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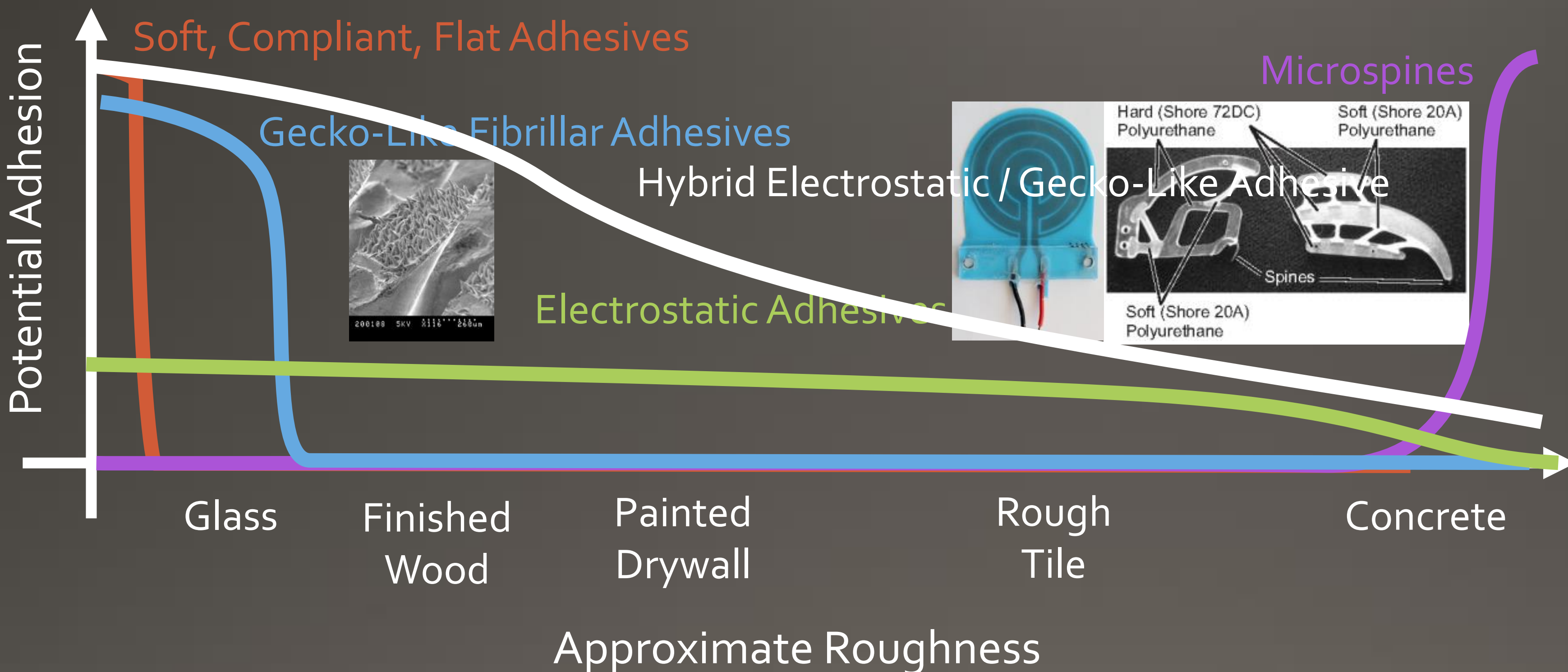
Hybrid Electrostatic/Gecko-Like Adhesives

Motivation



Provides greater adhesion over a wider range of surface roughness than both electrostatic and dry adhesives

Key Contributions

Question 1

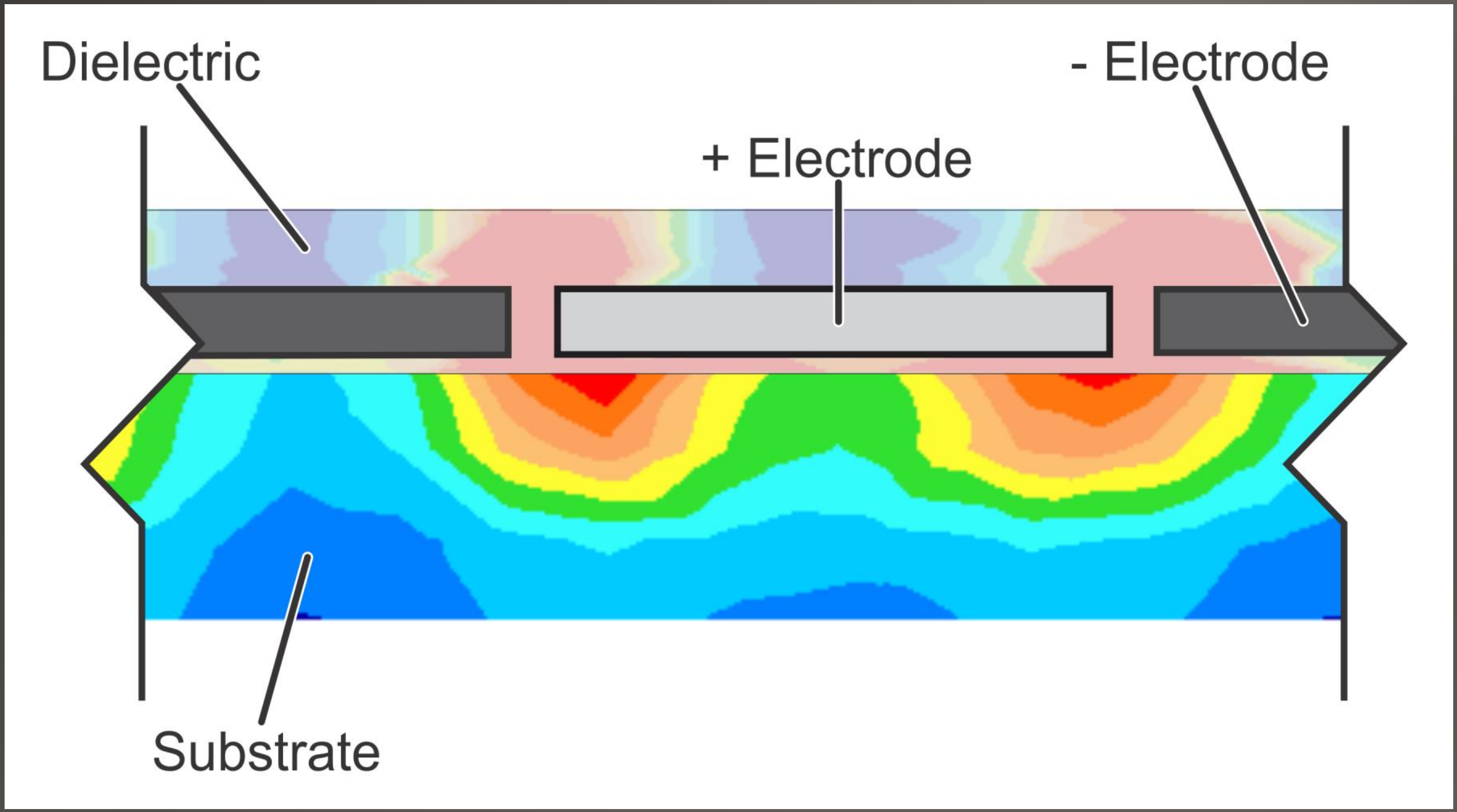
- How can we maximize the electrostatic adhesion force for smooth to micro-rough surfaces?

Question 2

- How can we integrate electrostatic adhesion with directional dry (gecko-like) adhesives for smooth to micro-rough surfaces?

Part 1:

Electrostatic Adhesion



- No chemical bonds
- Operate in a vacuum
- Applicable to most surfaces
- Relatively weak adhesion
- Does not work on some plastics

How Can We Increase the Electrostatic Adhesive Force?

Contact Area

Dielectric Constant

Electrostatic Force

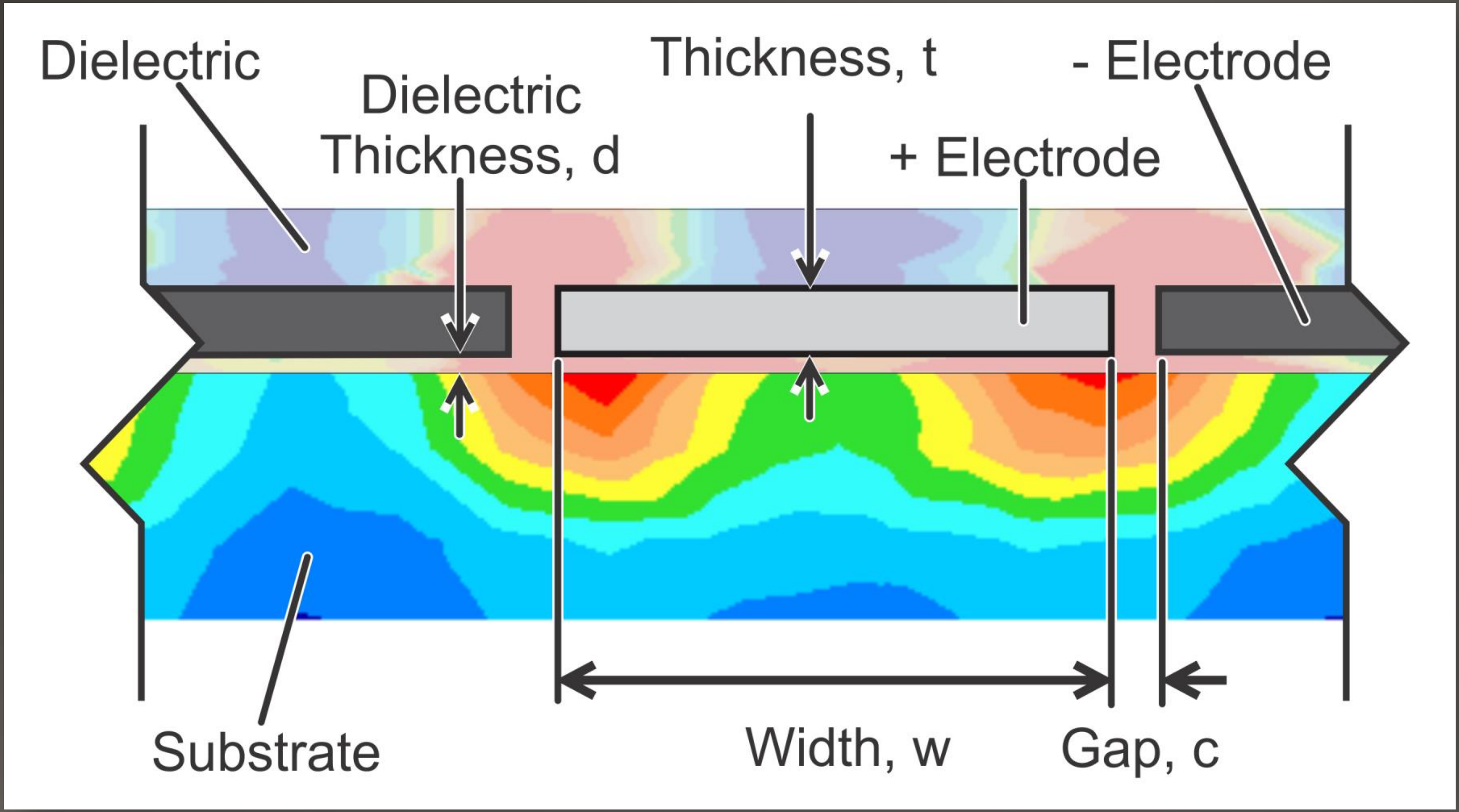
Applied Voltage

$$F = \frac{A \, \varepsilon_r \, V^2}{2 \, d^2}$$

Dielectric Thickness

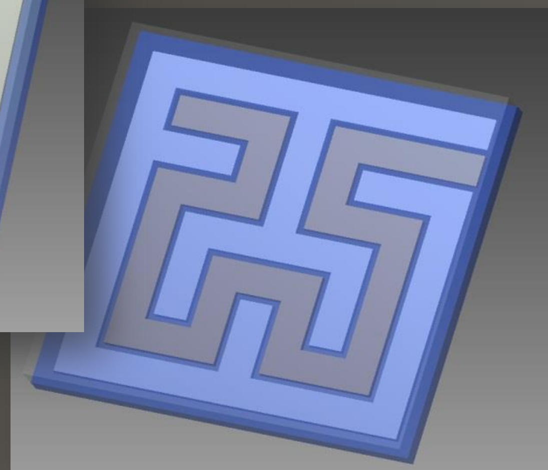
*Monkman, G.J. "An analysis of astrictive prehension". International Journal of Robotics Research, Vol. 16 No 1.

Evaluate Electrode Geometry



Evaluate Electrode Patterns

Interdigital or Comb

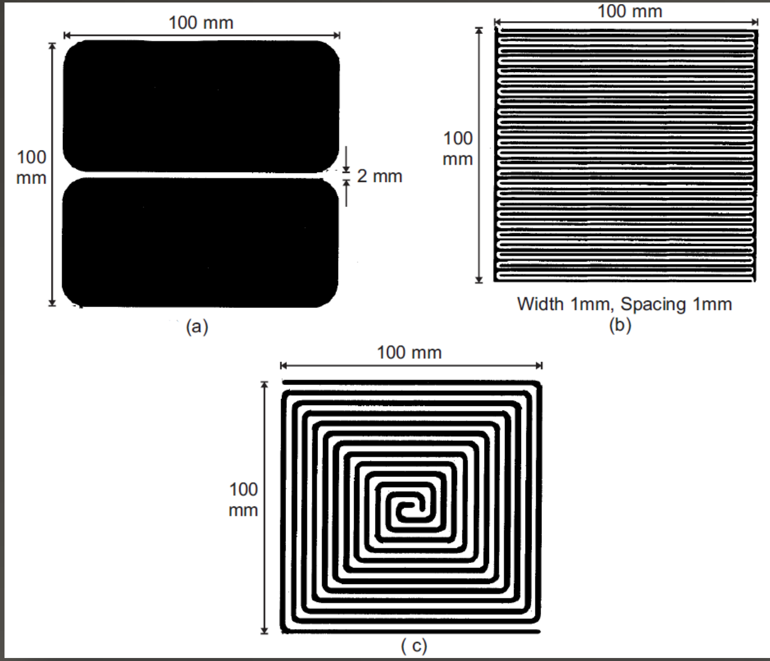


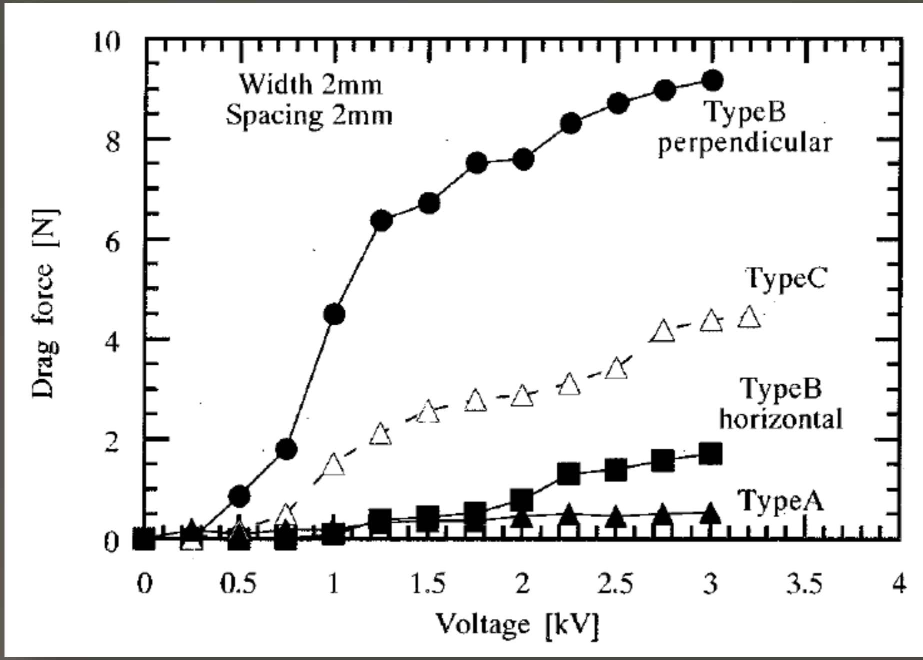
Hilbert Curve

Concentric Circles

Square Spiral

Previous Research

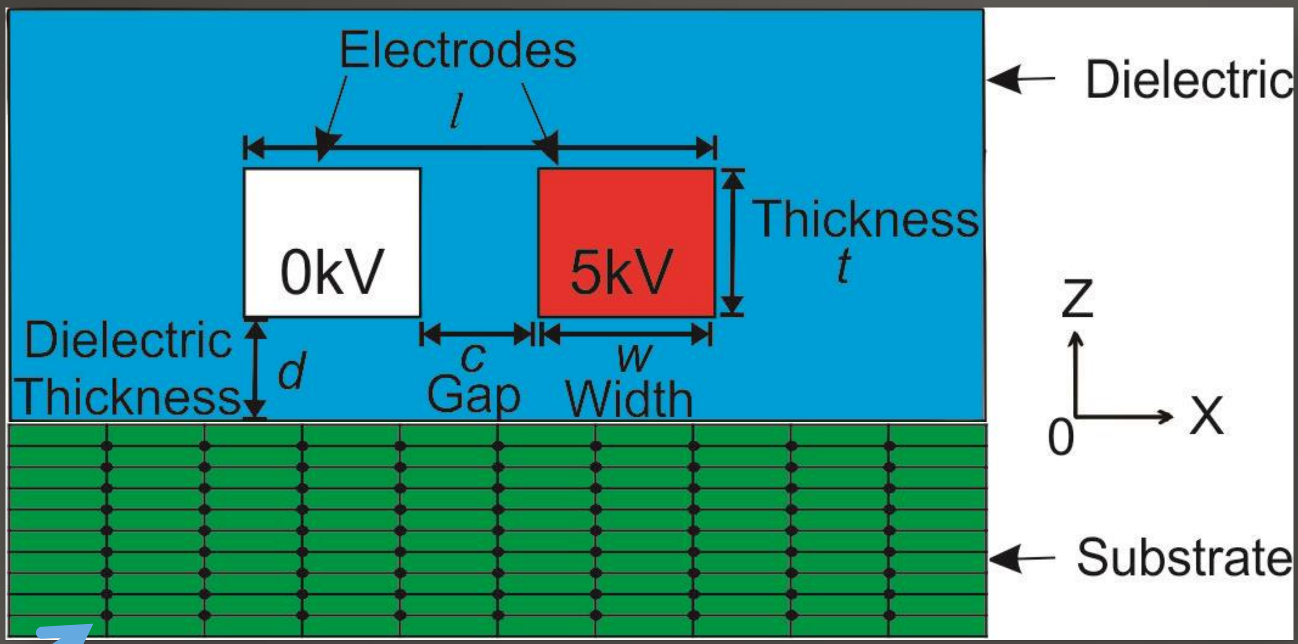




Shear force for different electrode configurations

- Asano, K., Fumikazu H., and Yatusuzka, F.

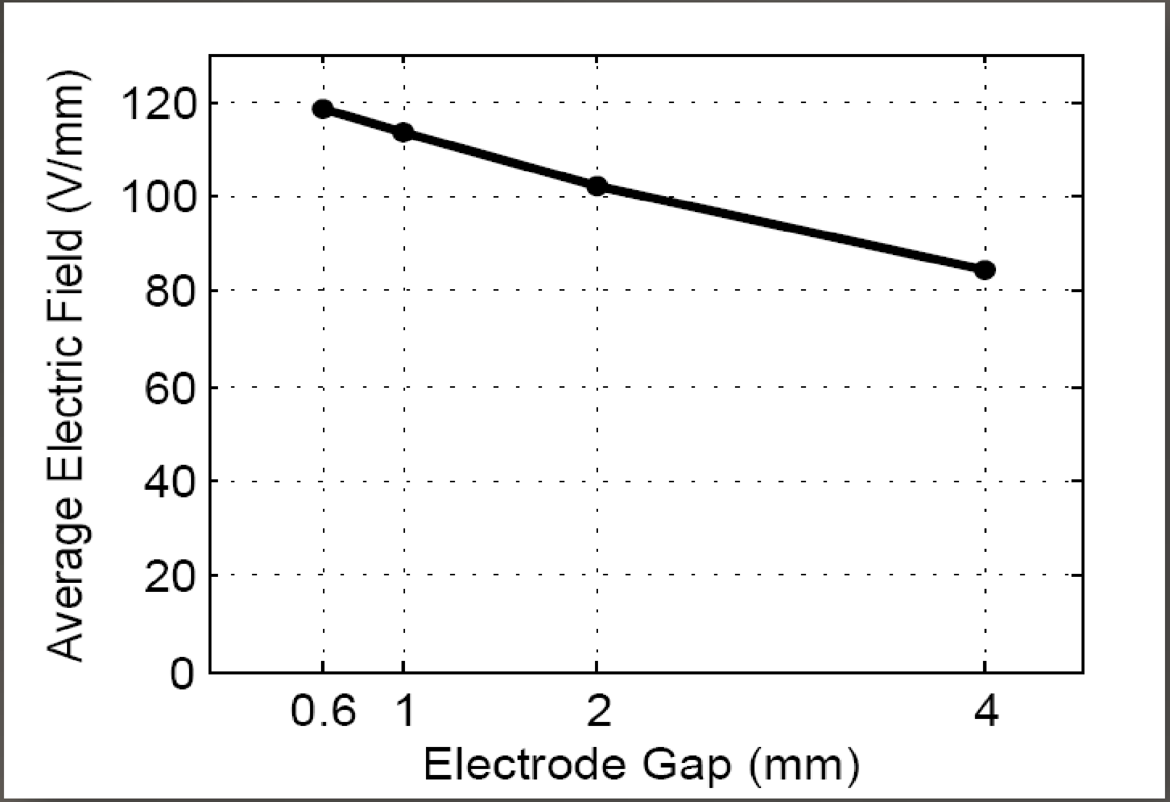
Simulation



Node

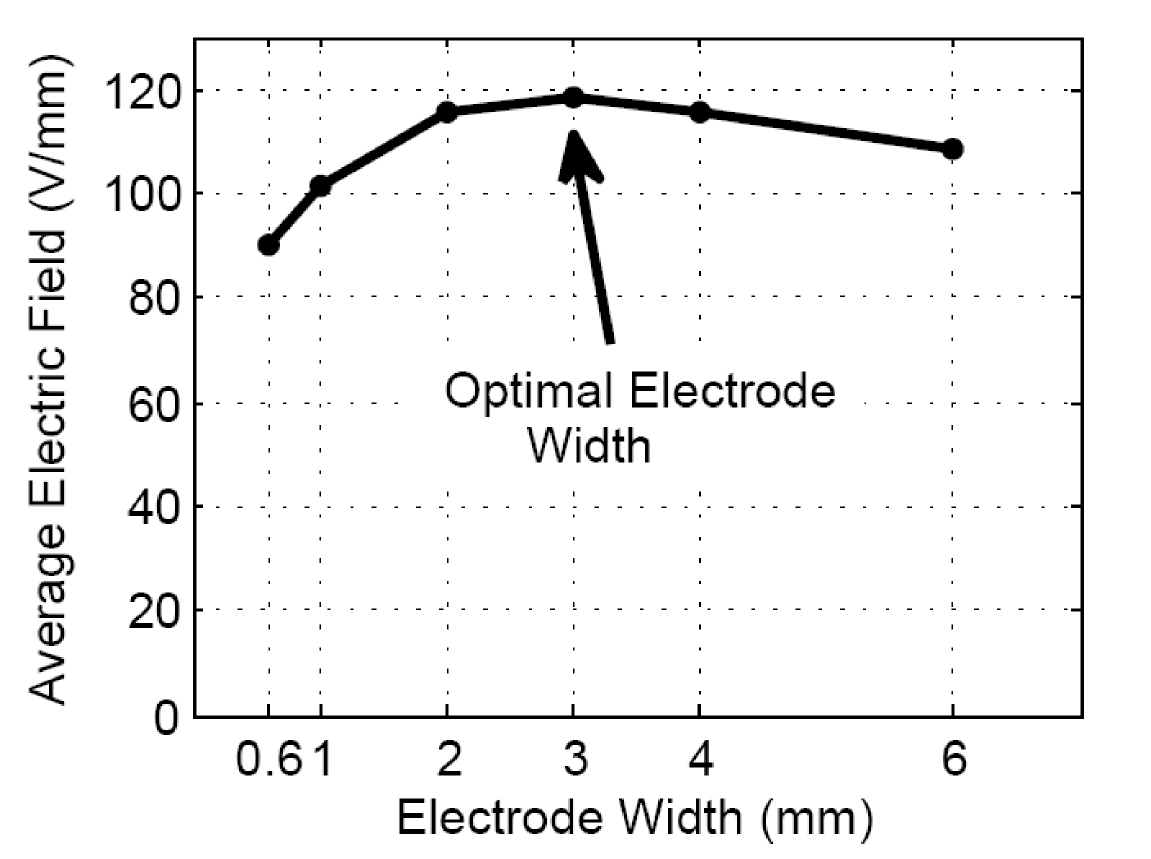
Electric Field measured at each node

Simulation Result 1 – Make the Electrode Gap as Small as Possible



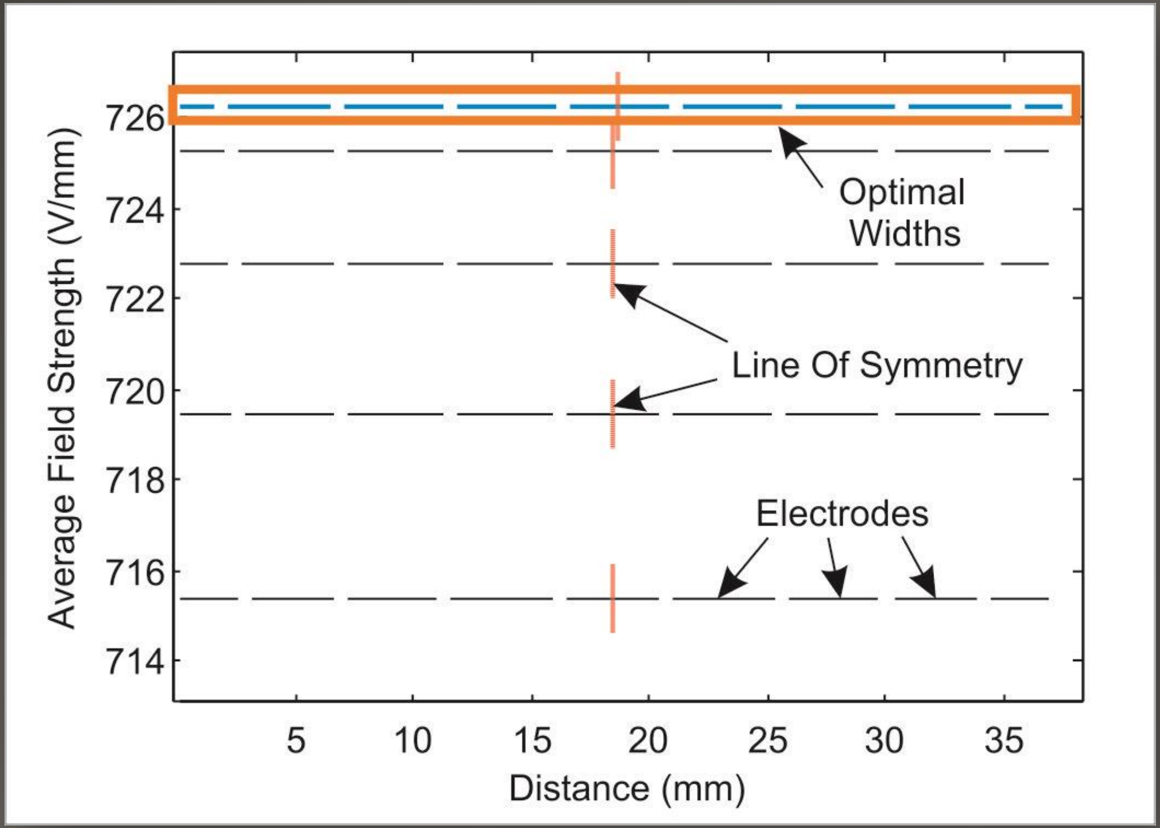
Fixed Electrode Width of 3 mm

Simulation Result 2: An Optimal Electrode Width Exists



Fixed Gap distance between electrodes of 0.6 mm

Simulation Result 3: Electrode Width Varies as a Function of Its Location

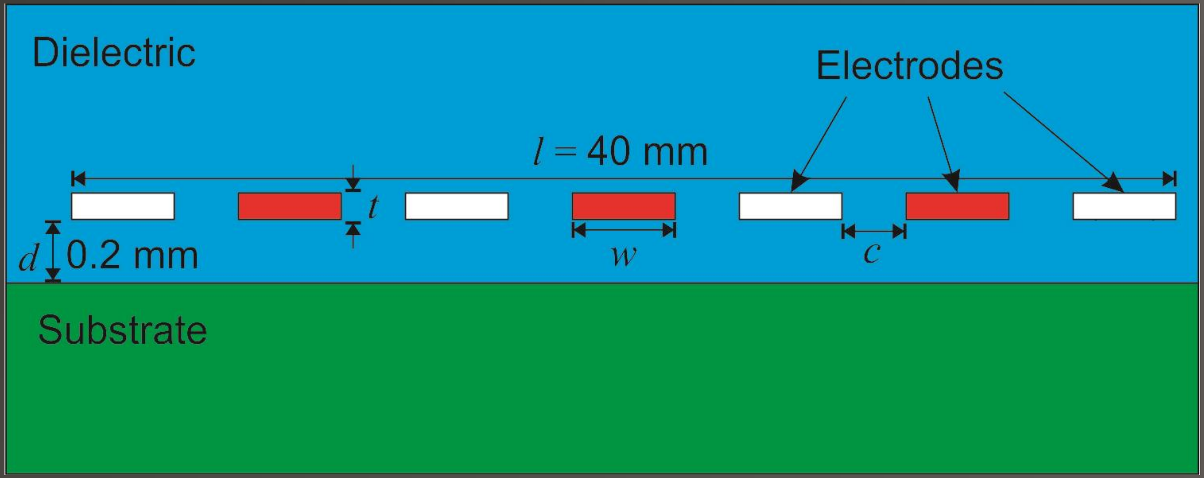


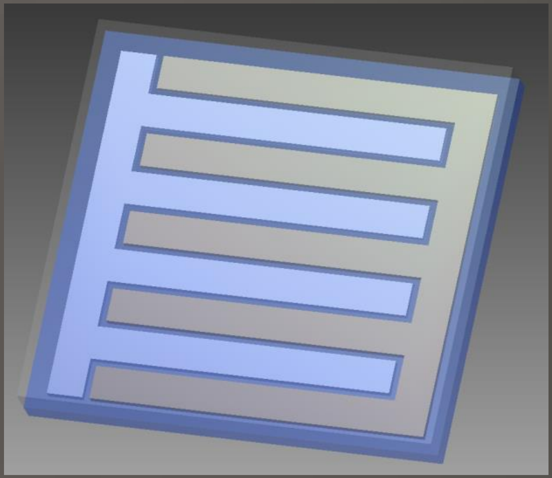
Varying Electrode Width – fixed gap (0.6 mm)

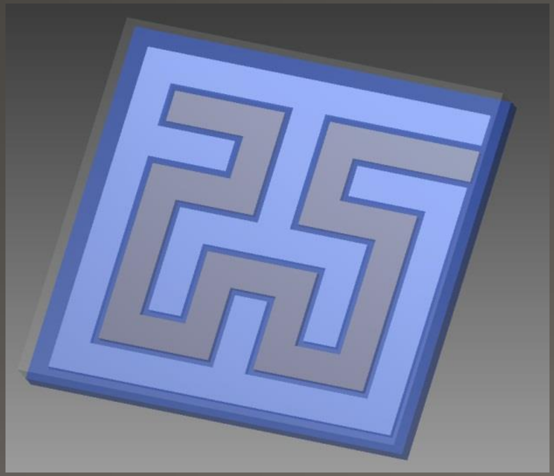
Simulation Results Summary

Variables	Optimal (mm)	Affects Electric Field
Gap, *c*	As small as possible	Yes
Thickness, *t*	N/A	No
Width, *w*	Varies	Yes

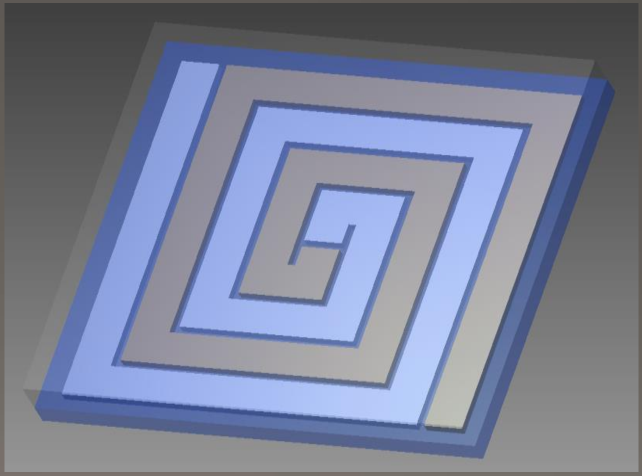
Simulation



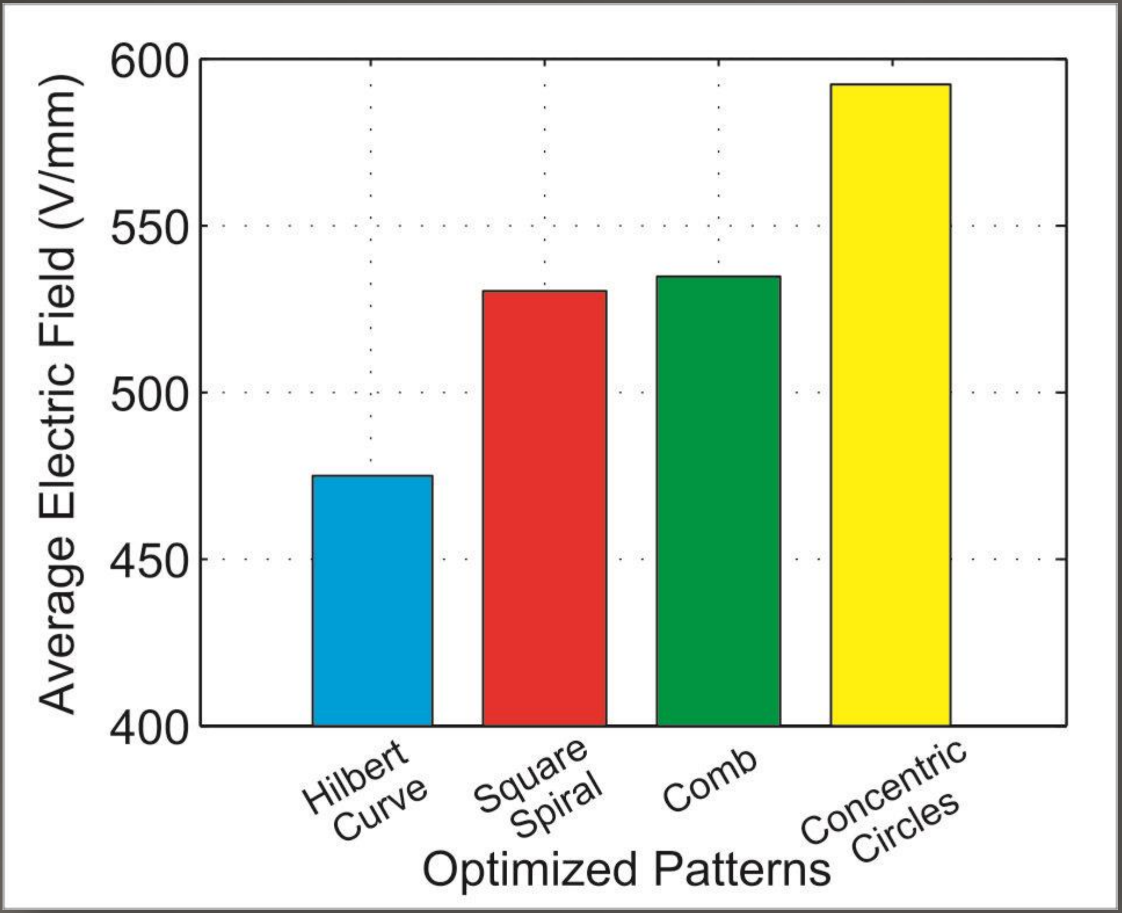

Comb


Hilbert Curve

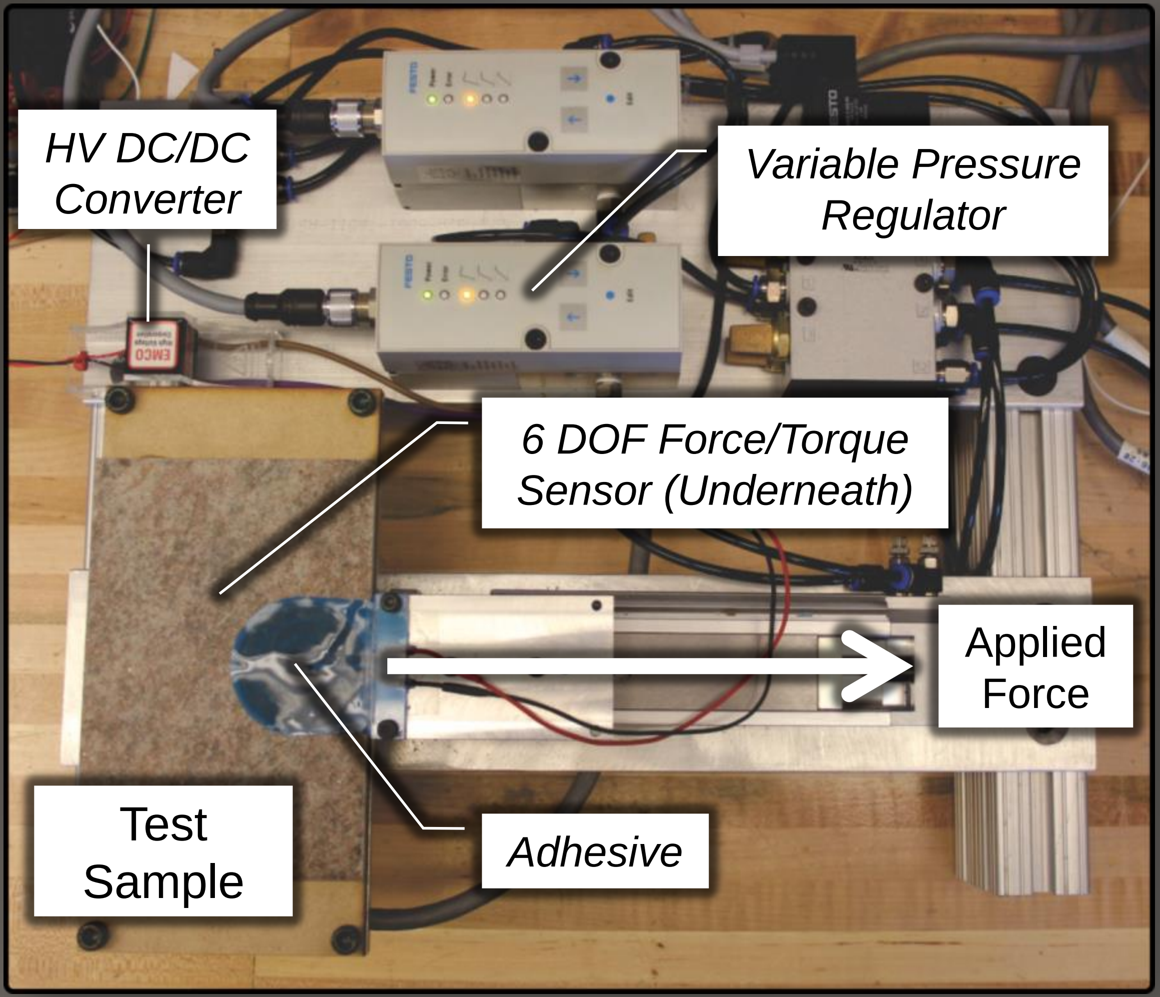

Concentric Circles


Square Spiral

Simulation Result 4: Concentric Circles Generate the Highest Adhesion Pressure

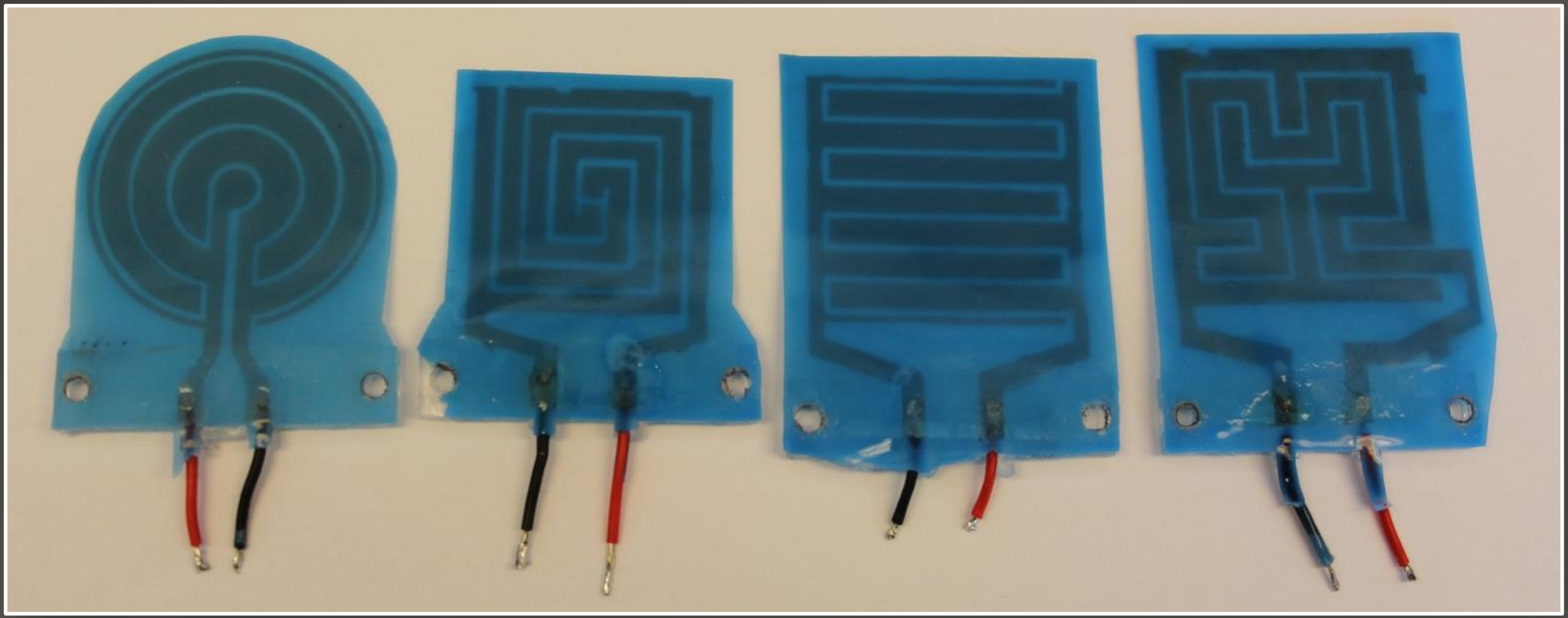


Electrostatic – Test Stage



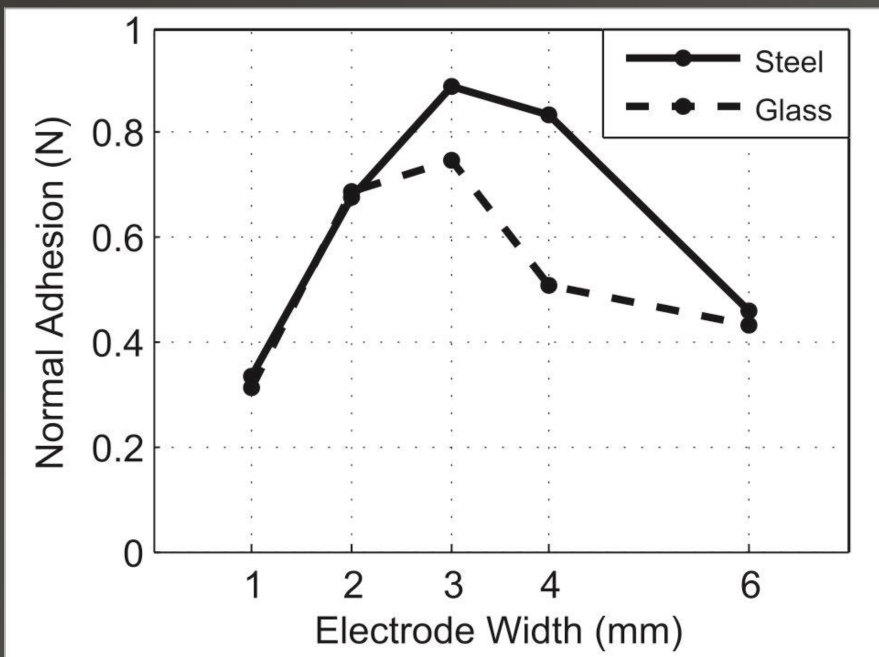
Electrostatic – Prototypes

Experimental Adhesives

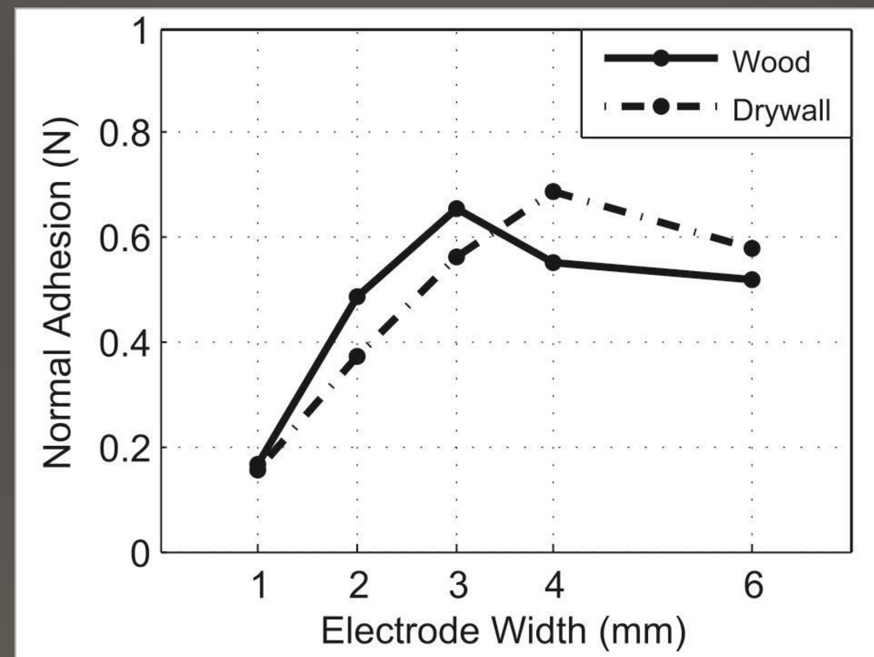


* Ruffatto, D., Shah, J., and Spenko, M., 2014. "Increasing the adhesion force of electrostatic adhesives using optimized electrode geometry and a novel manufacturing process". Journal of Electrostatics, 72(2), pp. 147–155.

Experimental Result 1: An Optimal Width Exists

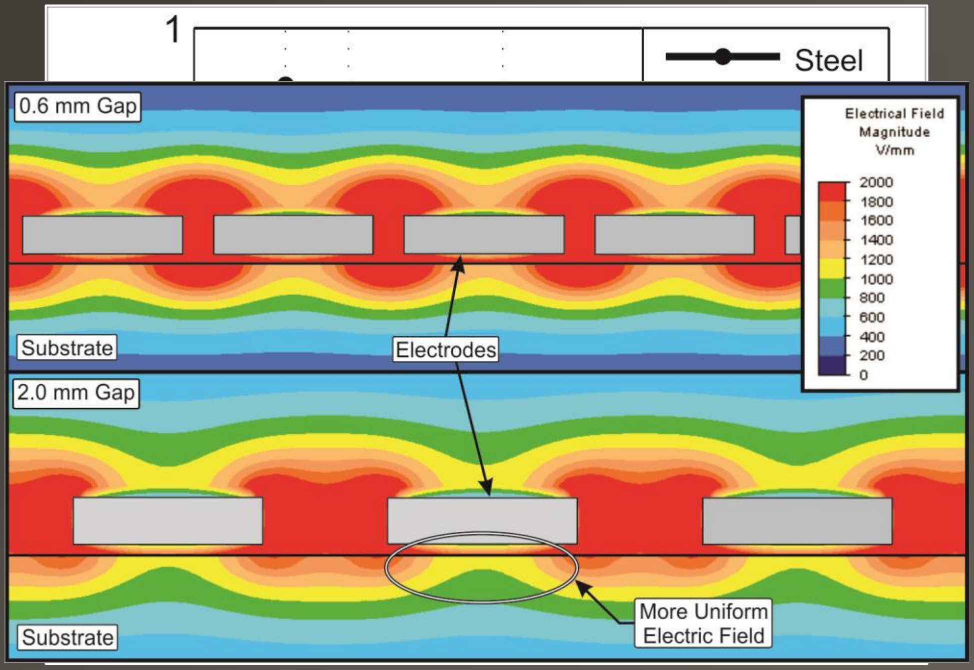


Normal adhesion force – varying electrode width but fixed gap (0.6 mm) – Smooth substrates

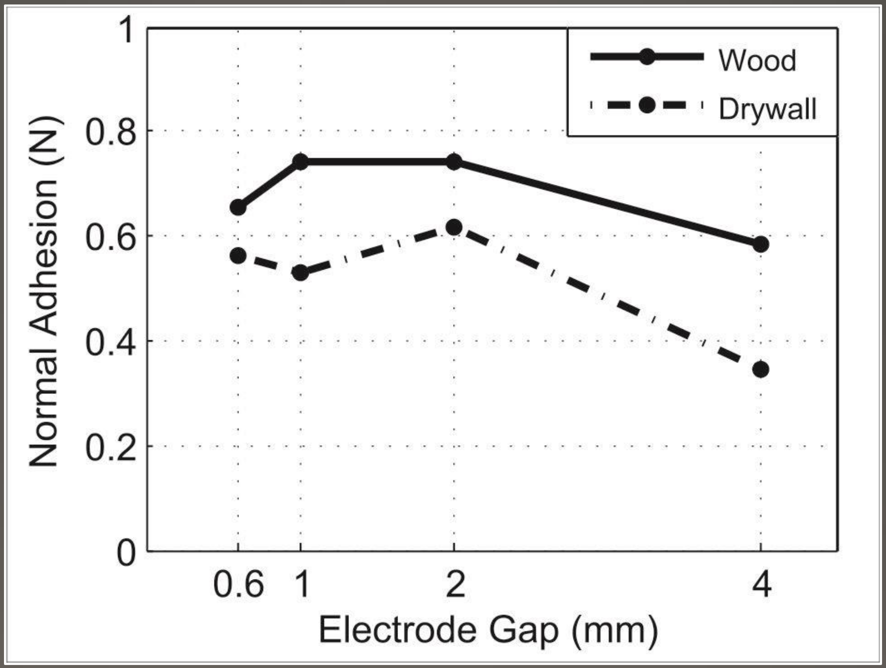


Normal adhesion force – varying electrode width but fixed gap (0.6 mm) – Rough substrates

Experimental Results 2: Rougher Surfaces Require a Larger Gap

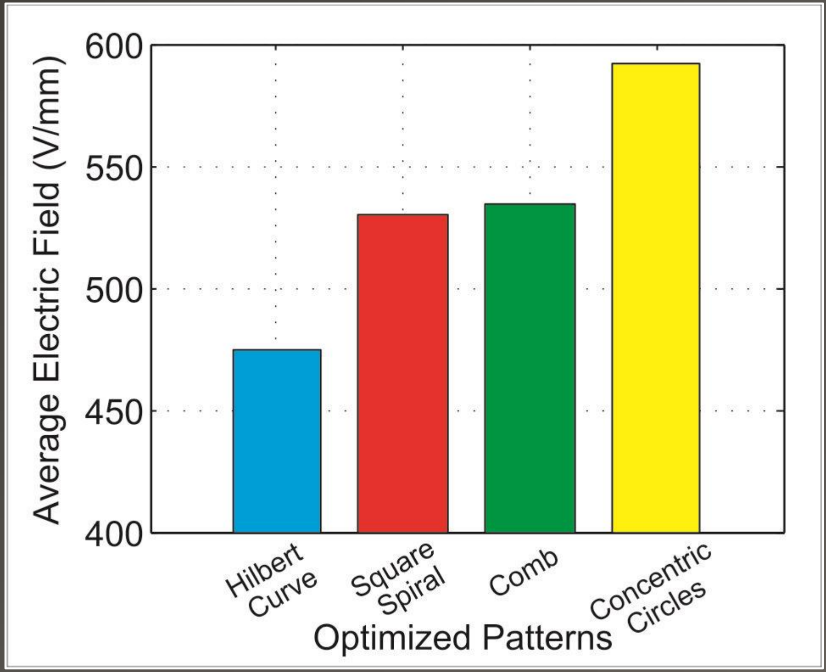


Normal adhesion force – varying gap but fixed electrode width (3 mm) – Smooth substrates

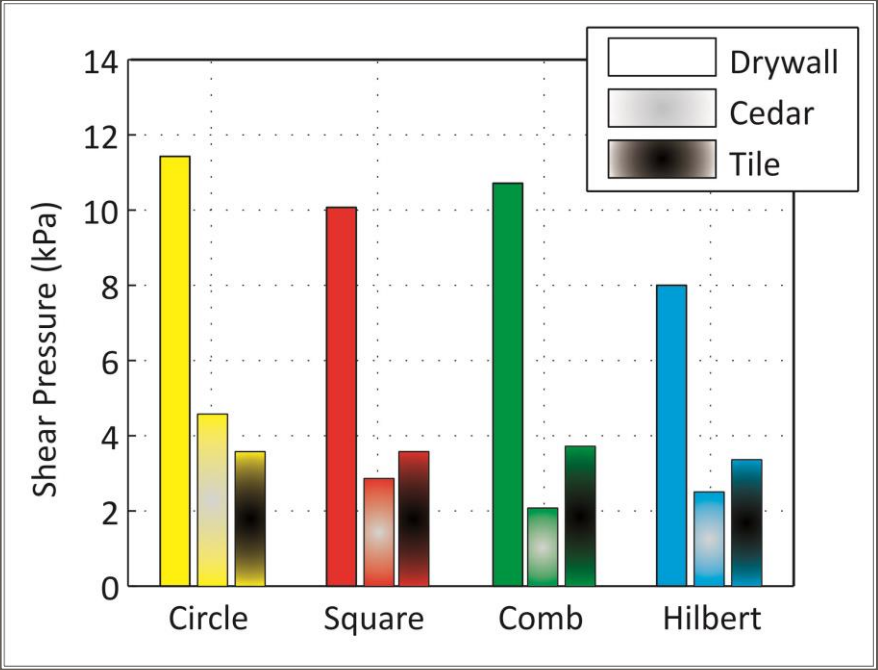


Normal adhesion force – varying gap but fixed electrode width (3 mm) – Rough substrates

Experimental Result 2: Concentric Circles are the Optimal Pattern*



Simulation Results



Experimental Results

*but, the difference is not as big as the simulation suggests

Electrostatic – Experimental Verification

Optimal Electrode Geometry

	Simulation		Experimental		
Pattern	(V/mm)	(%)	Drywall (%)	Cedar (%)	Tile (%)
Circles	592	100	100	100	100
Square Spiral	530	89	88	62	100
Comb Pattern	534	90	94	45	104
Hilbert	474	80	70	54	93

Normalized with Respect to the Concentric Circle Pattern

Experiments

- Optimized Concentric Circle

Material	Shear Pressure (kPa)	Previous Work* (kPa)	Improvement
Drywall	11.3	2.1	5.4x
Finished Wood	45.9	5.5	8.4x
Cedar	4.3	NA	NA
Tile	3.1	NA	NA
Glass	62.0	4.1	15.1x
Steel	36.0	14	2.6x

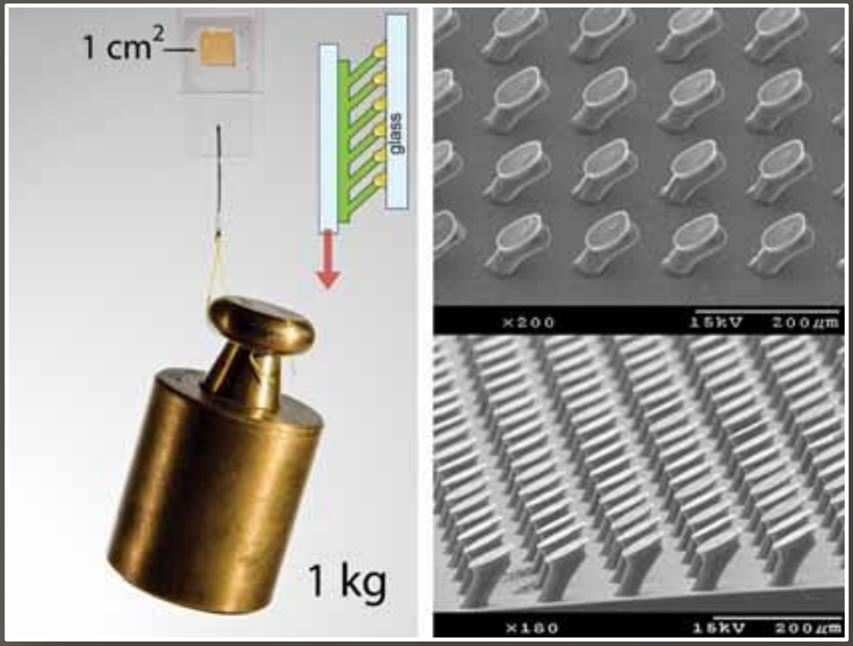
*Prahlad, H., Pelrine, R., Stanford, S., Marlow, J., and Kornbluh, R., 2008. "Electroadhesive Robots - Wall Climbing Robots Enabled by a Novel, Robust, and Electrically Controllable Adhesion Technology". In IEEE International Conference on Robotics and Automation, pp. 3028–3033.

Part 2

Electrostatic/Gecko-Like Adhesives

Background – Dry Adhesives

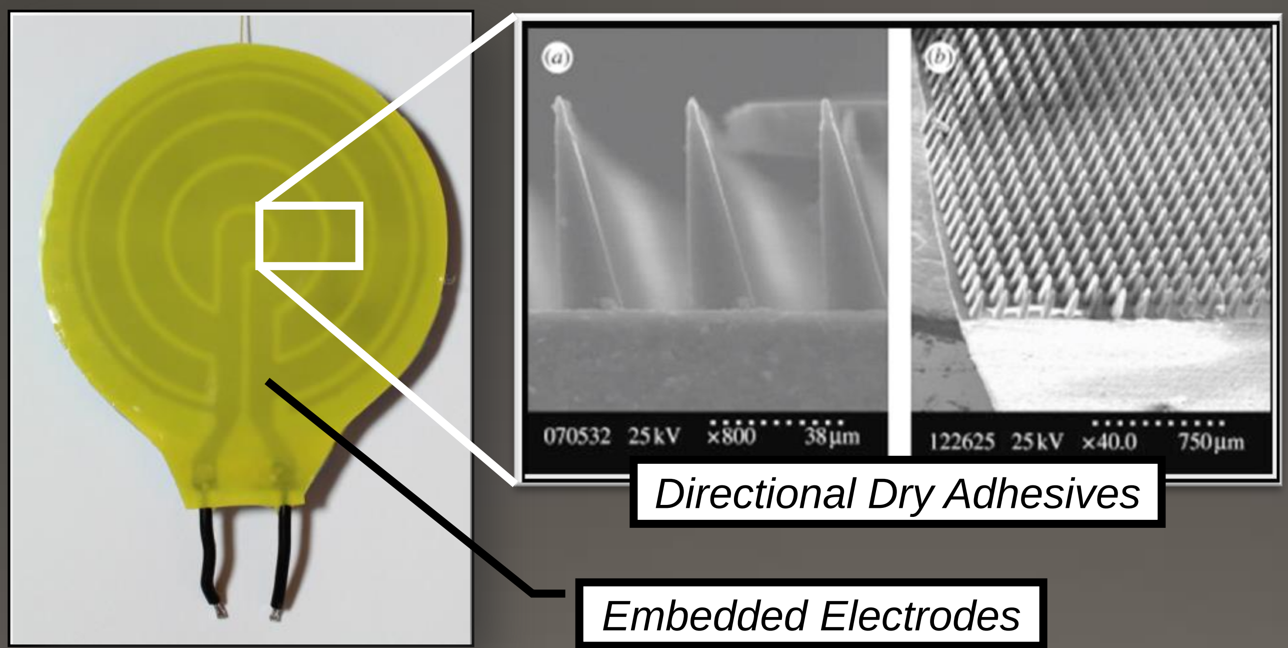
- Van der Waals forces
  - High real area of contact
- Anisotropic
  - Preferred direction through geometry
  - Generated normal adhesive when loaded in shear
  - Controllable
- Shown to handle over 30,000 cycles



* Anisotropic dry adhesive

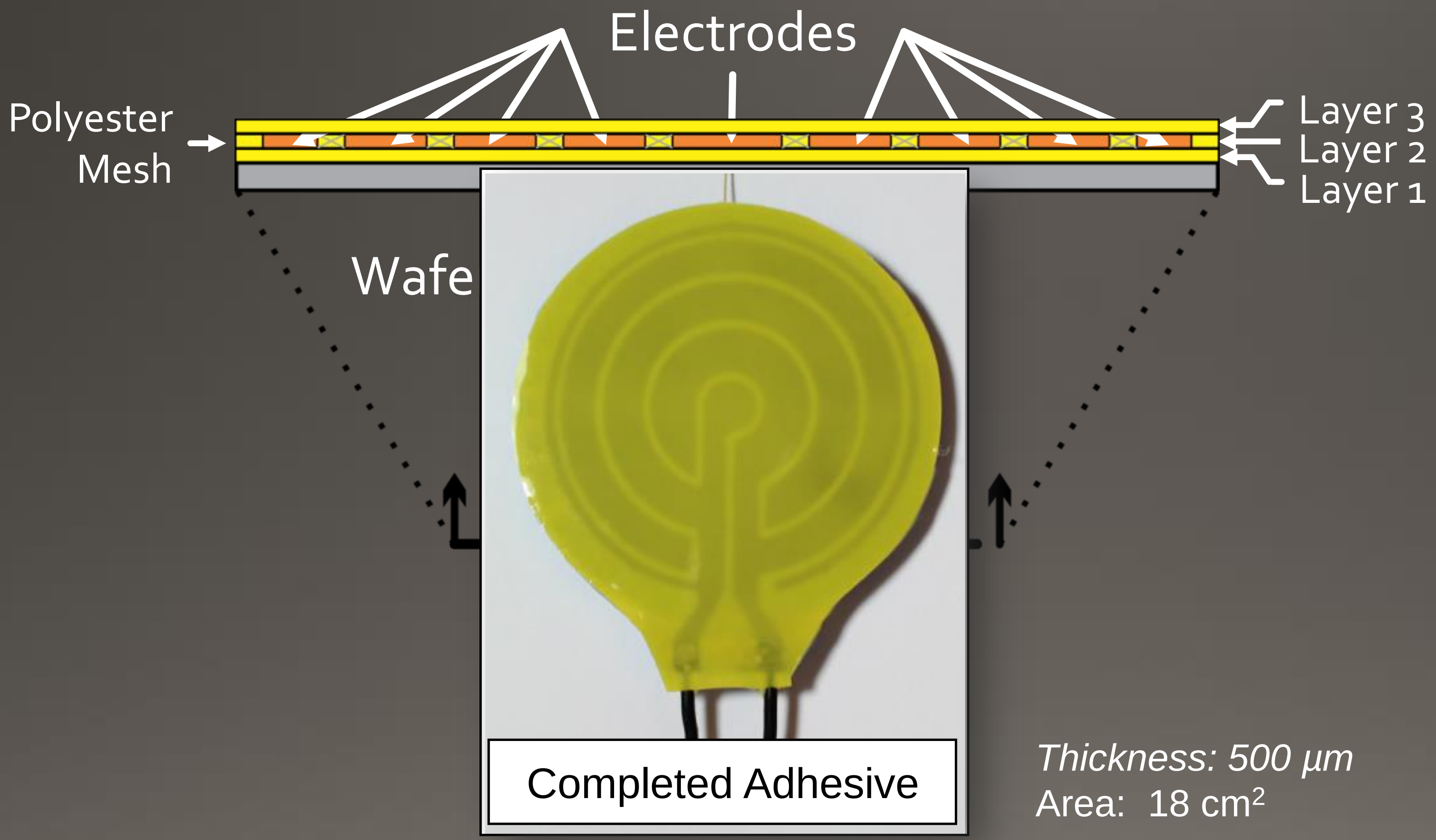
* Murphy M, Aksak B, Sitti M., "Gecko inspired directional and controllable adhesion." 2008, Small 5, 170–175.

Electrostatic Dry Adhesives



* D. Ruffatto, A. Parness, and M. Spenko, "Improving Controllable Adhesion on Both Rough and Smooth Surfaces with a Hybrid Electrostatic/Gecko-Like Adhesive," The Royal Society Interface, vol. 11, 2014.

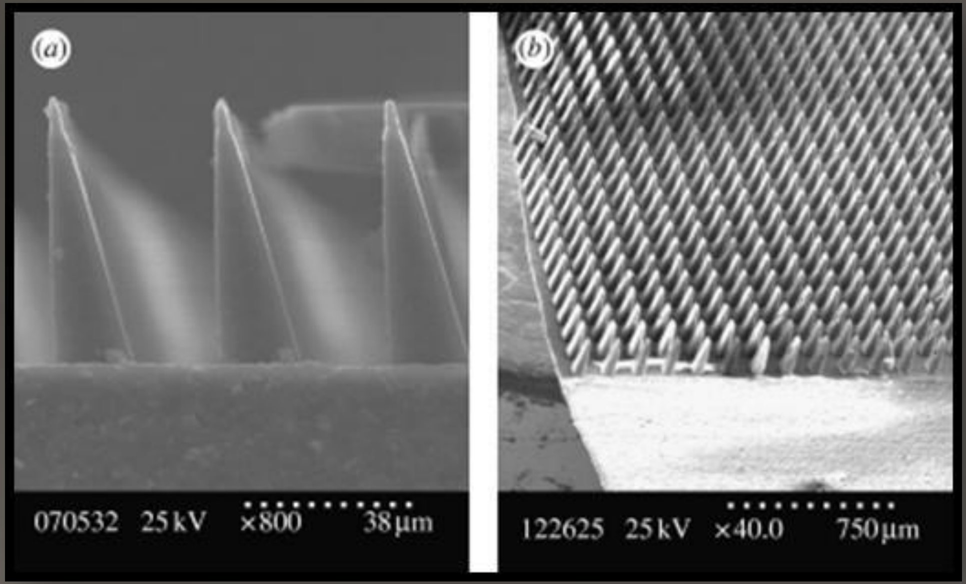
Electrostatic Dry Adhesive Fabrication



Thickness: 500 µm
Area: 18 cm^2

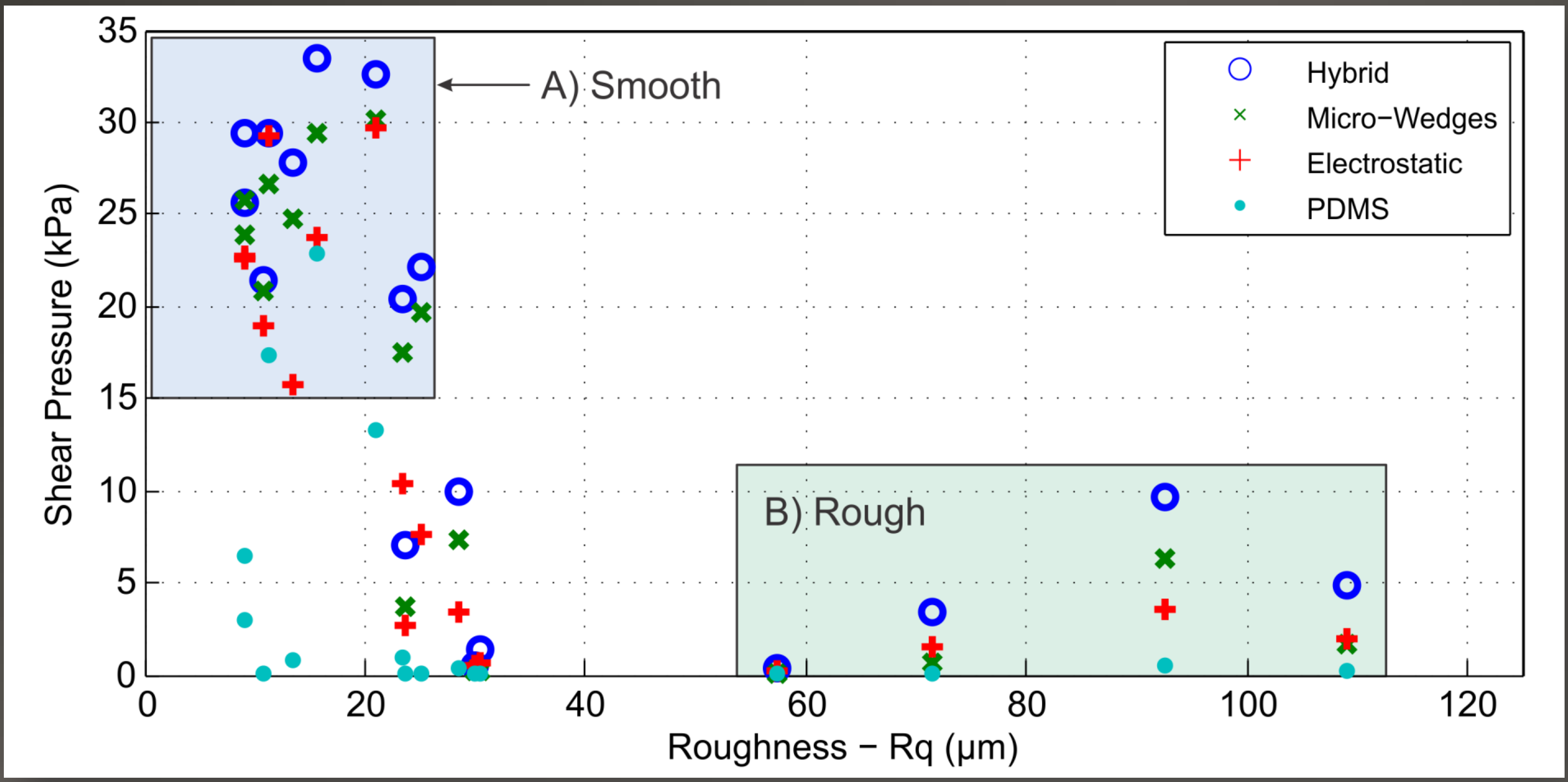
Dry adhesive – Overview

- Provided in collaboration with Dr. Parness from the NASA Jet Propulsion Lab
- Anisotropic properties
- 60 µm wedge structures (micro-wedges)

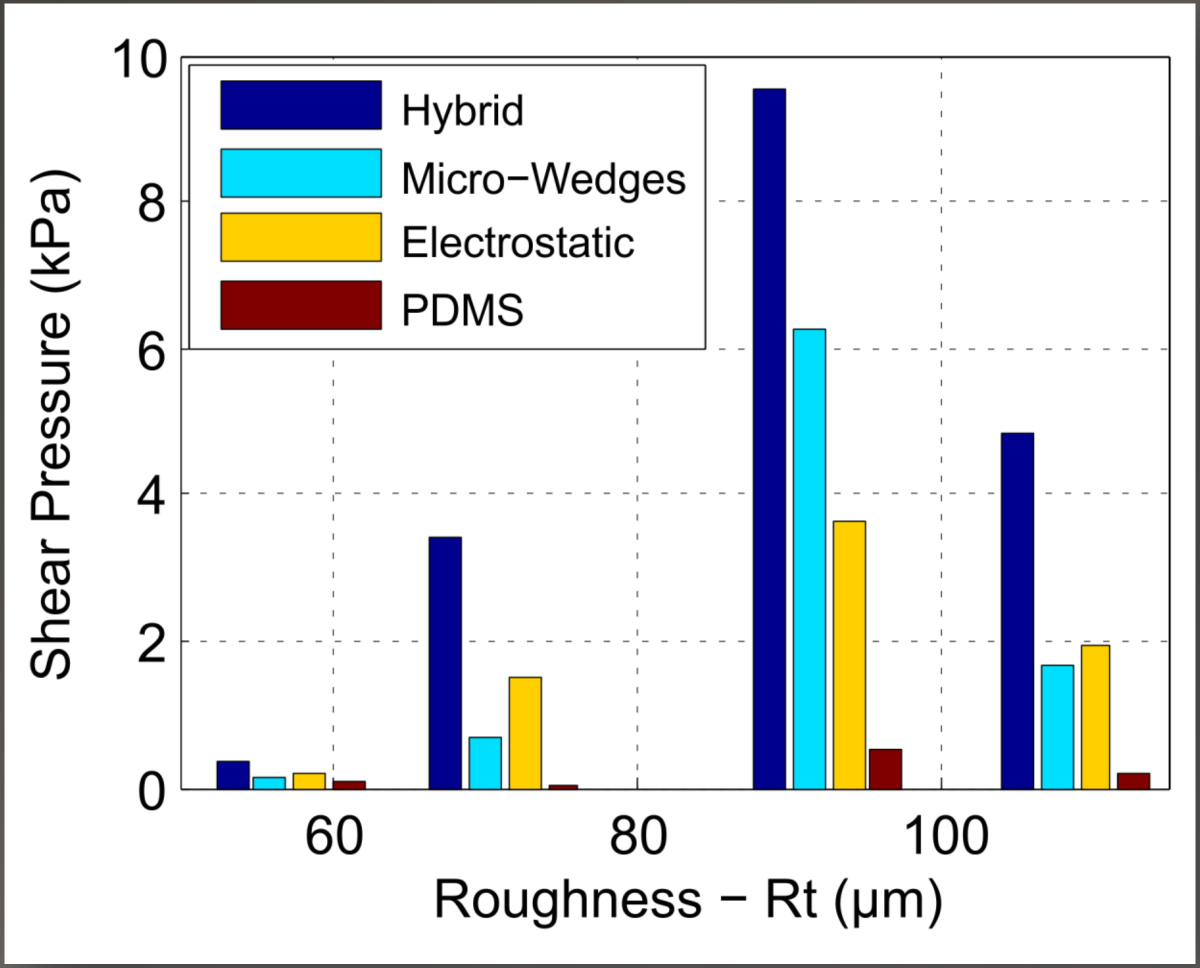


* Parness A, Soto D, Esparza N, Gravish N, Wilkinson M, Autumn K, Cutkosky M.,"A microfabricated wedge-shaped adhesive array displaying gecko-like dynamic adhesion, directionality and long lifetime," 2009, J. R. Soc. Interface 6, 1223–1232.

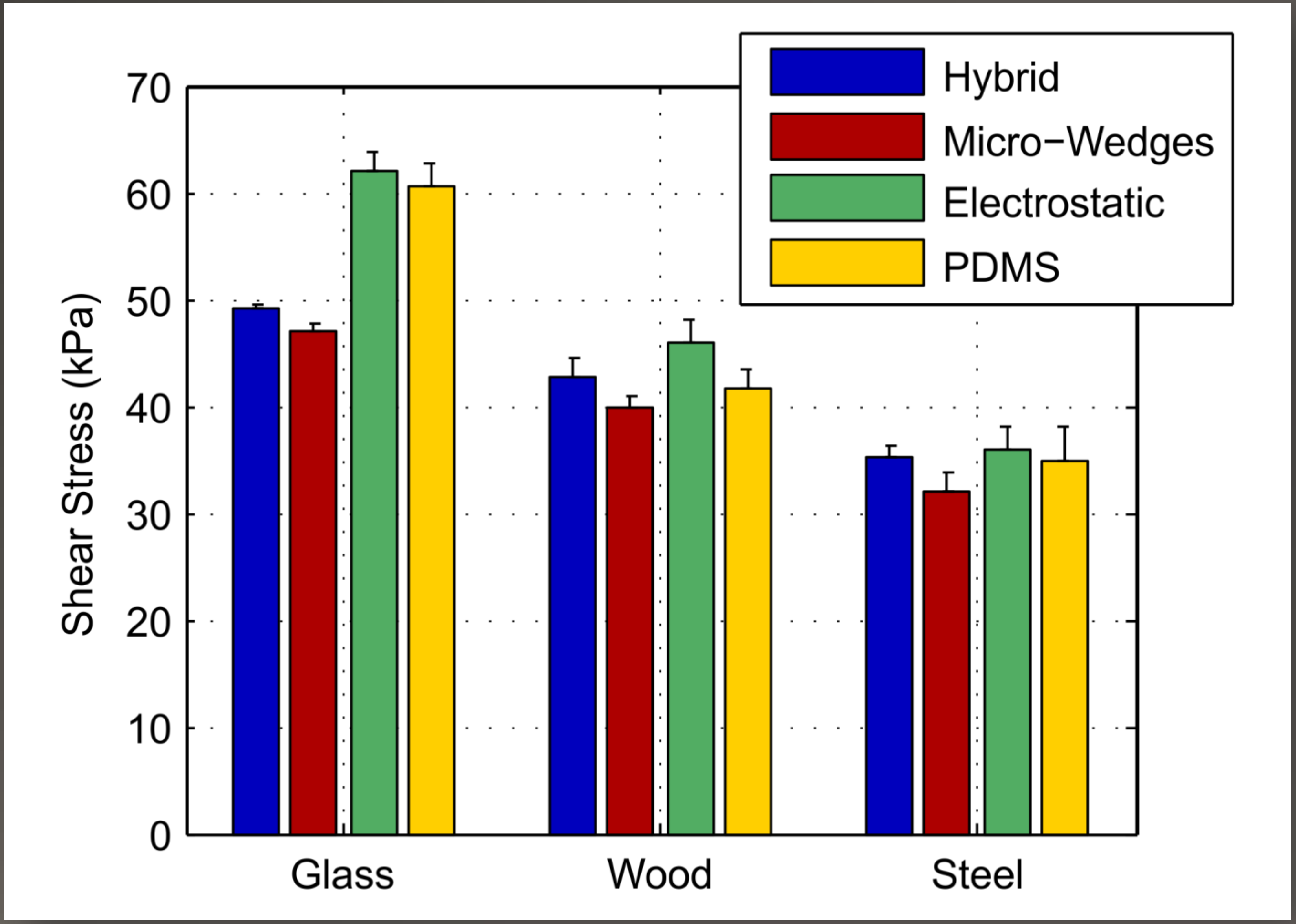
Experimental Results



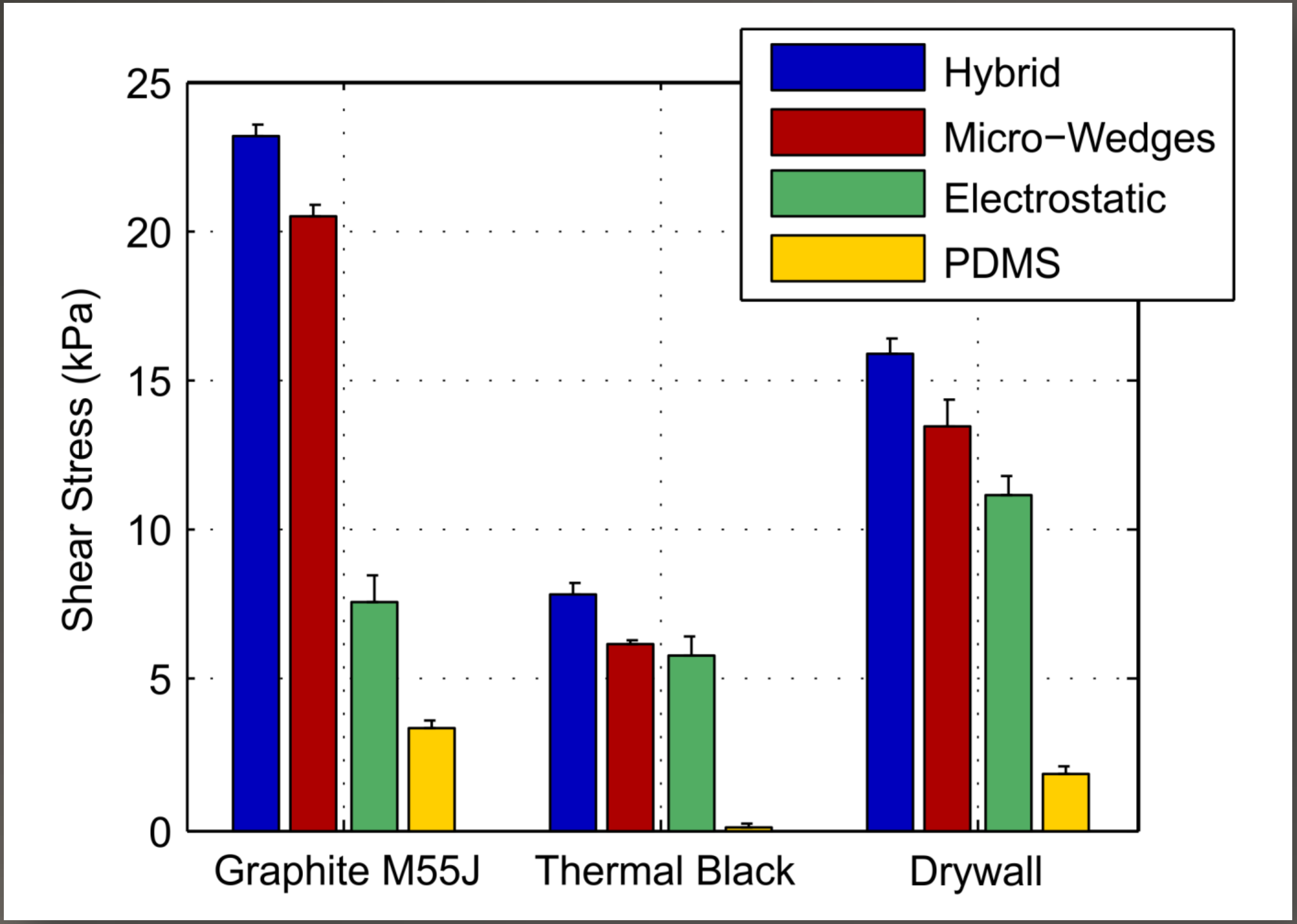
Experimental Results



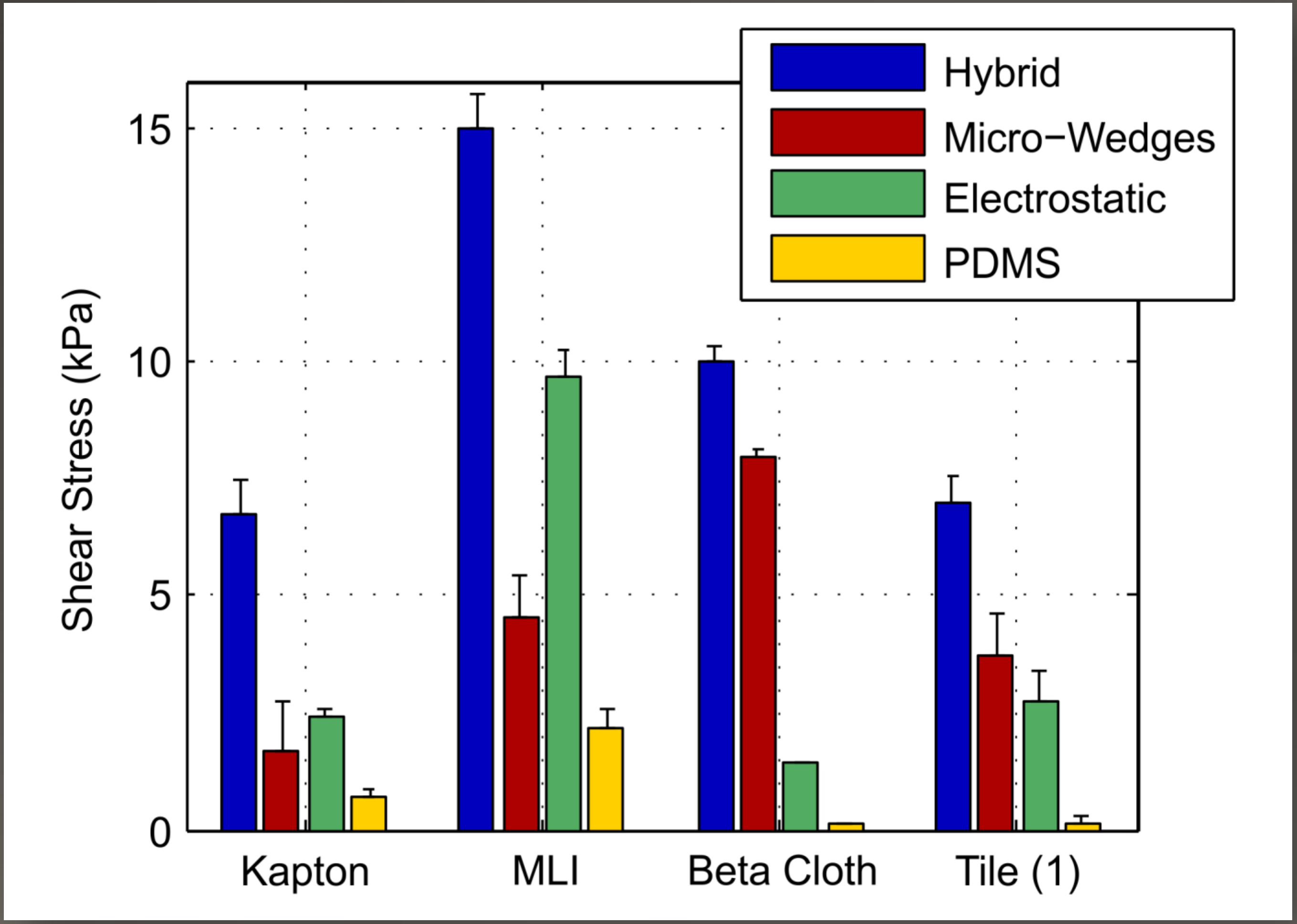
Experimental Results



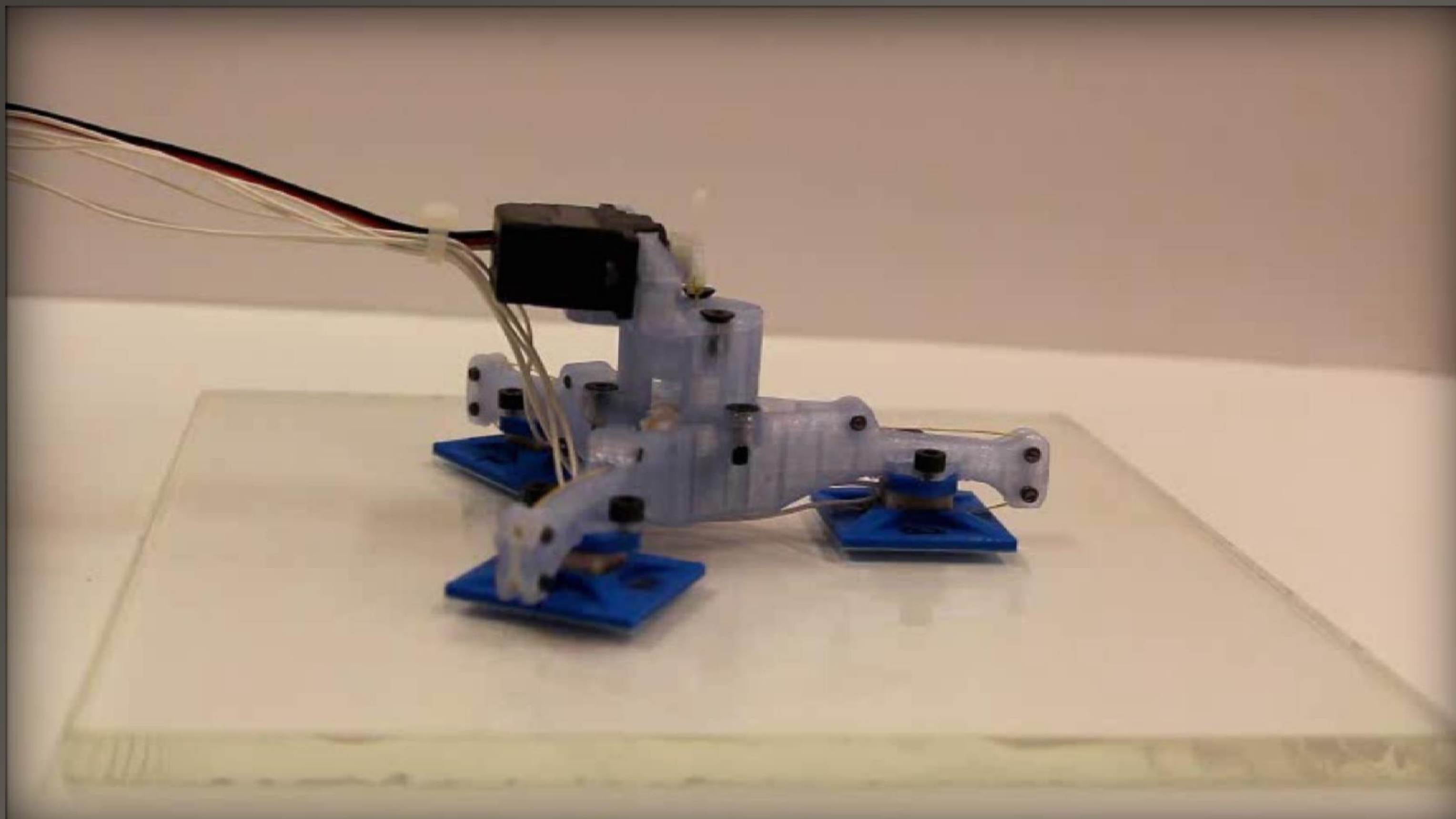
Experimental Results



Experimental Results



Gripper Demonstration



Conclusions

- Optimized electrostatic geometry
- Developed novel hybrid electrostatic/gecko-like dry adhesive
  - Increased performance
    - Electrostatic
    - Dry adhesive
  - Often outperforms the sum of its parts

Special Thanks

Don Ruffatto

Jainam Shah

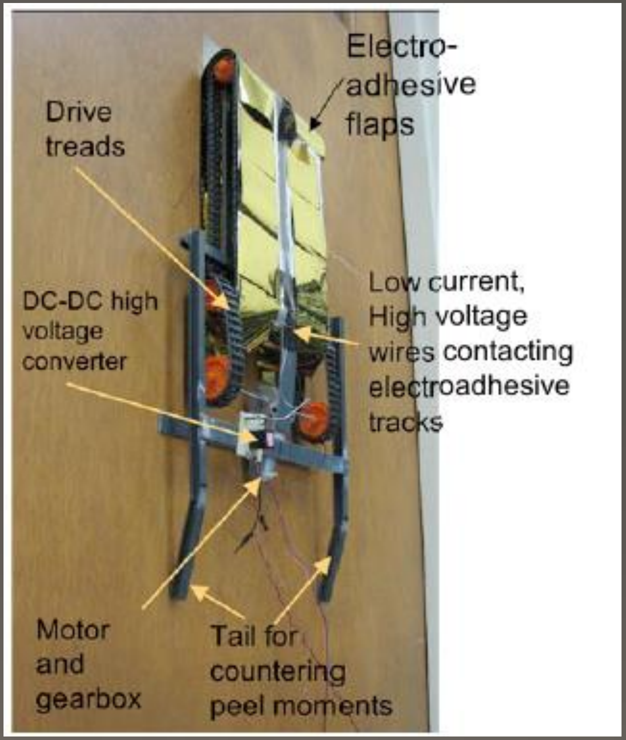
Backup Slides

Previous Research

- Prahlad, H., Pelrine, R., Stanford, S., Marlow, J., and Kornbluh, R.

MEASURED CLAMPING PRESSURES ON A VARIETY OF SUBSTRATES, MEASURED WITH 4 KV DC ACTUATION VOLTAGE

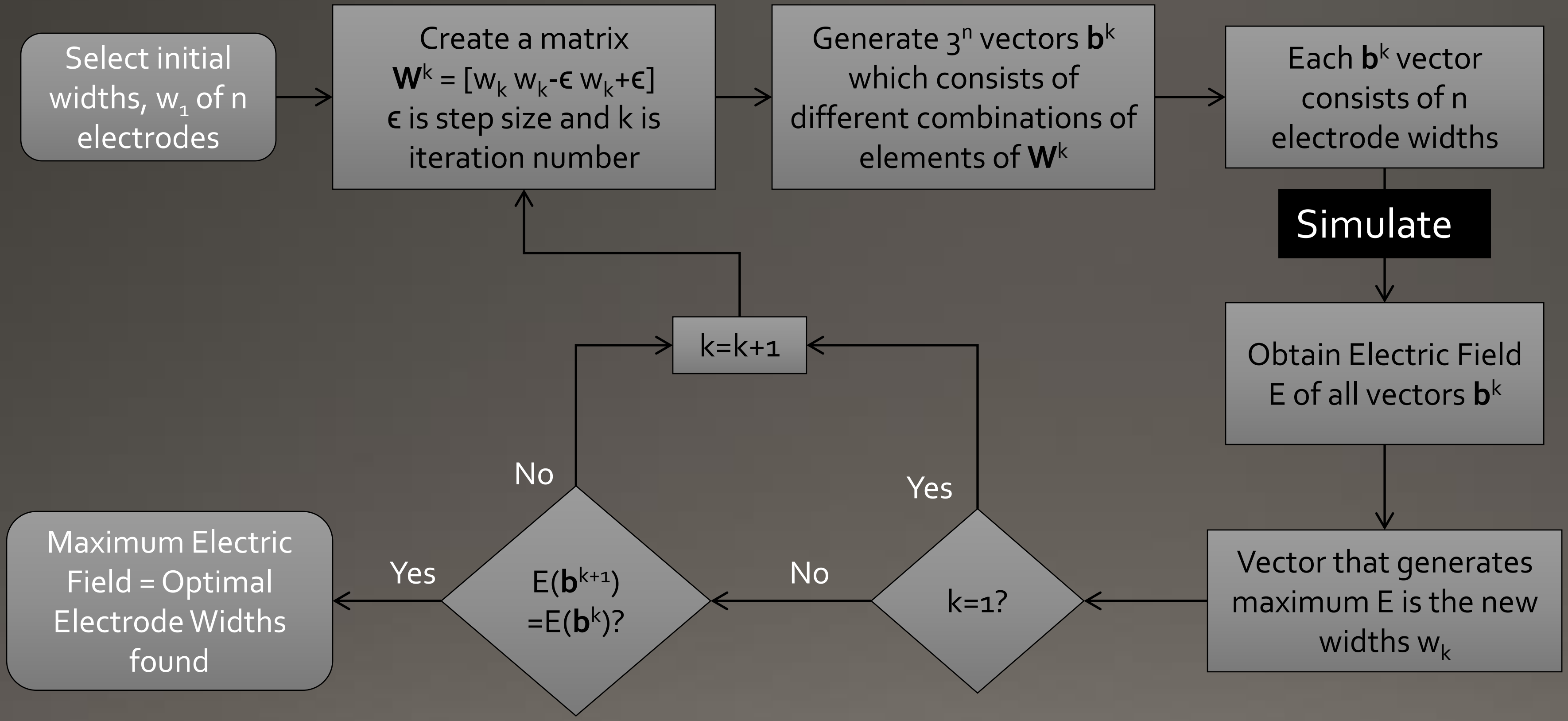
Material	Measured Lateral Force per Unit Area P_L (N/cm^2)	Measured Frictional Coefficient	Estimated Normal Pressure P_N (N/cm^2)
Finished wood (shelf wood)	0.55	0.4	1.375
Drywall	0.21	0.40 (estimated)	0.525
Paper	0.24	0.46	0.52
Glass	0.41	0.45	0.84
Concrete (dry)	0.17	0.57	0.3
Concrete (damp)	0.08	0.40 (estimated)	0.2
Steel	1.4	0.33	4.24



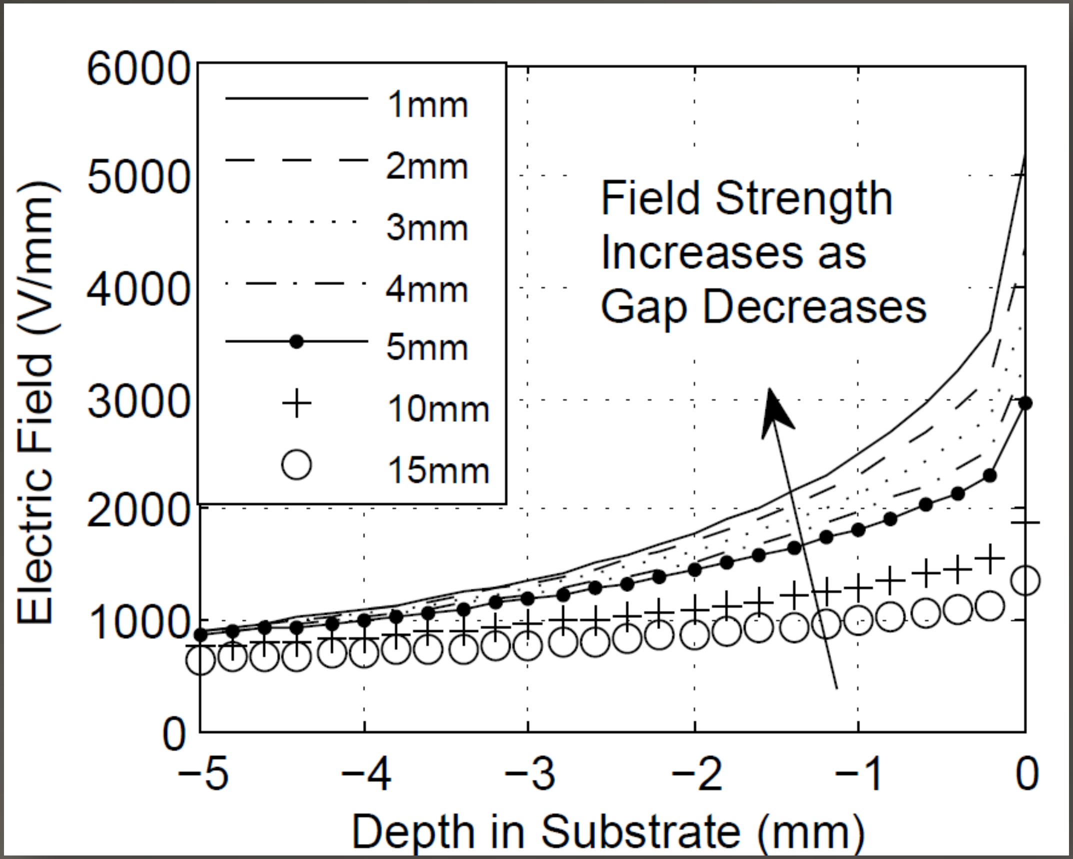
Electroadhesive robot made by SRI

Simulation

- Gradient Descent Optimization Algorithm

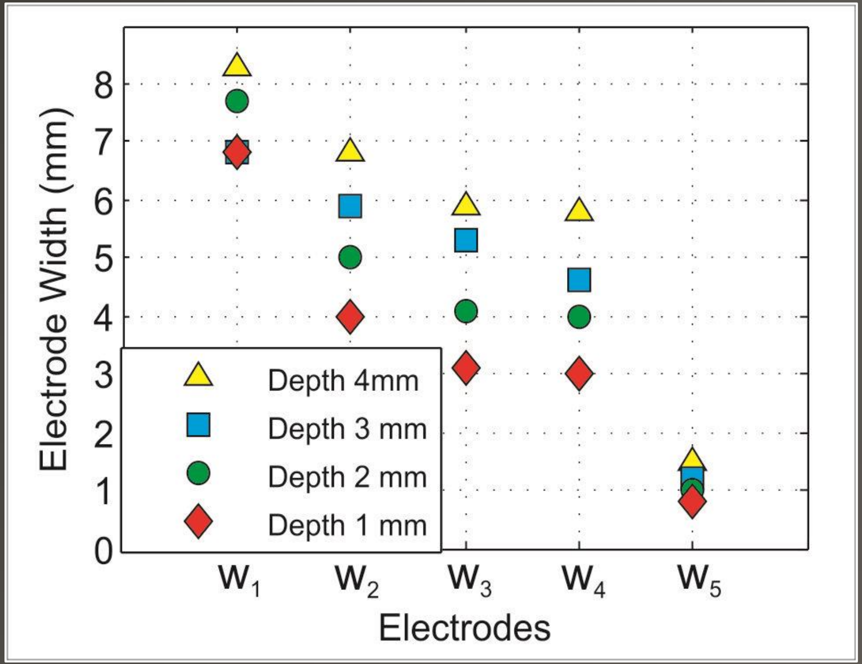


Simulation Result 1 – Make the Electrode Gap as Small as Possible

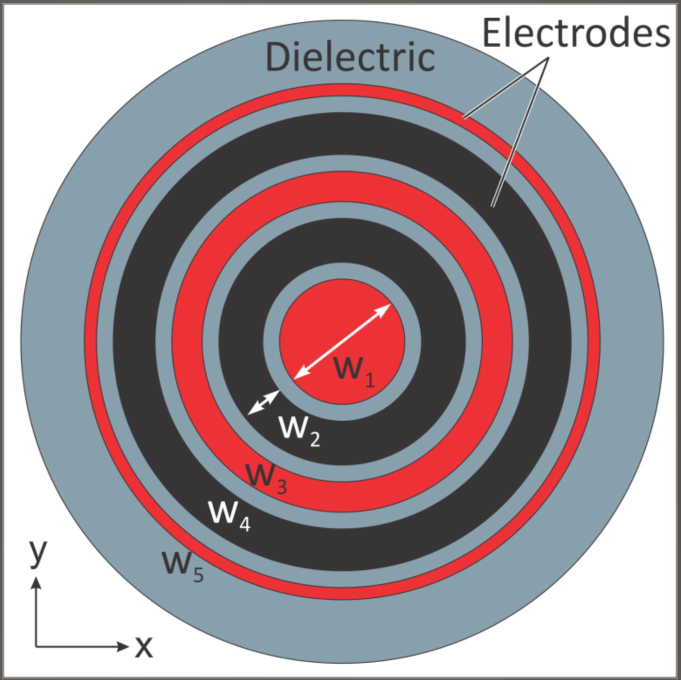


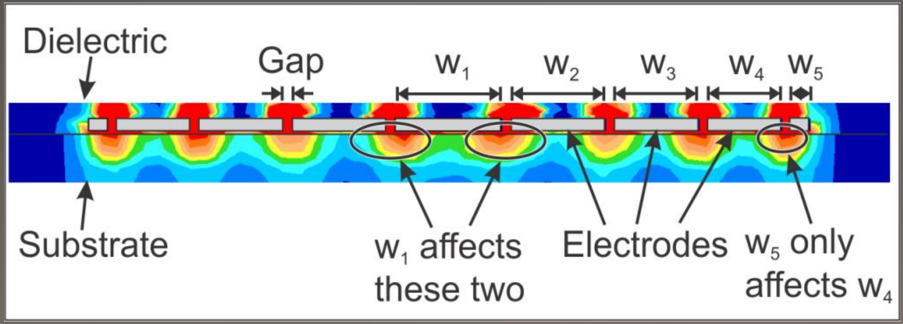
Two Electrodes – only Gap varied

Simulation

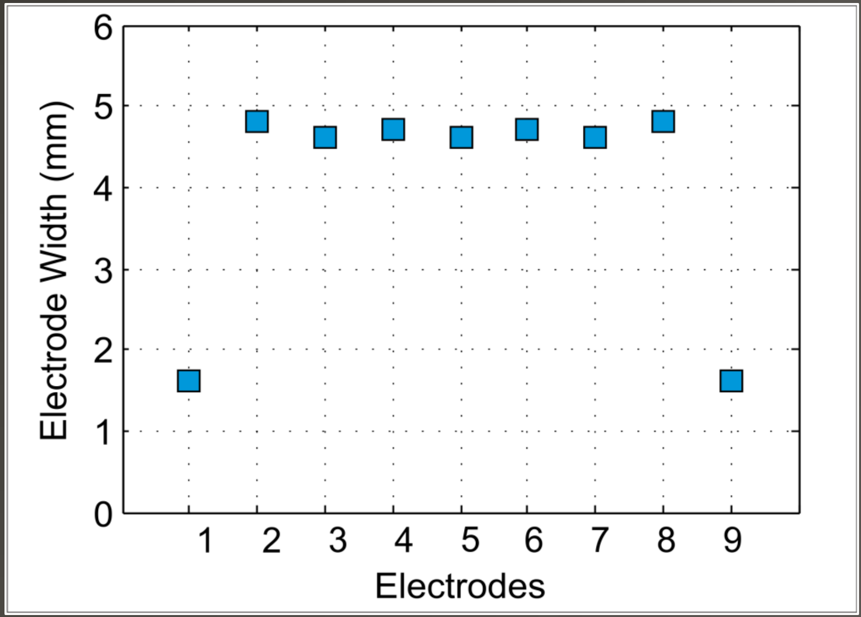


Optimized widths for concentric circle

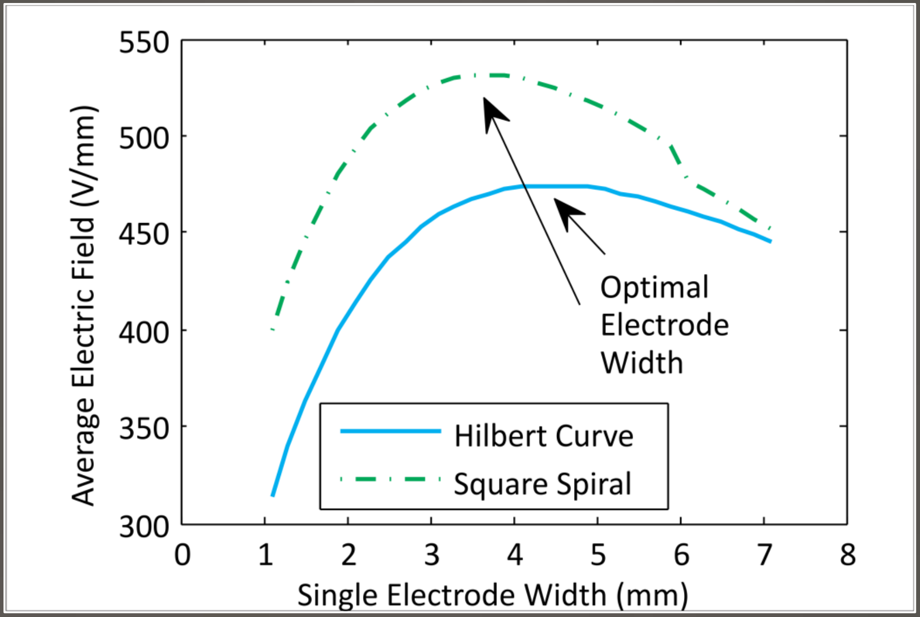




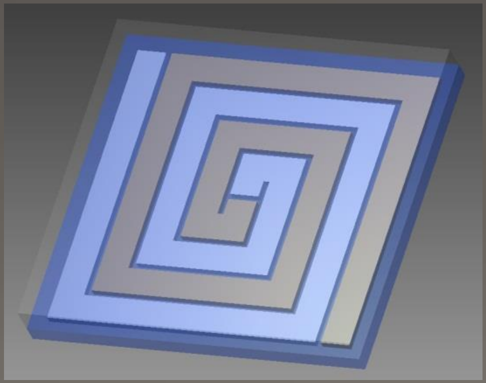
Simulation

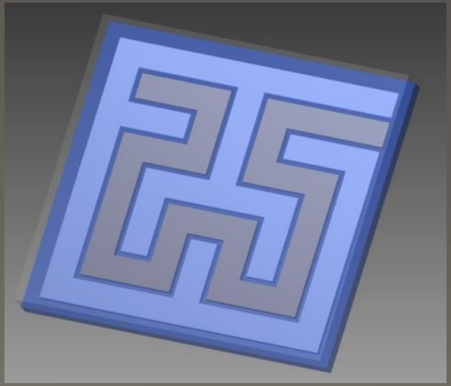


6
5
4
3
2
1
0
Electrode Width (mm)
1 2 3 4 5 6 7 8 9
Electrodes

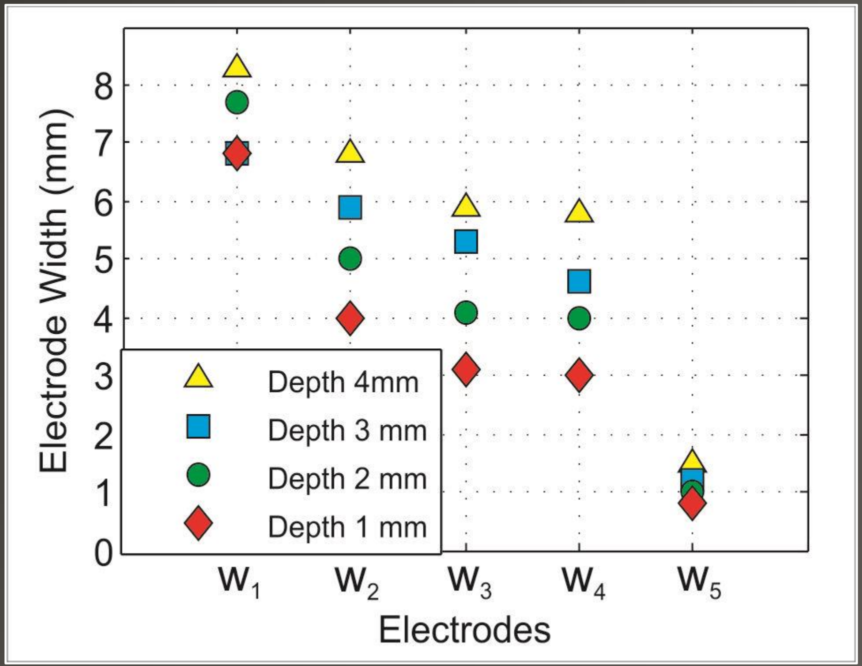


550
500
450
400
350
300
Average Electric Field (V/mm)
0 1 2 3 4 5 6 7 8
Single Electrode Width (mm)
Optimal
Electrode
Width
Hilbert Curve
Square Spiral

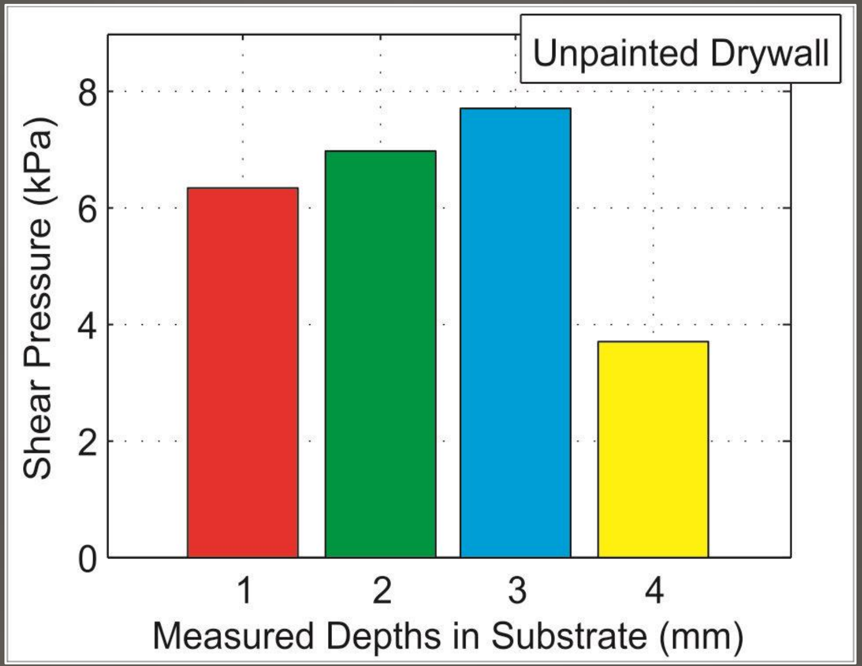




Experiments

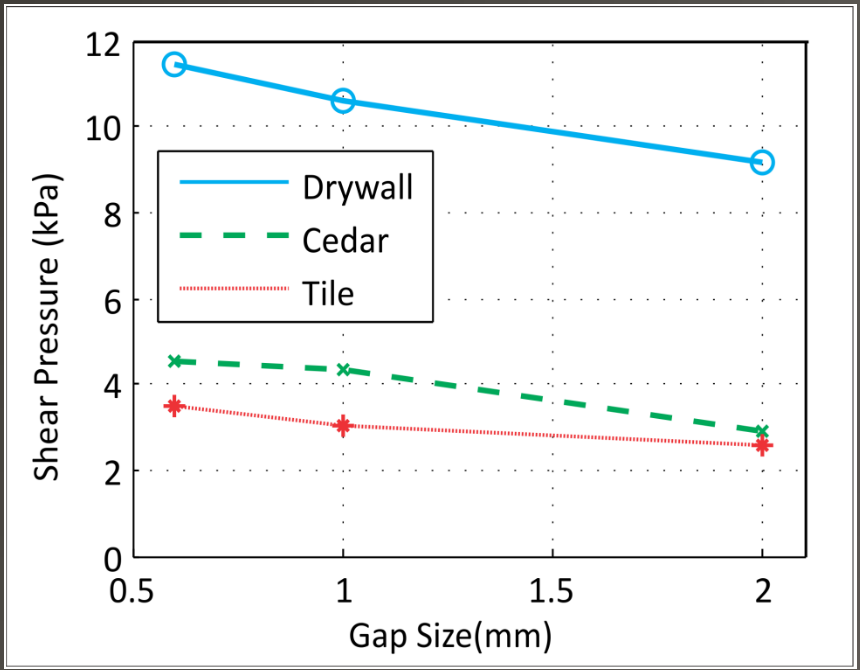


Simulation Results – Optimized widths for concentric circle found when electric field was measured at certain depths in substrate



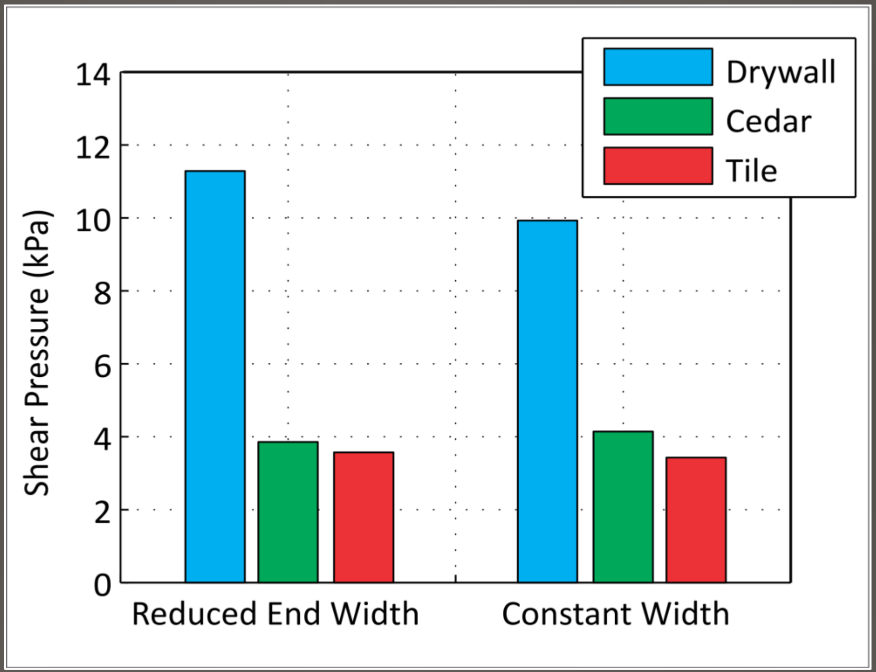
Experimental Results – Shear pressure of different optimized concentric circle pattern as measured on unpainted drywall

Experiments



Simulation Results with Fixed Electrode concentric circles with varying gap distance between the electrodes

Experiment Results – Optimized Width of 3 mm



Simulation Results – Shear pressure of concentric circle pattern with different end electrode

Experiment Results – Optimized electrode widths for concentric circle