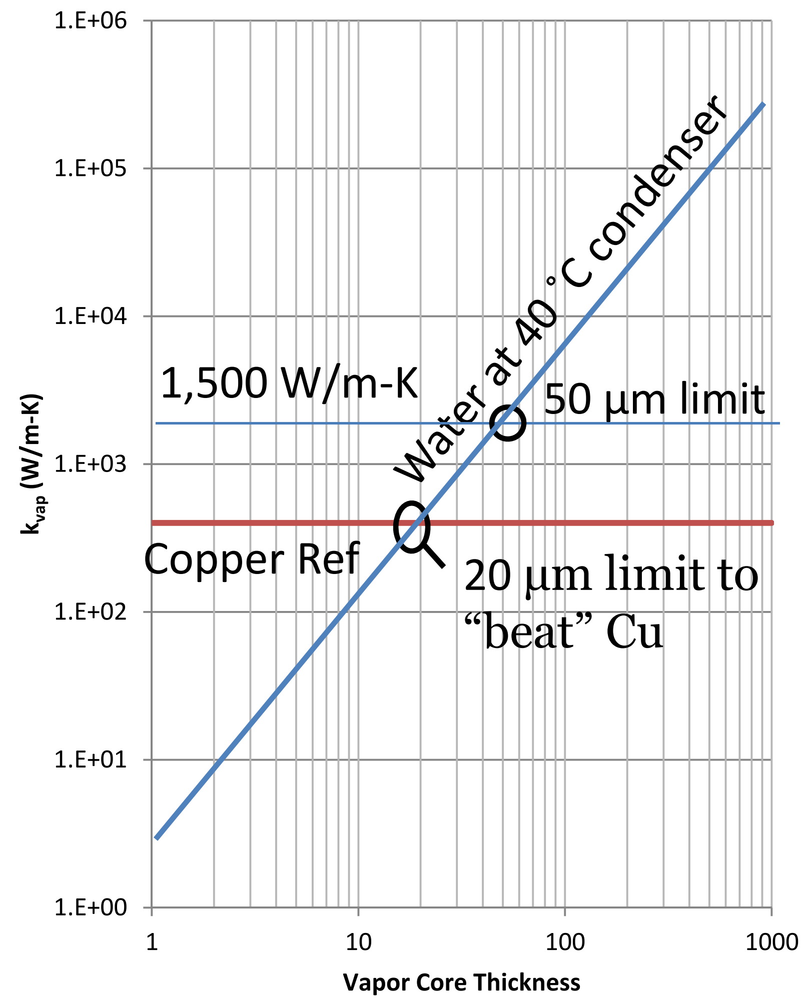
  Fourier's Law *k=Q/(dT/dx)*

  -Temperature Gradient proportional to pressure gradient dT/dx~dP/dx

  -Pressure gradient proportional to flow-rate, which is proportional to heat applied dP/dx~m~Q

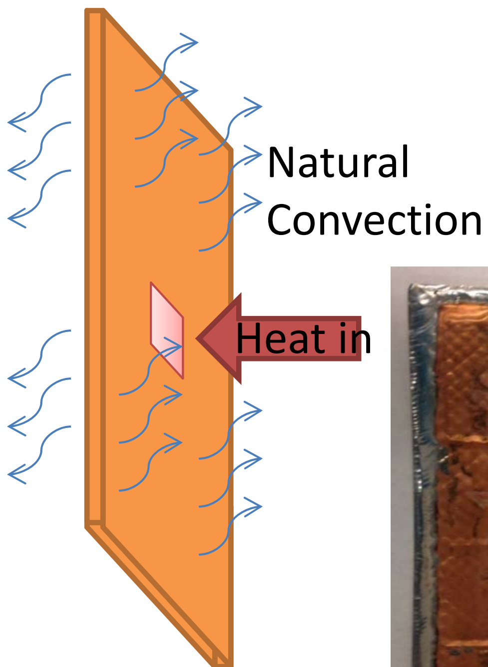
  -NOT A DIRECT FUNCTION OF POWER

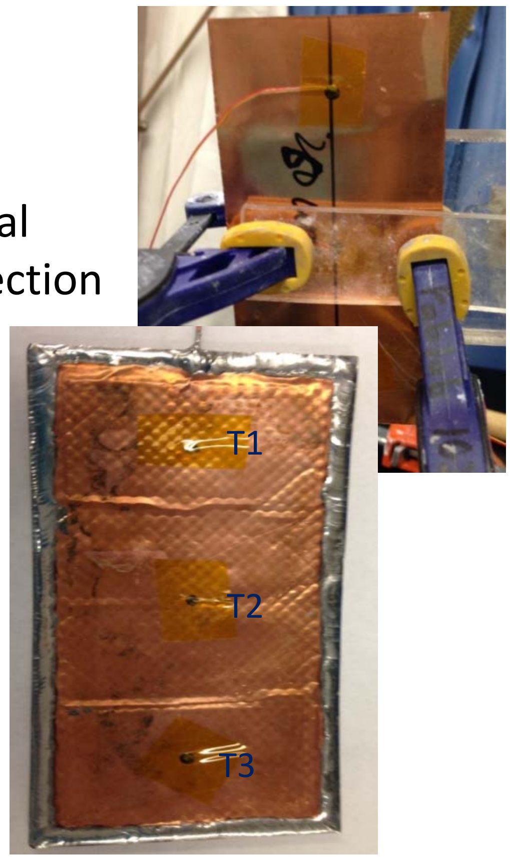
$$k_{eff} = \left(\frac{\rho_v^2 \Delta h^2}{T_v \mu_v}\right)\left(\frac{fRe}{2}\right)\delta_v^2$$



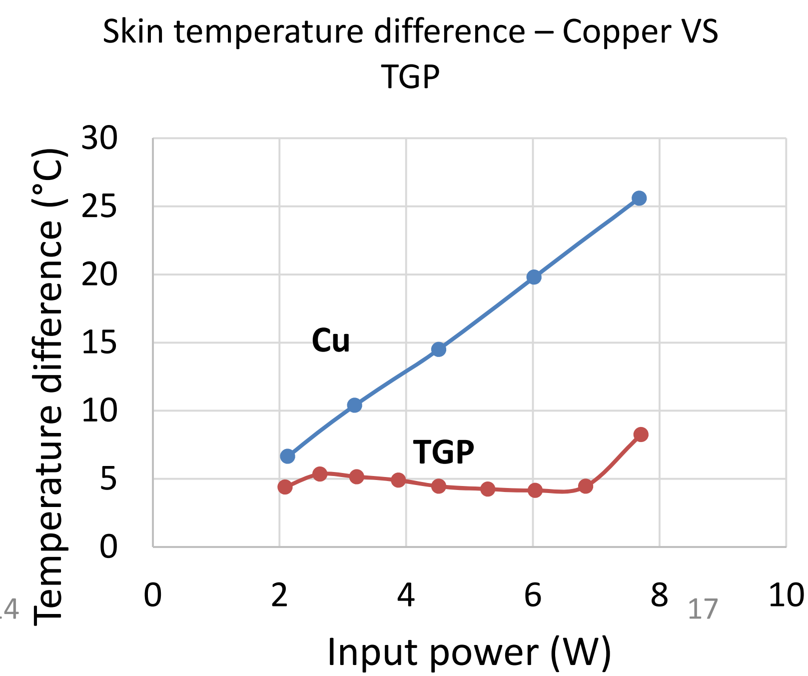
TGP Limited by 50um Vapor Core? No!

- As a Heat Spreader
  - Distributed condenser

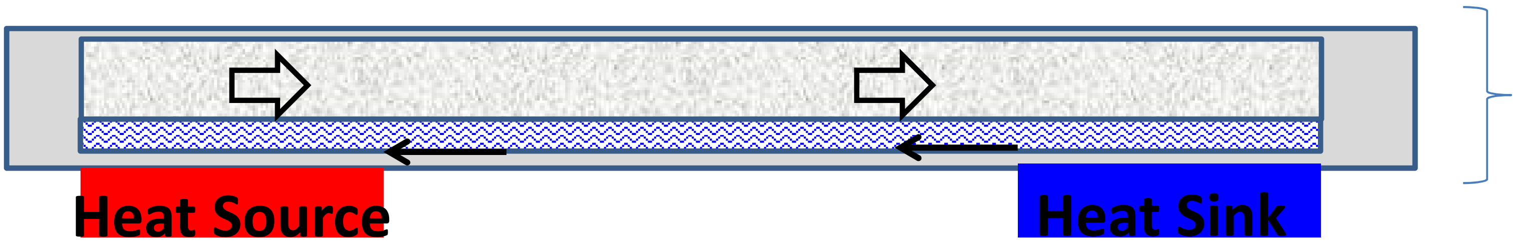




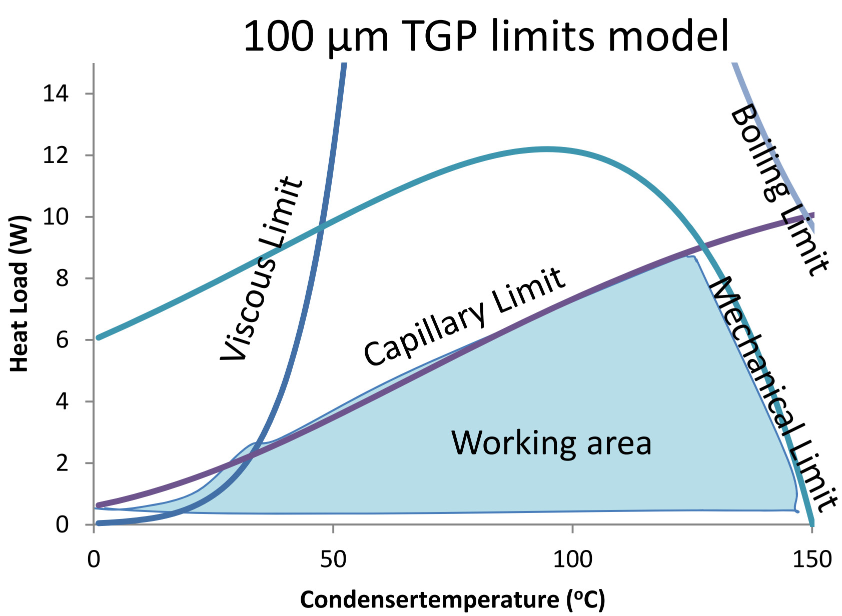
- Measurement of uniformity of skin temperature
- TGP= **5x lower** ΔT than Cu at 6W



TGP's Limit?



Overall Thickness
100 µm?



Summary

- Copper + Air-gap not enough!
- Short-term improvement via vacuum-enabled heat spreaders: copper or graphite + vacuum
- Thermal ground planes!
  - PCB substrate
  - Built-in insulator layers
  - Phase-change heat transfer
  - <0.1mm TGP with K_{eff} > 3,000 W/m-K feasible.
- Quarter-mm, demonstrated k_{eff}=1,400 W/m-K. Prototypes are to be distributed.

Acknowledgements

- TGP research at CU has been supported by:
  - University of Colorado
  - State of Colorado AIA:

    award number: 2015-3212
  - Defense Advanced Research Projects Agency (DARPA)

    Thermal Ground Plane Program N6601-08-C-2006
  - Intelligence Community

This project was supported by a grant from the Intelligence Community Postdoctoral Research Fellowship Program through funding from the Office of the Director of National Intelligence. All statements of fact, opinion, or analysis expressed are those of the author and do not reflect the official positions or views of the Intelligence Community or any other U.S. Government agency. Nothing in the contents should be construed as asserting or implying U.S. Government authentication of information or Intelligence Community endorsement of the author's views.