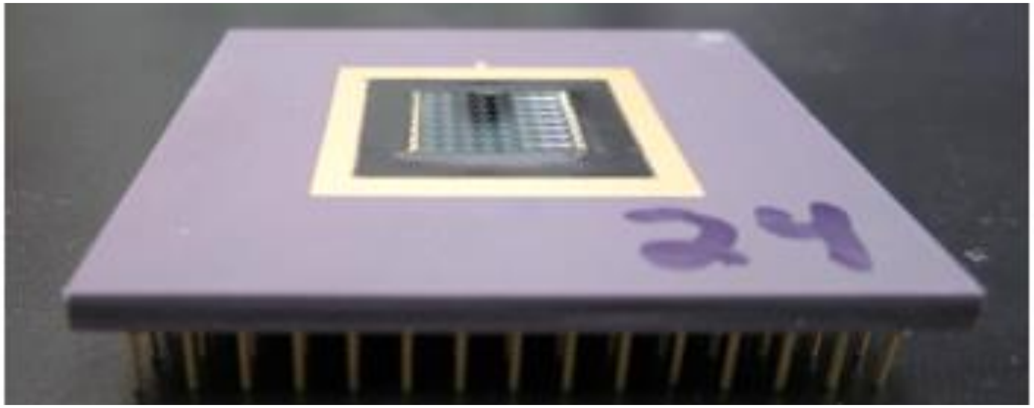
Packaging of MEMS for Aerodynamic Measurements

iMAPS New England, 43rd Symposium & Expo May 3, 2016



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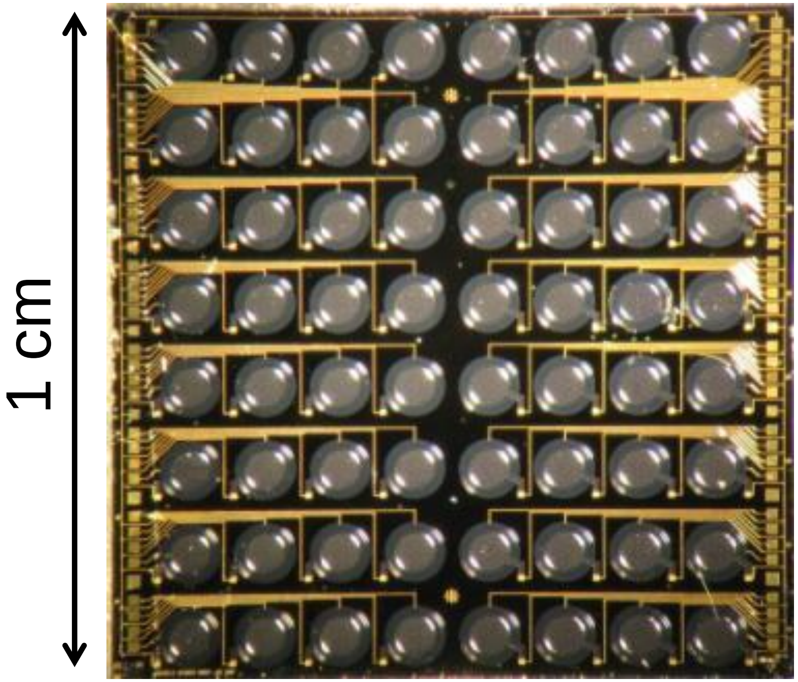
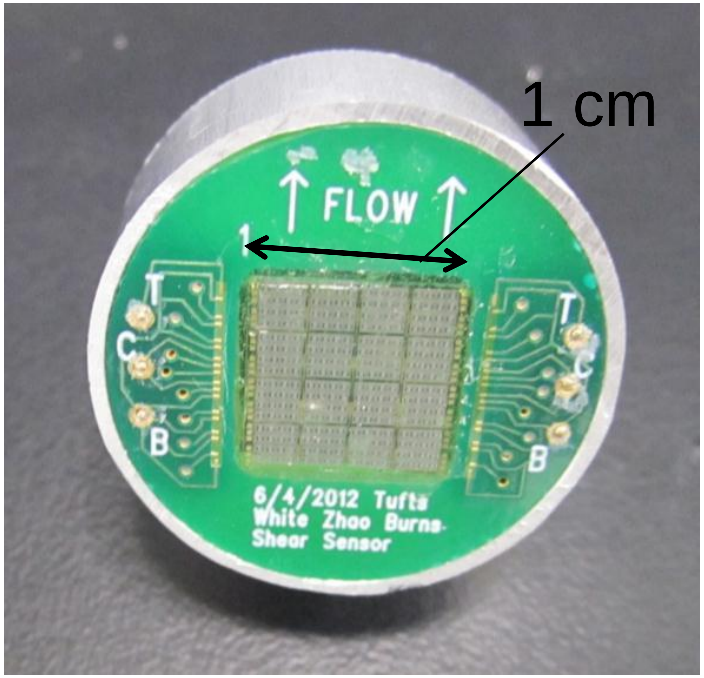
Overall Goal

- Develop ***MEMS pressure and shear sensor arrays*** to measure ***unsteady turbulent boundary layer spectra*** and ***quasistatic local shear stress*** in wind tunnel tests for velocities up to Mach 0.9.
- Achieve a ***high spatial resolution*** by using an ***array-on-a-chip***.



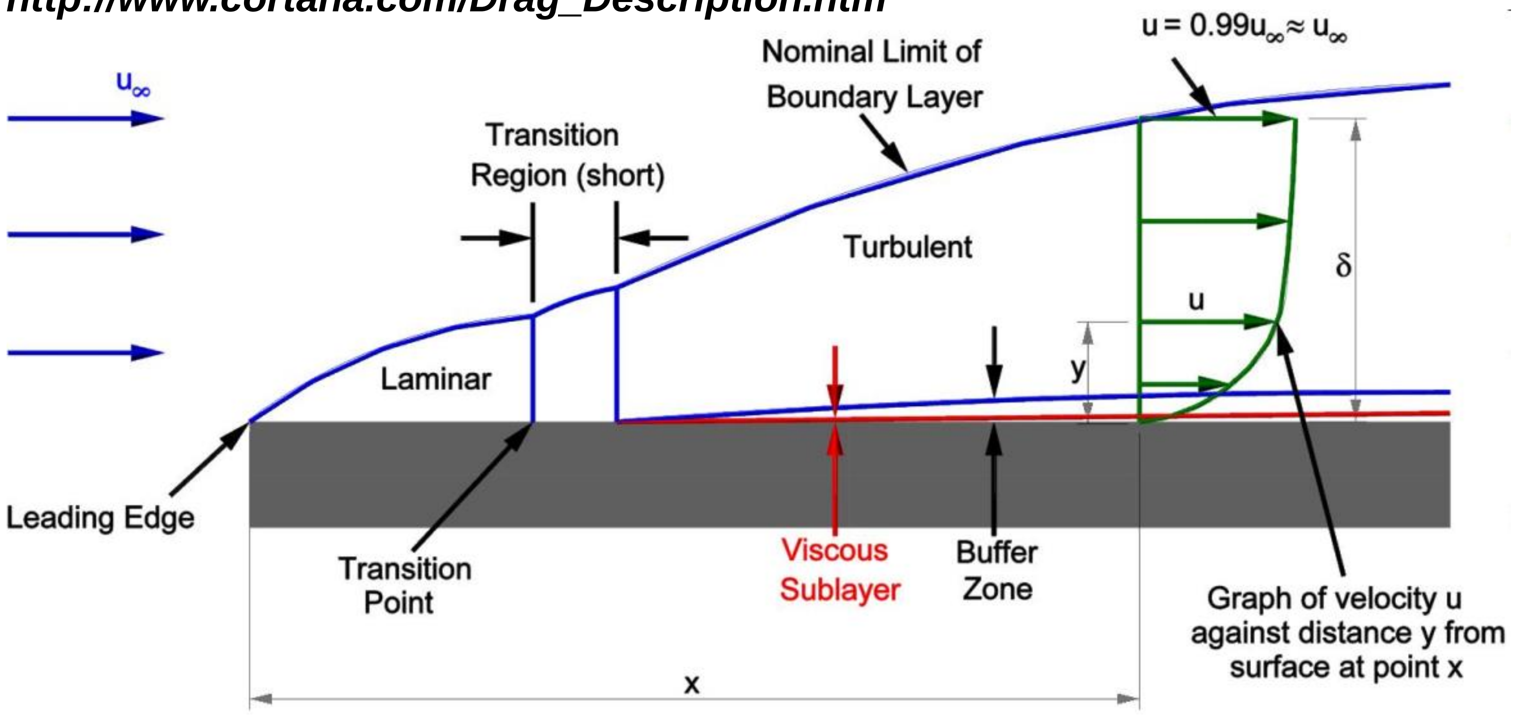
64 element microphone array



16 element shear sensor array

Background - Turbulent Boundary Layer

Image : http://www.cortana.com/Drag_Description.htm



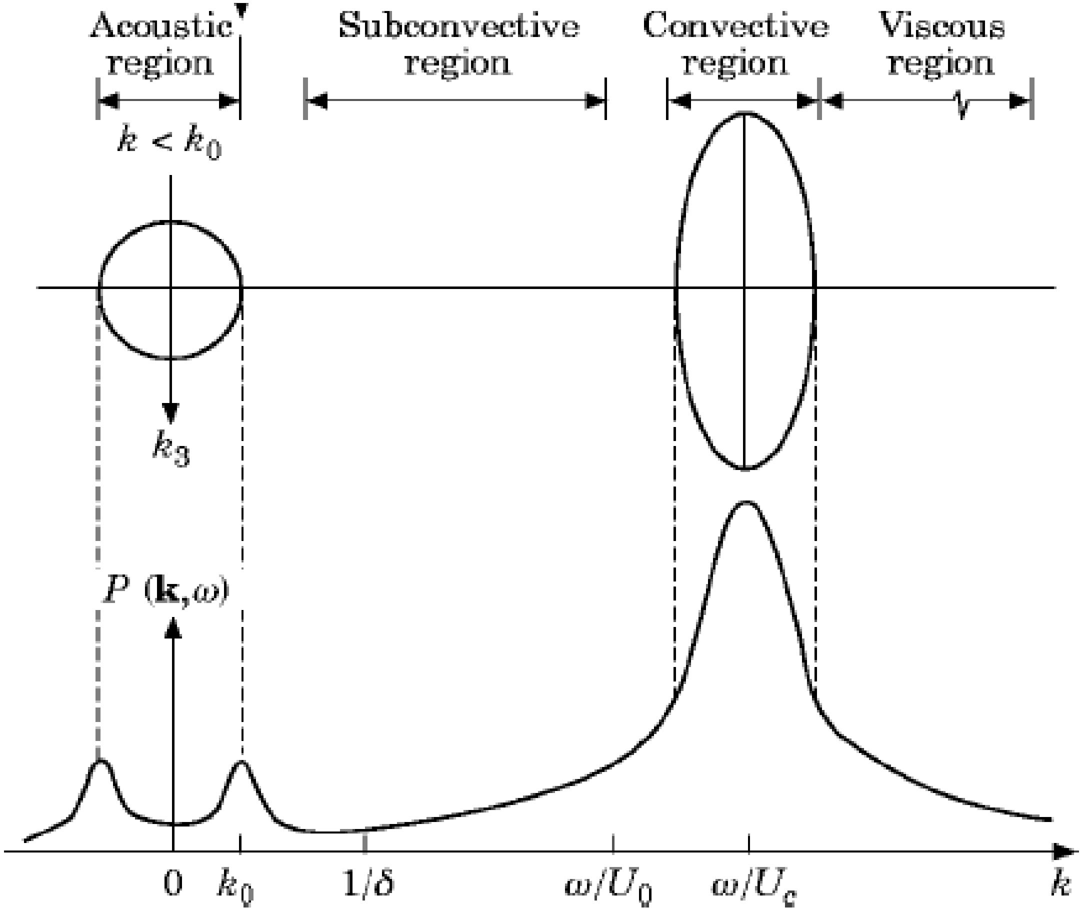
(1) ***Steady*** (time averaged) shear stress measurements are important for total drag measurement. ~ 50% of drag is skin friction for commercial air.

(2) Wavenumber-frequency spectrum of ***unsteady*** turbulent pressure and shear is important for structural vibrations and acoustic design.

TBL Pressure Fluctuations

- The stress fluctuations have particular **wavenumbers** at which **most of the energy** is concentrated.
- **Convecting turbulent stresses** (unsteady pressure and shear) are mainly **near $k=\omega/U_c$** where U_c is approximately $0.7U_\infty$
- **Acoustic** pressures are within the circle **$k<\omega/c$**

Bull, M. K. "Wall-pressure fluctuations beneath turbulent boundary layers: some reflections on forty years of research" ***Journal of Sound and Vibration*** **(1996), 190(3), pp. 299-315.**



Smallest Scales of Interest

- The **surface roughness** should be less than the **viscous sublayer thickness**, which is on the order of 5 wall units.

- Energy cascades down from the largest scale eddies to the **Kolmogorov microscale** where the energy is rapidly dissipated. This is the smallest scale of interest.

Wall Unit

$$y_w = \nu \sqrt{\frac{\rho}{\tau_w}}$$

For $Re_x \approx 10^7$

At $U_\infty \approx 250$ *m/s,* $\tau_w \approx 100$ *Pa* $\rightarrow$ $\boldsymbol{y_w \approx 2\ \mu m}$

So viscous sublayer thickness ≈ ***10 μm***

Kolmogorov Length Scale

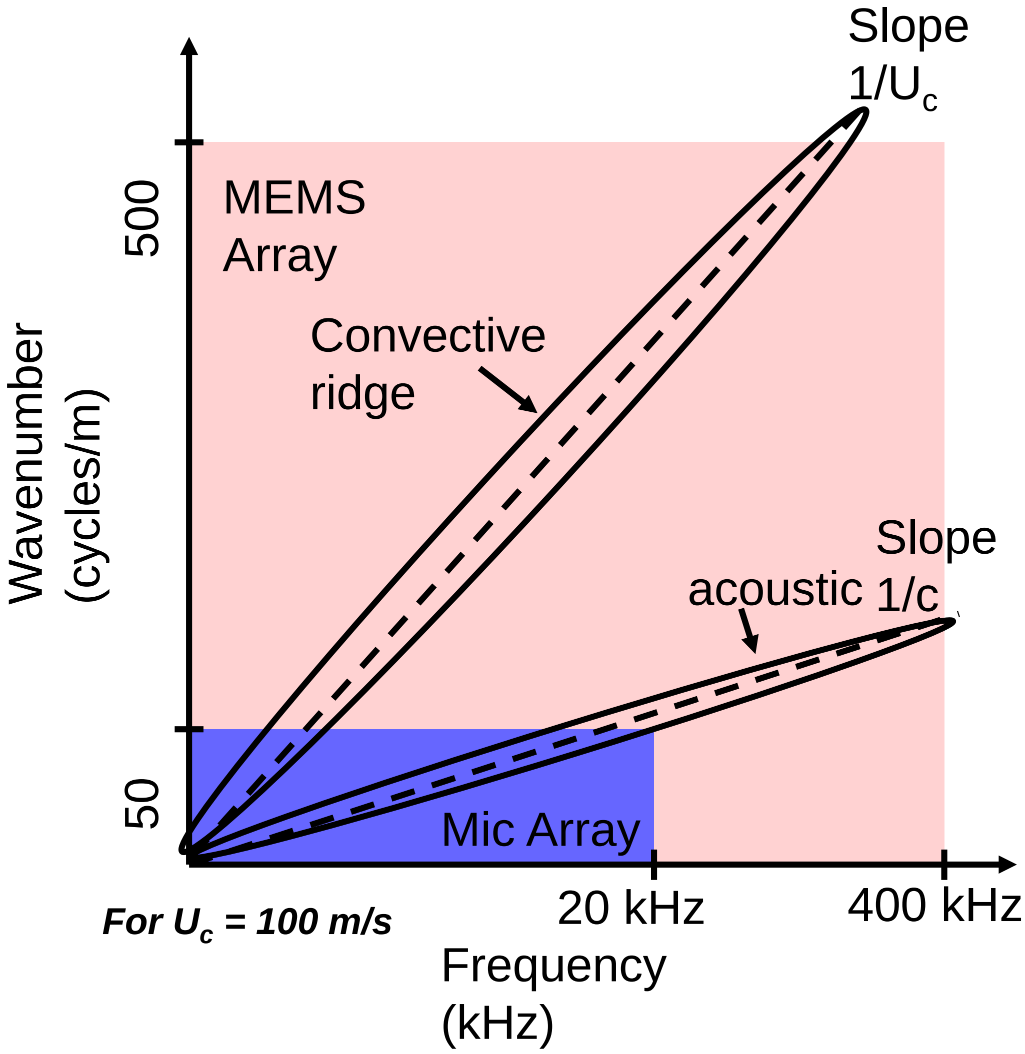
$$\eta \sim \left(\frac{\nu^3 \delta}{U_T{}^3}\right)^{\frac{1}{4}}$$

For $Re_x \approx 10^7$ at $x \approx 3$ m

At $U_T \approx 250$ *m/s,* $\delta \approx$ *3-5 cm* $\rightarrow$ $\boldsymbol{\eta \approx 5\ \mu m}$

See for example, Lofdahl and Gad-el-Hak, Meas. Sci. Tech, 1999

Wavenumber-Frequency Spectrum



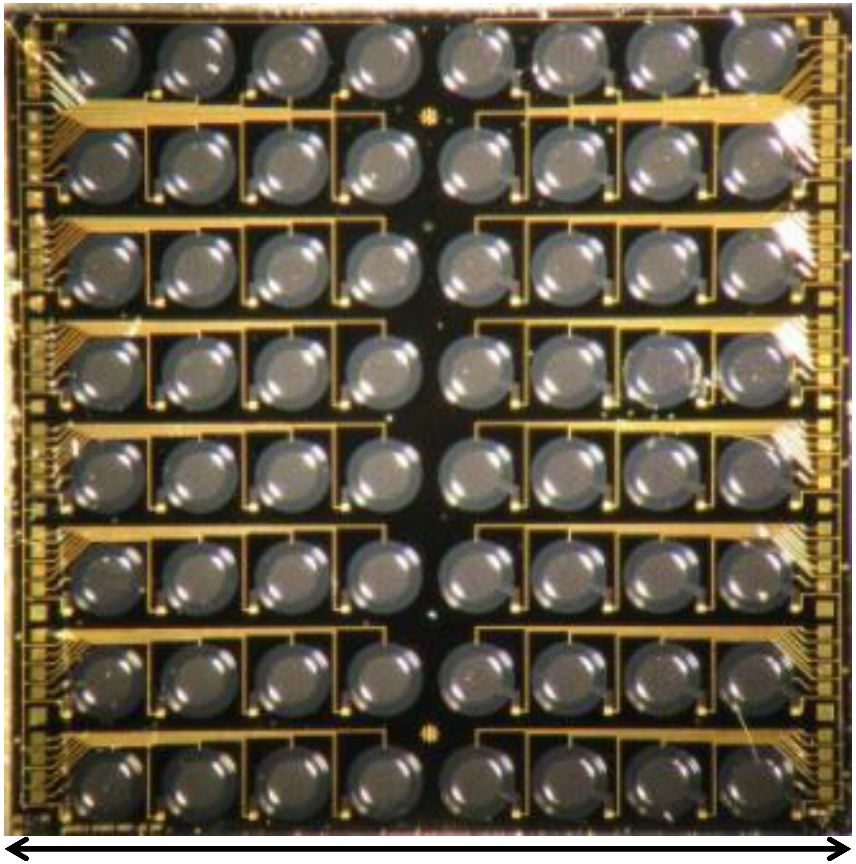
For U_c = 100 m/s

Advantages of a MEMS sensor array:

- **Fine pitch** to capture high wavenumber turbulent components (convective ridge, maybe eventually the Kolmogorov scales).
- **Low surface topology** to limit flow disturbance (< 10 μm).
- **Large dynamic range:**
  pressure: 60 to > 150 dB SPL
  shear: 0-100 Pa
- **Large frequency range** (DC to >300 kHz) useful for scale model measuments (λ/L remains constant).

Tufts - Microphone Array on a Chip

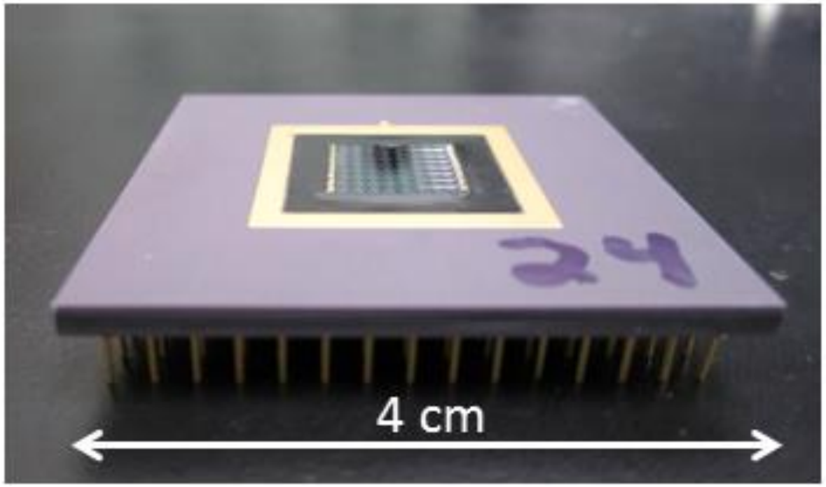
Primary feature: This system micromachines the array together on a single chip.

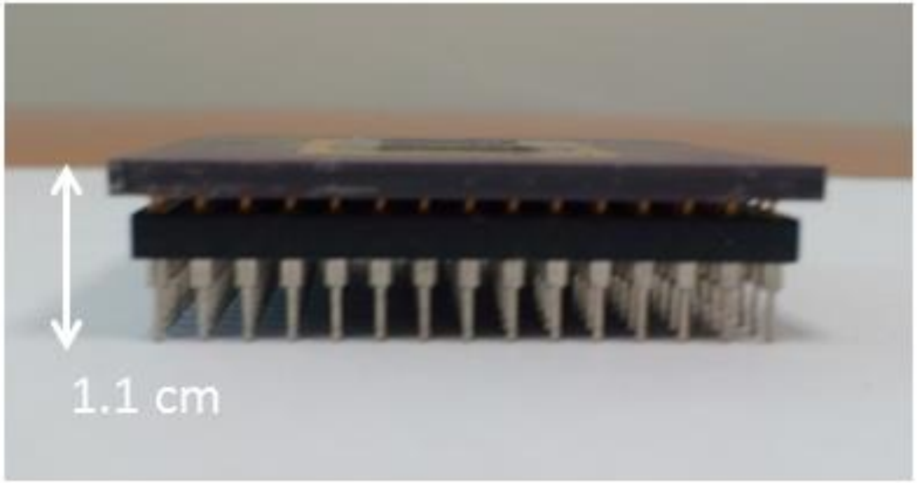


1 cm

- 8×8 array (64 elements) on a 1 cm^2 chip
- 0.6 mm diameter elements
- Element pitch is ~1.25 mm center-to-center.
- Microphones can be routed individually (as shown) or connected together in various parallel arrangements to act as larger aperture transducers.

Packaging

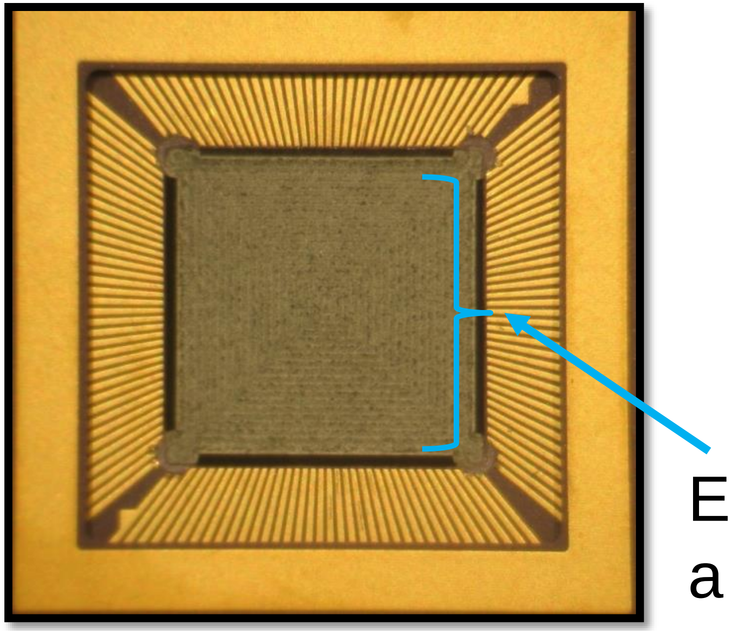




- Current design is packaged in a **4 cm x 4 cm** CPGA.
- Package **height is 1.1 cm** to the bottom of the pins.

Packaging – Step 1

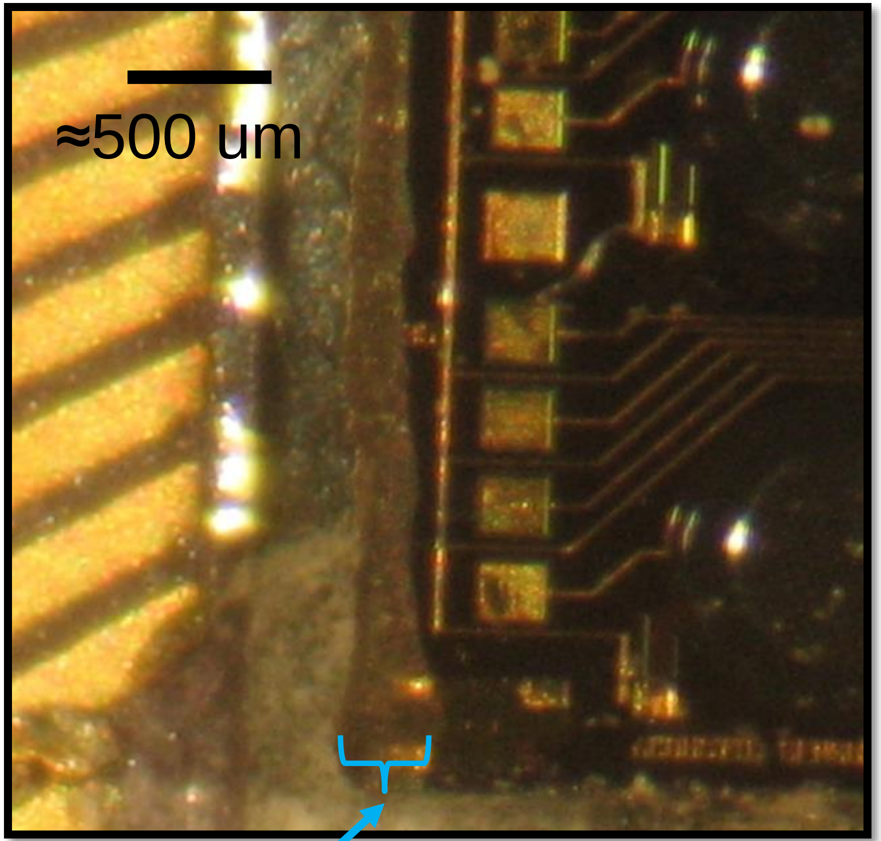
- Packaging uses a **hybrid CPGA package** and **wirebonding**.
- The first step is to partially fill the cavity with potting epoxy.
- The epoxy is milled down using a Roland MDX40A milling machine.



Epoxy is milled down to create a pocket to set the chip height and center the chip.

Packaging – Step 2

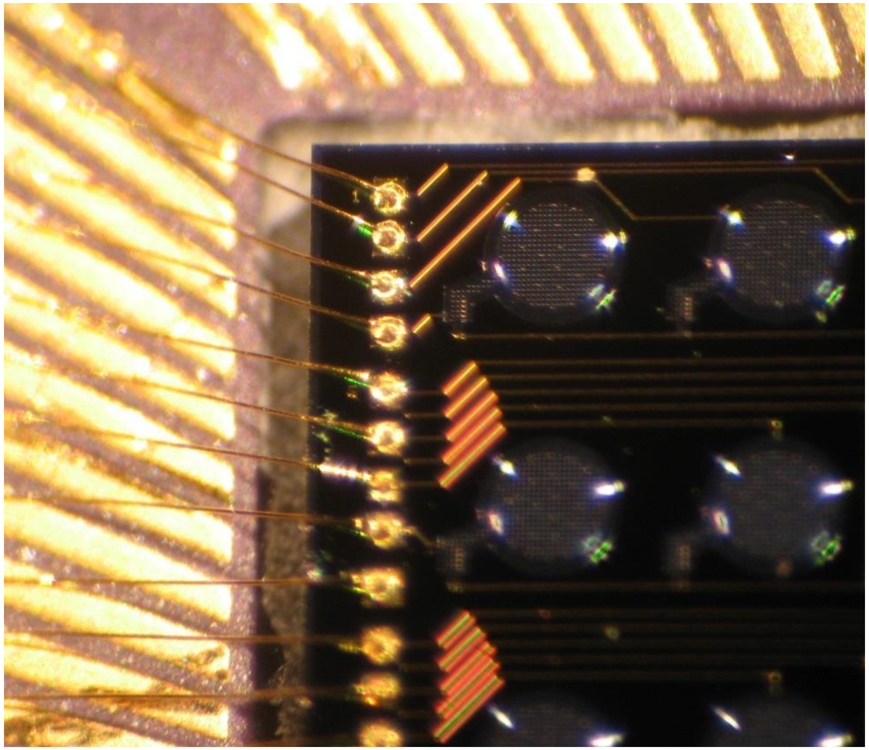
- The edge of the die is protected by hand-painting on additional epoxy.
- This step was added to avoid shorting problems where the wirebonds would touch the edge of the die which is bare silicon.
- This step is difficult and is a source of failure due to either too much or too little epoxy.

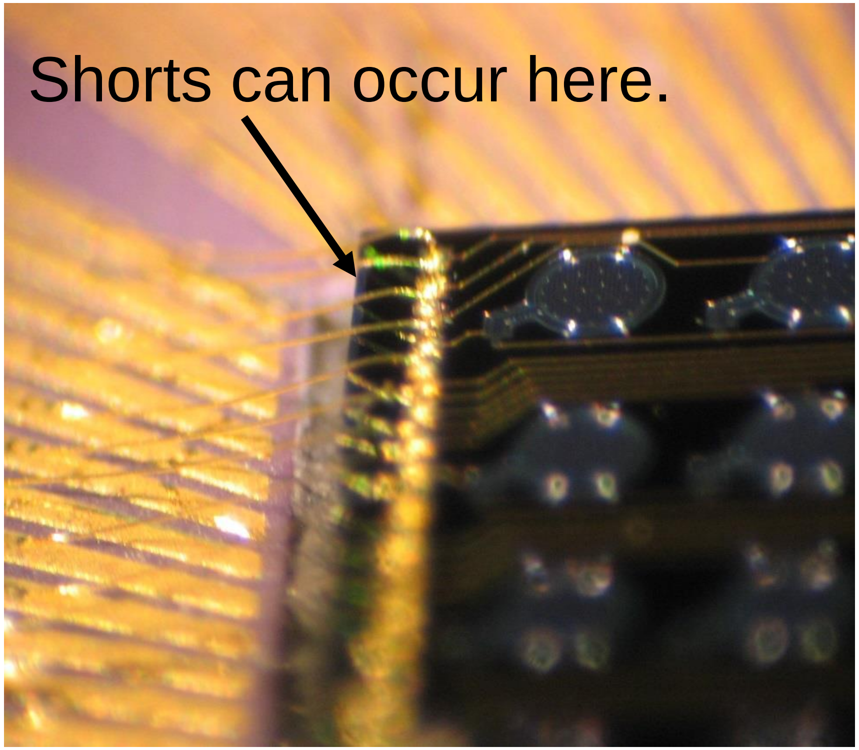


Epoxy hand painted on edge to cover the corner.

Packaging – Step 3

- Wirebonds are used to make the connections. These are 1 mil gold ball bonds.
- The largest cause of microphone failures is shorting of the wirebond to the silicon at the edge of the die.



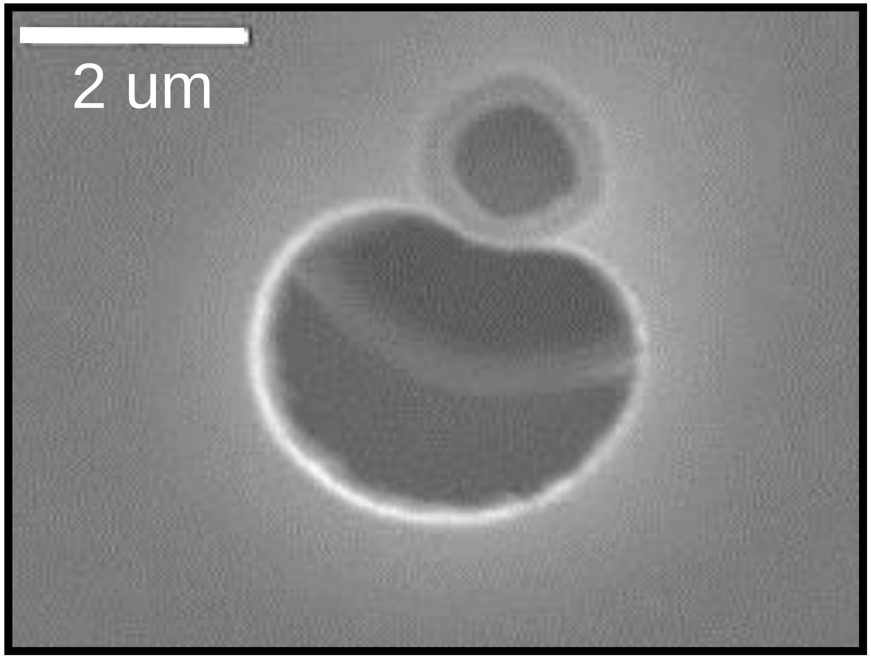


Shorts can occur here.

Diaphragm Vent Holes

- Due to misalignment during fabrication, the diaphragm vent holes were larger than designed.

- The sensor and wirebonds are then fully coated in Parylene-C, a pinhole free vapor phase deposited polymer that can act as a moisture barrier.

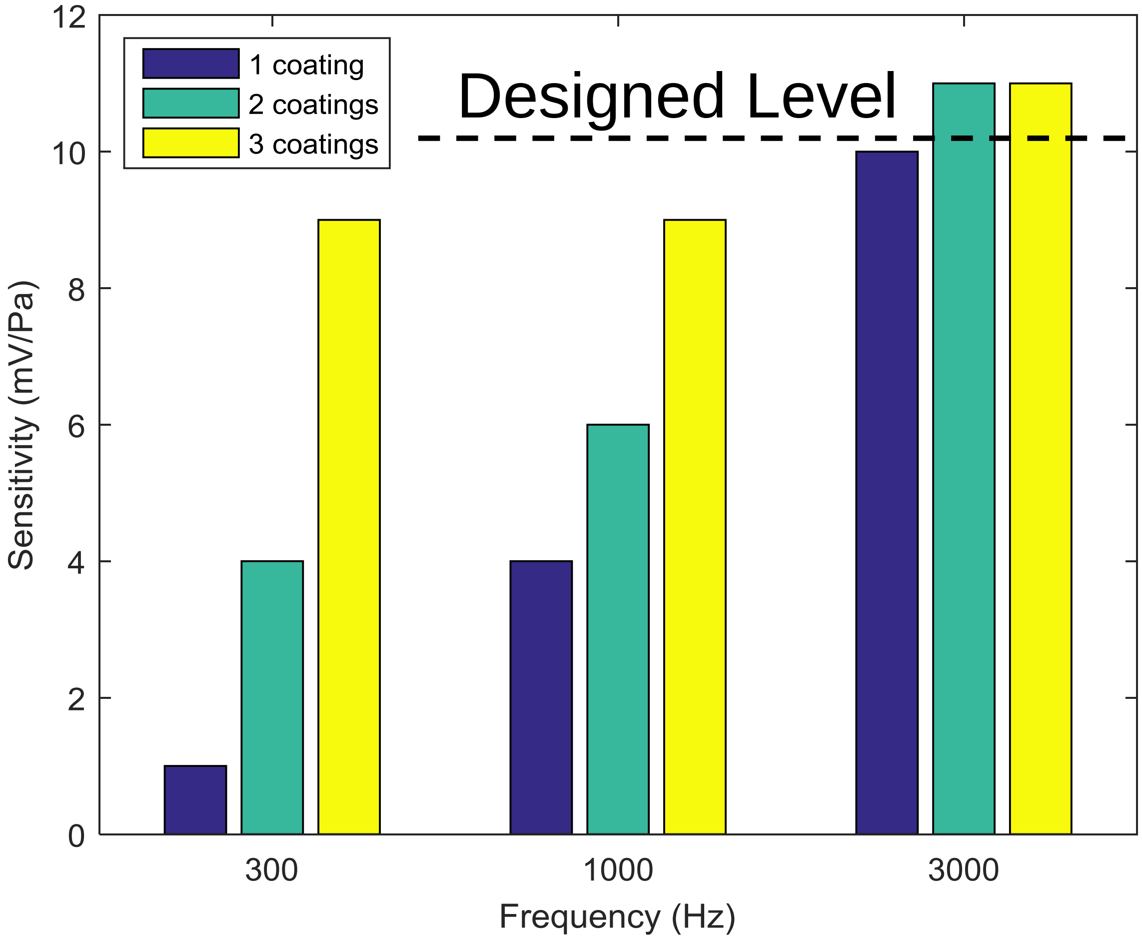


- The Parylene also allows control of the size of the vent holes in the diaphragm.

Parylene Coating – Step 4

- Acoustic calibration data shows the recovery of the low frequency sensitivity as the vent hold diameter is reduced by subsequent Parylene depositions.

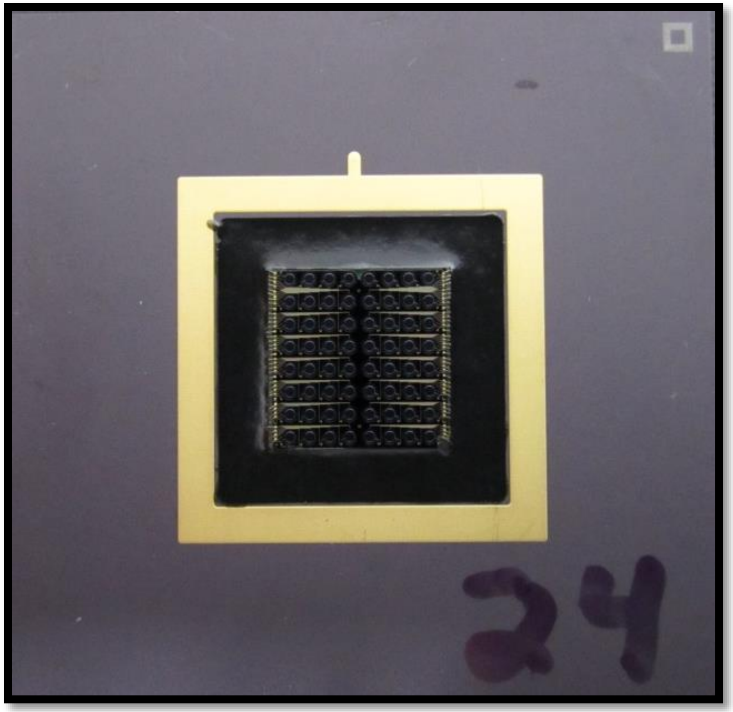
- Each layer deposited here was approximately 500 nm thick.



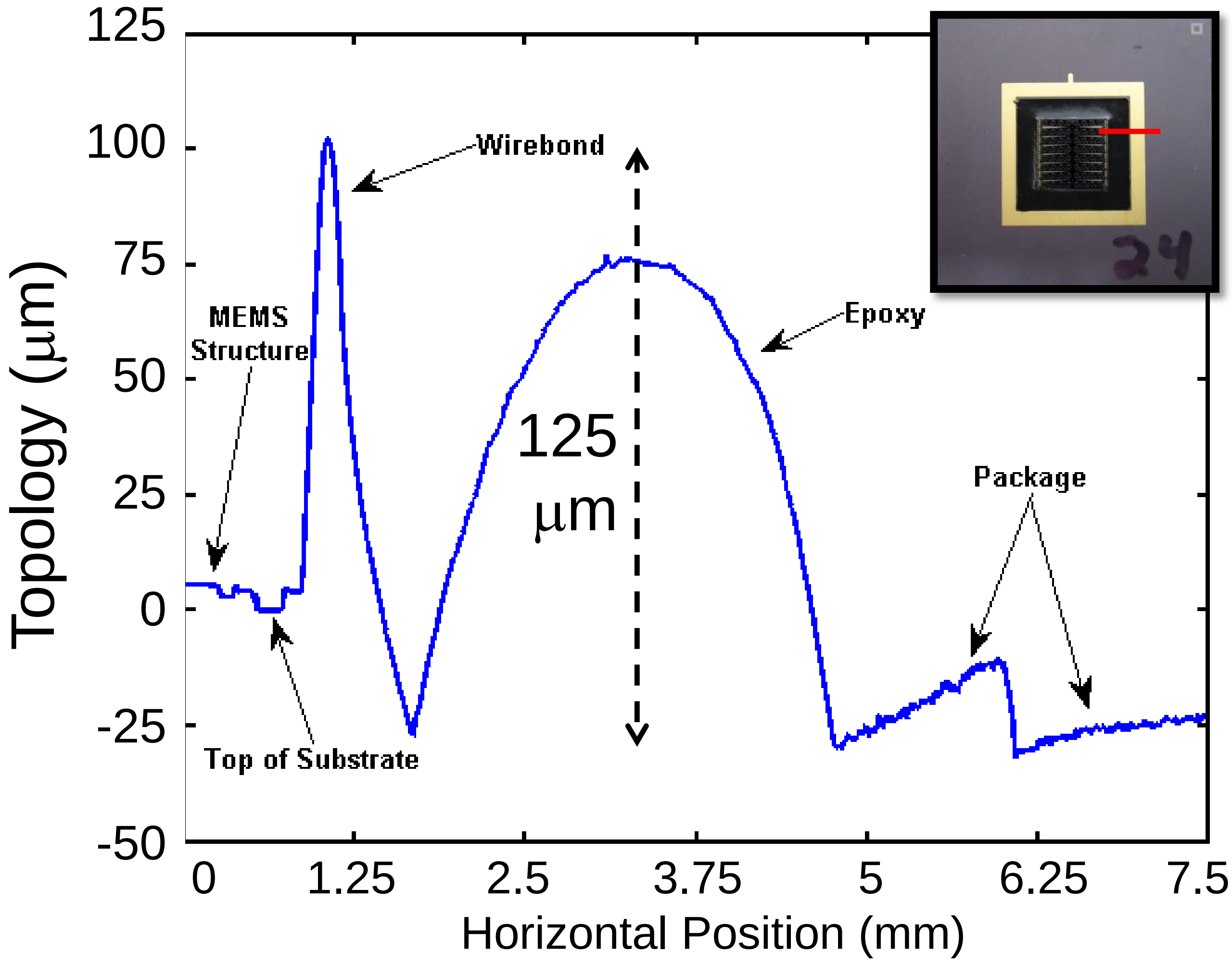
Packaging – Step 5

- In the final step, potting epoxy is used to fill the cavity and cover the wirebonds.

- The filling epoxy is done in multiple steps with cures in between until a flat top surface is achived.



Surface Topology



- Surface topology due to wirebonds is 100 microns.
- Chip to package topology is 25 microns.
- Surface roughness from package to tallest feature is on the order of 125 microns.

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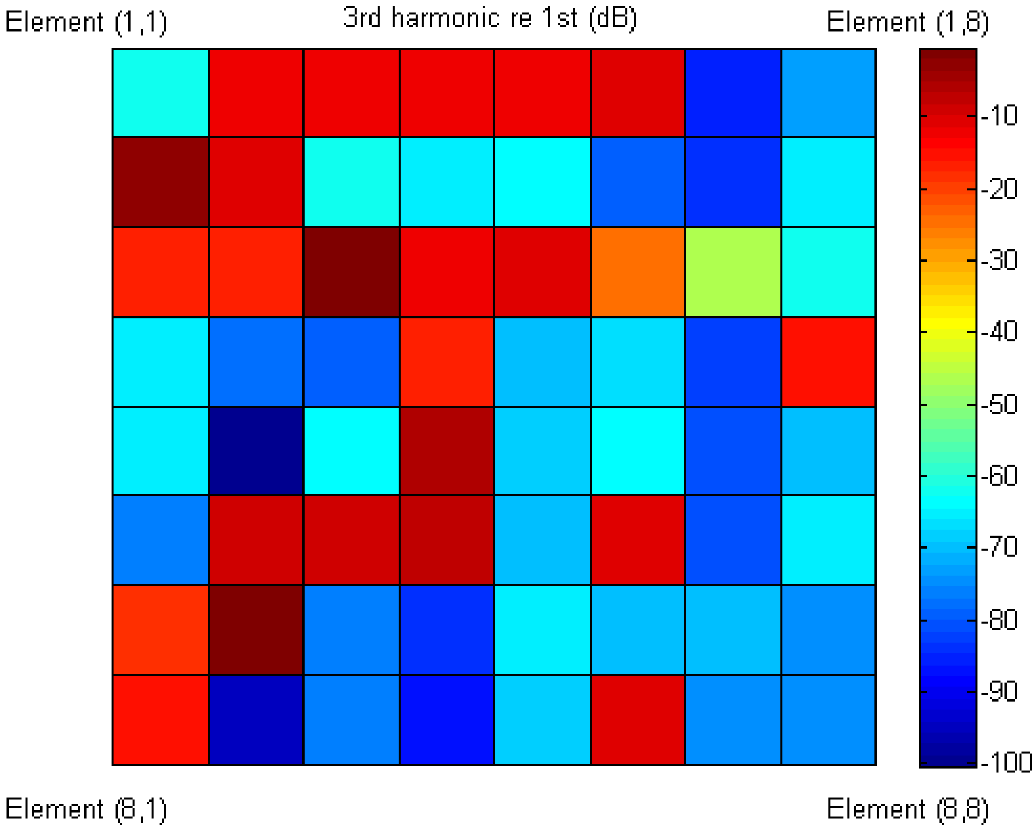
Yield

- Microphone yield is tested by observing the distortion when the microphone is driven electrostatically.

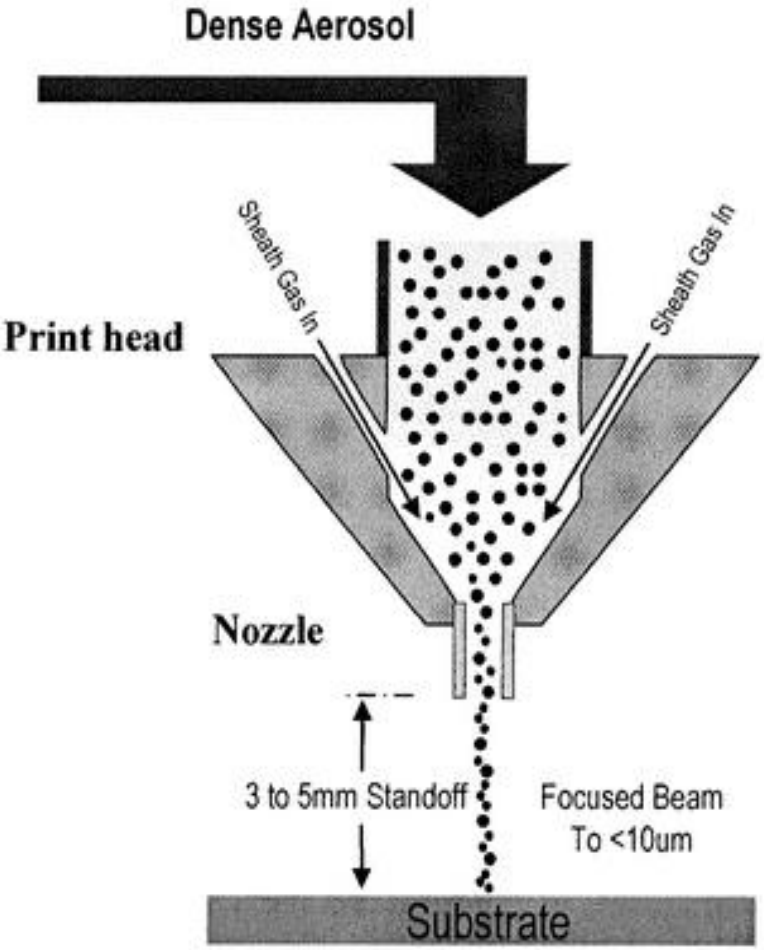


- A 3rd harmonic distortion of worse than -60 dB is considered a failure.

- For this recently packaged device, 25/64 microphones fail (39%). This is primarily due to shorts between the wirebonds and the silicon die corner.

Aerosol Jet Printing

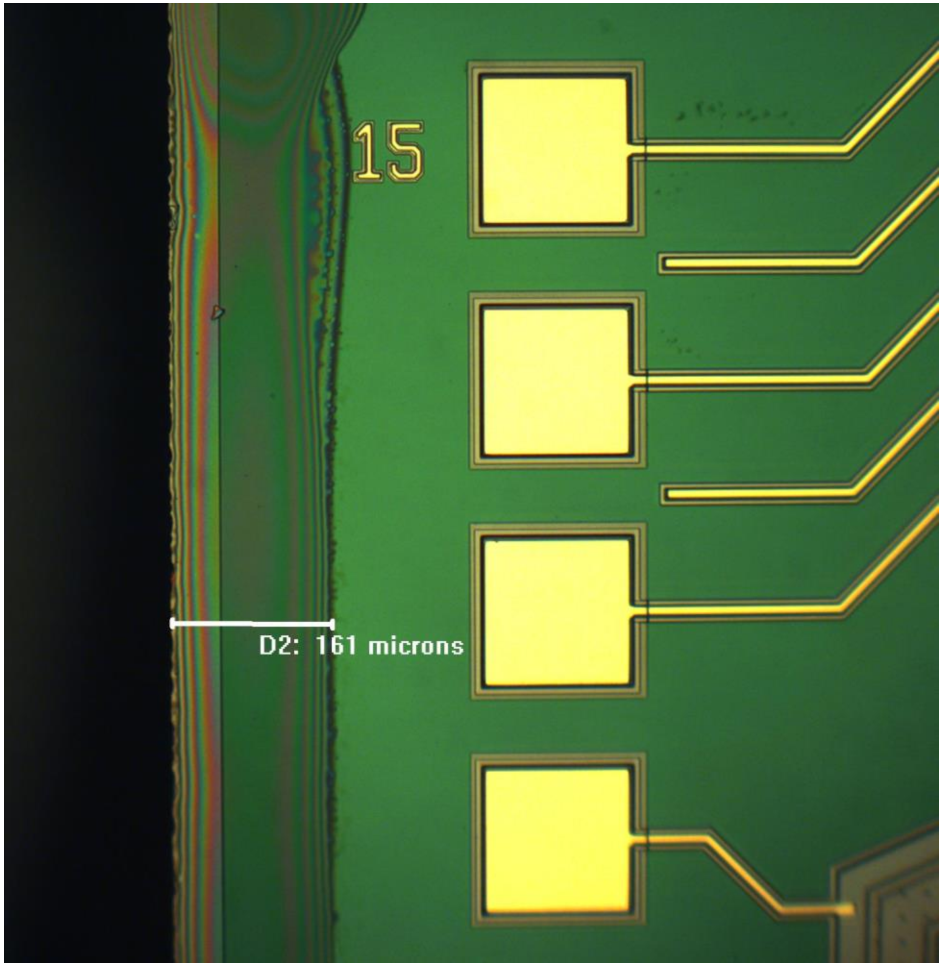
- To address this problem, an aerosol jet printing (AJP) method was used to print polyimide along the edge of the die.
- The primary advantage of AJP for this application is the standoff distance, which is much larger than inkjet.



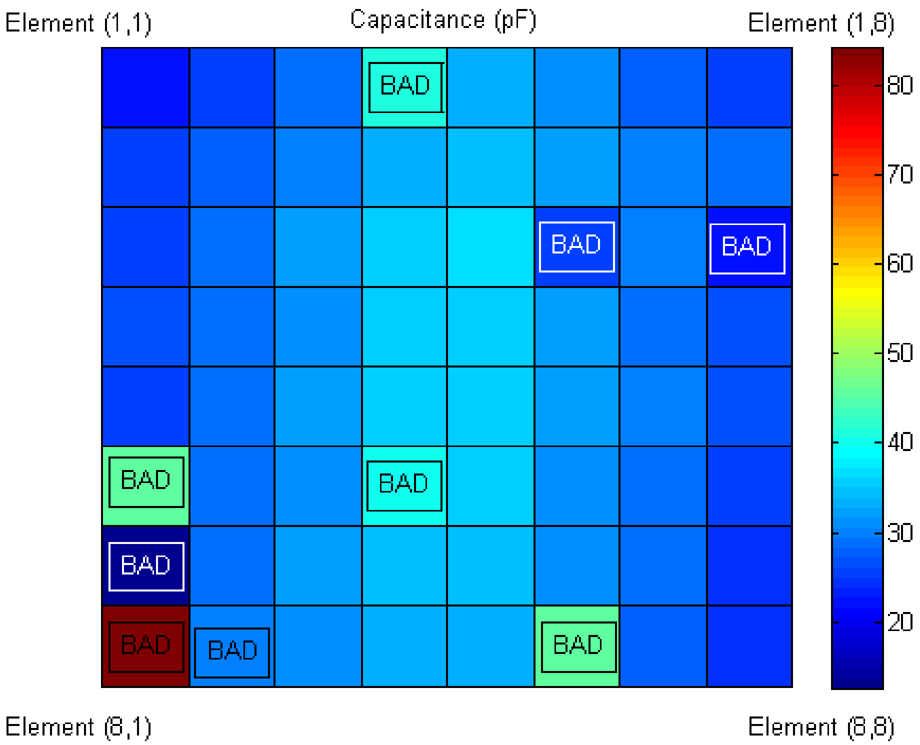
J. Chou, M. McAllister, and P. Schottland, "Aerosol Jet Printable Metal Conductive Inks, Glass Coated Metal Conductive Inks and UV-curable Dielectric Inks and Methods of Preparing and Printing the Same," 2014.

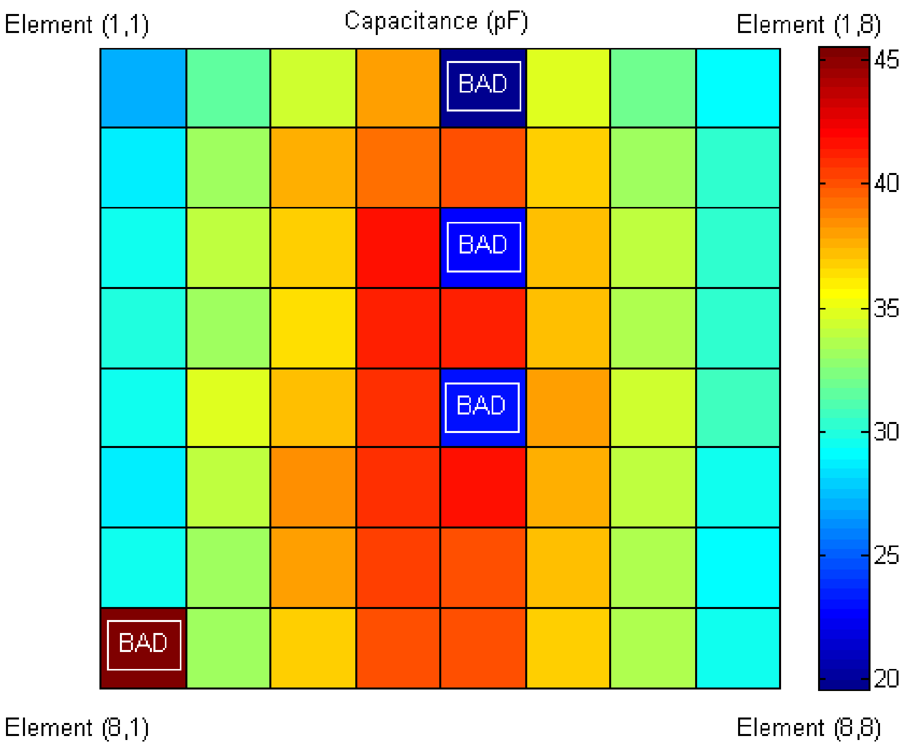
Polyimide Insulation by AJP

- NeXolve Corin XLS Polyimide ink in an Optomec 300 printing system.
- Two layers were printed, 150 um wide lines 50 um in from the die edge.
- Cured in air in an oven overnight at 130 C (13 hours).
- Gold wirebonds were used as before.



Improved Yield


Chip #1


Chip #2

- With the AJP printed insulation, the number of bad microphones drops to 9/64 (14%) on Chip #1, and 4/64 (6%) on Chip #2.

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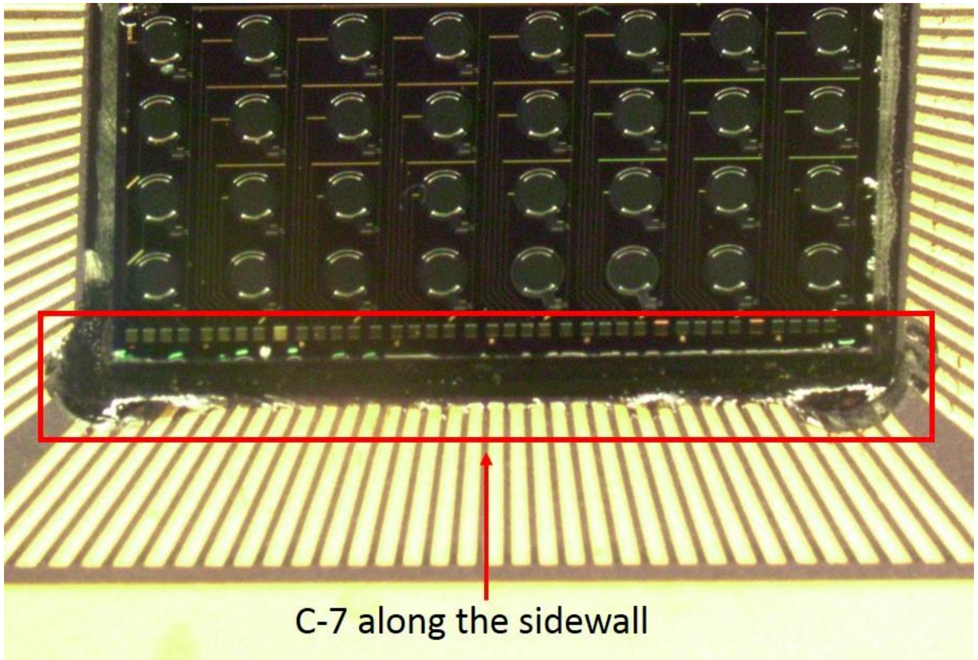
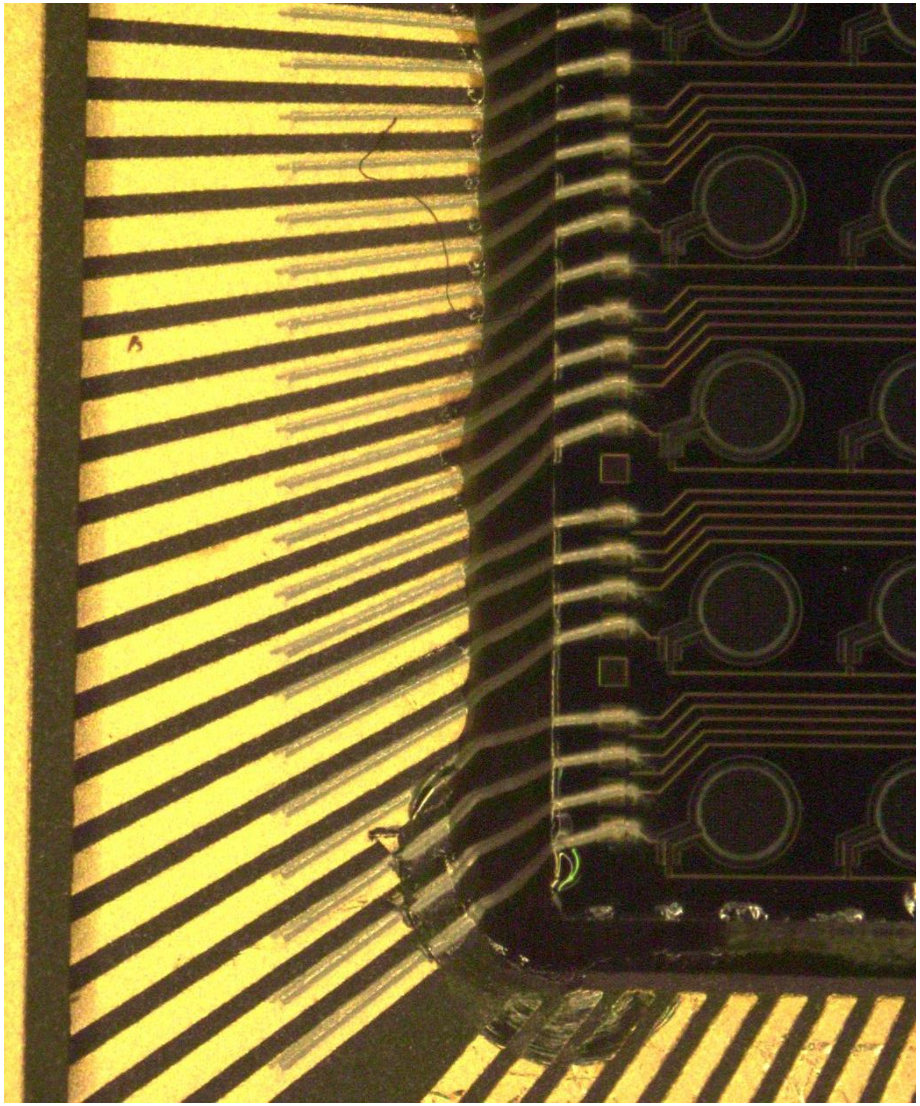
Silver Ink Interconnect by AJP

- First, Armstrong C-7 epoxy was hand applied along the edge of the die to provide a fillet between the die and the package.
- NeXolve Corin XLS Polyimide ink was then AJP printed along the corner and cured, identically as done with the previous chip.



Silver Ink Interconnect by AJP

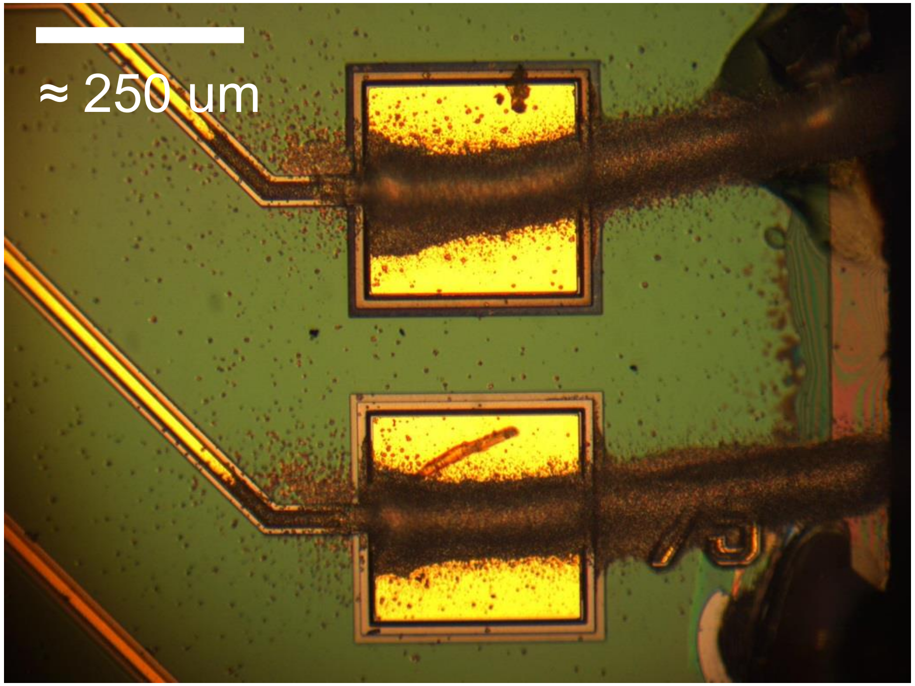
- Interconnects were then printed using NovaCentrix HPS-030AE1 Silver Flake Ink in the Optomec 300 printing system.
- All interconnects taken from CAD file; alignment to chip and package corners.
- Sintered 19.5 hours for 130°C in oven.

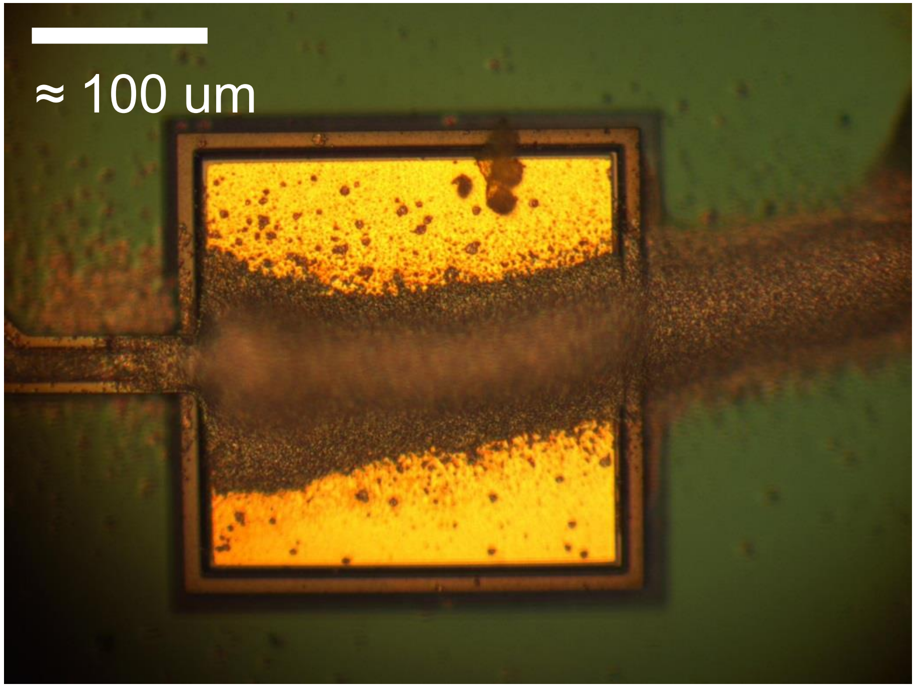


Silver Ink Interconnect by AJP

- Interconnect lines are approximately 130 um wide.

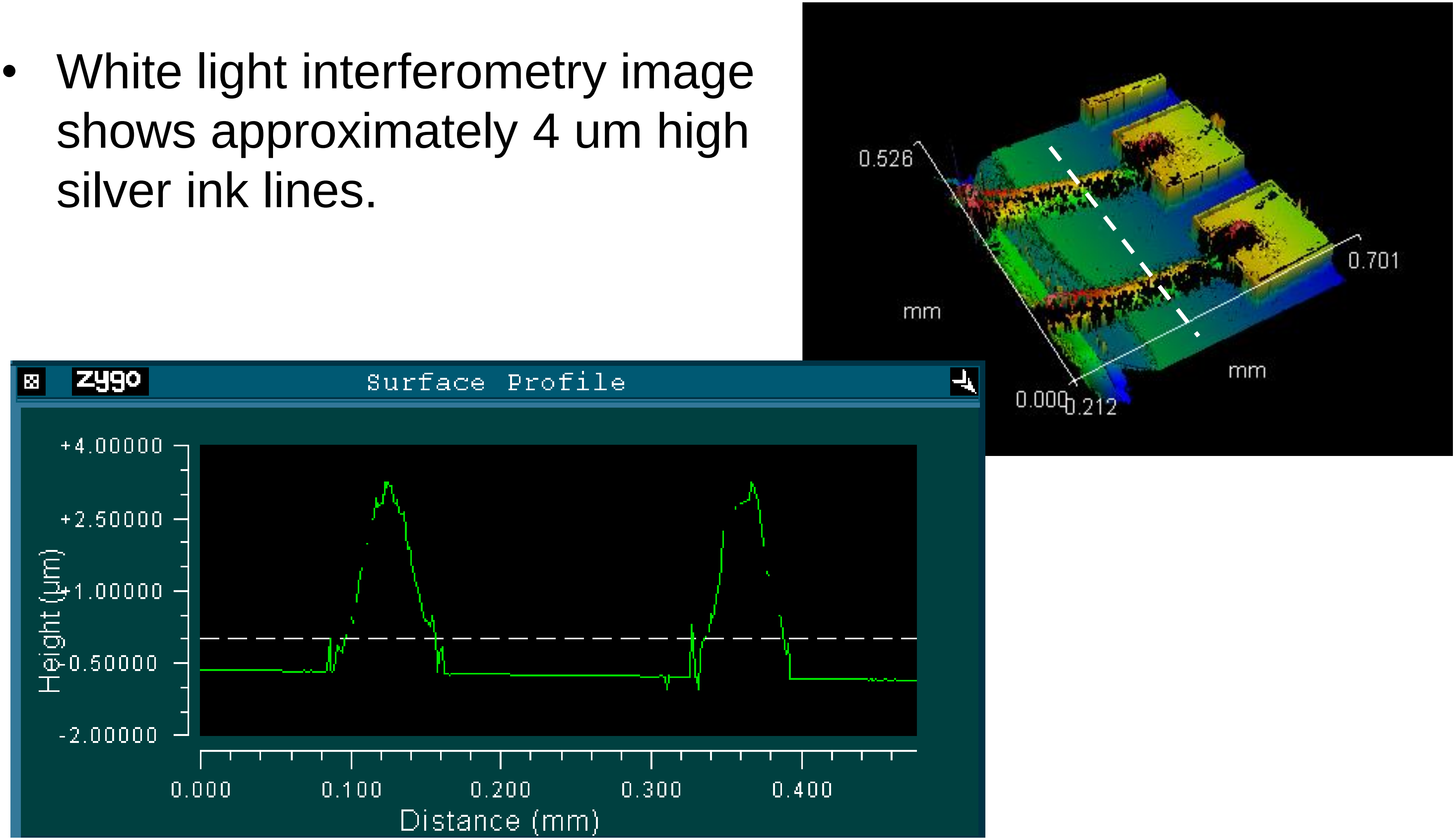
- Some overspray is observed.





Silver Ink Interconnect by AJP

- White light interferometry image shows approximately 4 um high silver ink lines.



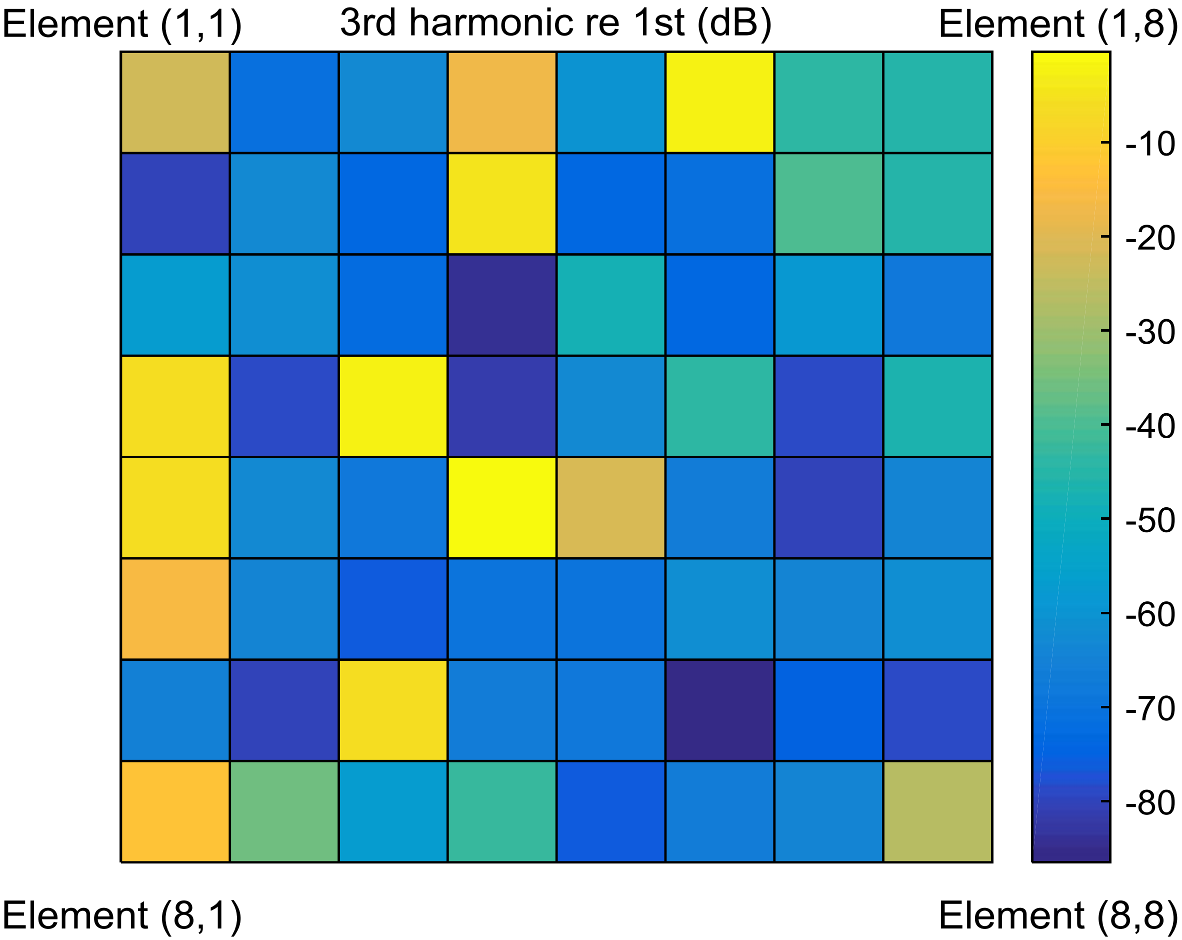
Yield with AJP Silver Ink Interconnect

With this first attempt at AJP silver ink interconnect:

- 37/64 (58%) of elements are successful

- 25/64 (39%) of elements are shorted

- 2/64 (3%) appear unconnected



Conclusions

- Packaging topology of 0.13 mm is too high for aeroacoustic MEMS measurement applications under the turbulent boundary layer.
- Aerosol Jet Printing (AJP) was explored to improve yield and reduce MEMS-package interconnect topology.
- AJP polyimide insulation was successful at reducing defective elements from 39% to 6% by preventing shorting of wirebonds to the silicon die corner.
- AJP silver ink interconnects were successfully printed, and on our first module 58% of the microphone elements are active.
- 39% of the microphones are shorted to the substrate. This may be due to pinholes or incomplete coverage in the AJP polyimide at the chip edge, or possibly due to overspray.