Mechanosensitive Ion Transport in Nanoparticle-Blocked Nanopores

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Introduction

Our goal:

- Investigate the behavior and characteristics of nanopores and nanoparticles under external pressure and voltage

Nanoparticle trapping (electrokinetic trapping phenomena) shown in Fig 1a and nanoparticle under pressure depicted in Fig 1b:

- Balance among the electrophoretic force (EP), electroosmotic drag force (EOF), and dielectrophoretic force (DEP) on the nanoparticle near the entrance of the nanopore[1]
- When external pressure is applied, we observe a reduction in ionic current across nanopore, exhibiting similar behavior to mechanosensitive ion channels regarding pressure-induced ionic current suppression

Why this is important:

- Simple microfabrication design of the nanopores and set up of the experiment offer possibilities for various other future applications ranging from chemical refinement and water desalination to drug delivery and bio nanofluidic applications

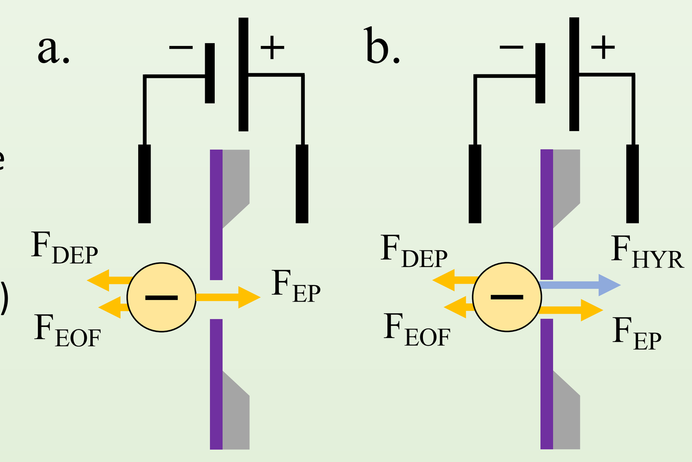

Fig 1. a. Schematic of nanoparticle trapping and electrical forces on nanoparticle; b. Schematic of electrical and mechanical forces on nanoparticle when applied external pressure.

Conclusion

- In a nanoparticle-blocked nanopore confinement, the ionic current across the nanopore exhibits a linear relationship with the cubic root of pressure in kilopascals (kPa) until 4 atm
- This is crucial in creating pressure sensitive microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS)
- However, at higher pressures, the linear trend between the current and cubic root of pressure in kPa is not consistent

Methods

Fabrication[2,3]

The nanopore device shown in Fig 2. was fabricated with a <100> silicon wafer approximately 500 µm thick with a dimension of 5 mm x 5mm.

1. Wet thermal oxidation to form a 2 µm insulating layer of silicon dioxide (SiO_2) on both sides
2. 50 nm layer of silicon nitride (Si_3N_4) was deposited on both sides of the oxide layer through low-pressure chemical vapor deposition (LPCVD)
3. Through a photolithography and etching process, a single 20 µm x 20 µm silicon nitride (Si_3N_4) membrane was made
4. Finally, a nanopore with diameters ranging from 100 nm to 500 nm was drilled through the membrane using a focused ion beam (FIB)

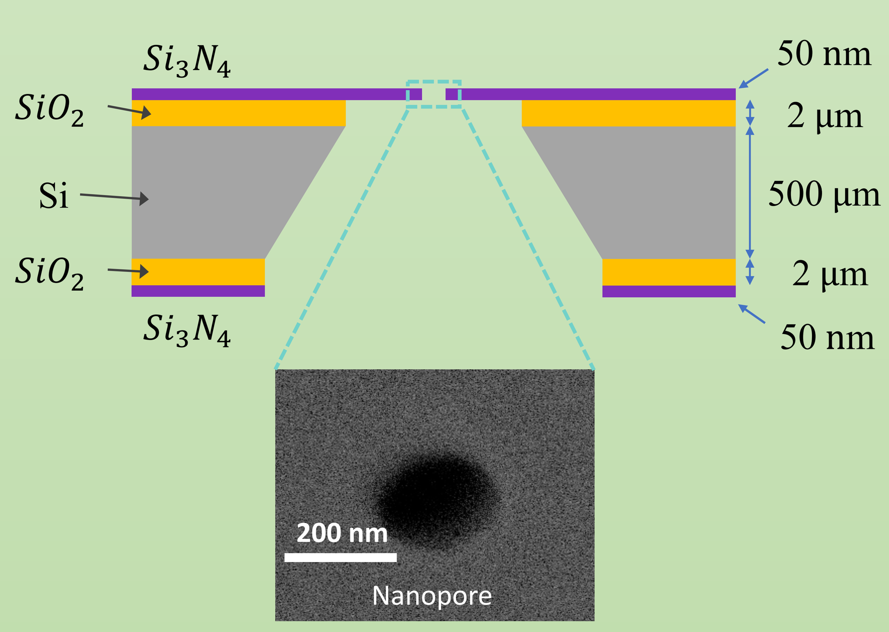

Fig 2. Schematic of the fabricated device and SEM photo of nanopore used in this project.

Experimental Setup[2,3]

- Before testing our devices, each device was cleaned in piranha solution (96% sulfuric acid/30% hydrogen peroxide, 3 : 1) at 110˚C for 5 minutes
- As shown in Fig 3, the chips were bonded with epoxy to the pipette tips on both sides of the chip, creating two separate *cis* and *trans* chambers
- Both chambers were filled with an electrolyte buffer phosphate-buffered saline (PBS) equivalent to 137 mM NaCl, 10 mM phosphate, and 2.7 mM KCl at pH 7.4
  - The *cis* chamber was filled with a nanoparticle solution consisting of 510 nm diameter PS-COOH nanoparticles and 1X PBS solution
  - *The trans* chamber was filled with 1X PBS solution
- Each chamber was inserted with an Ag/AgCl electrode to apply a voltage across the nanopore and to measure the ionic current

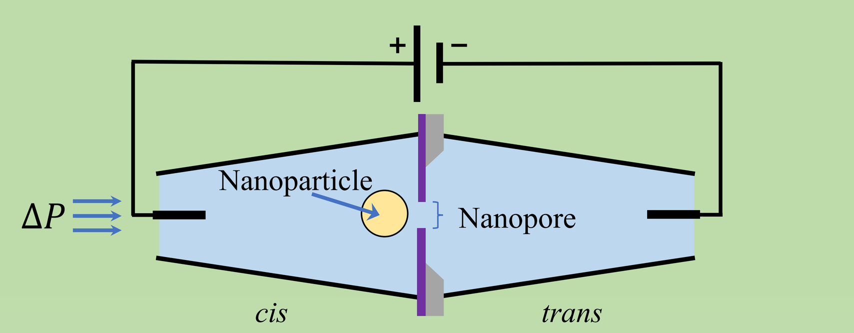

Fig 3. Schematic illustration of the nanoparticle–nanopore confinement and the experimental setup sealed by two pipette tips with external pressure and voltage source.

Data Collection[3]

- Current recordings were performed with an eOne amplifier
- Data were acquired with Elements Data Reader software at a sampling rate of 1.25 kHz
- The external pressure stimuli were provided by compressed air through an analog circuit card pressure transducer, which was controlled using LabVIEW to monitor the pressure output precisely

Results

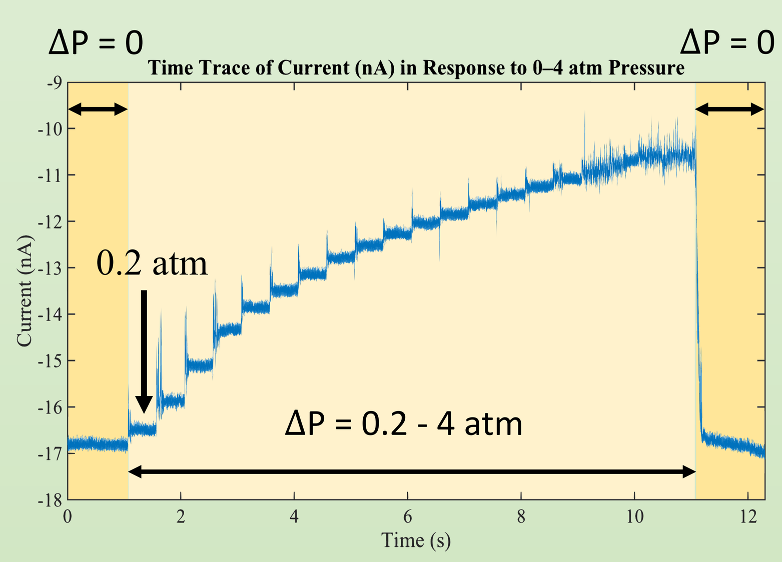

Fig 4a. Time trace of the ionic current through the system in response to 0–4 atm pressure ramp at −200 mV with each step increasing by 0.2 atm.

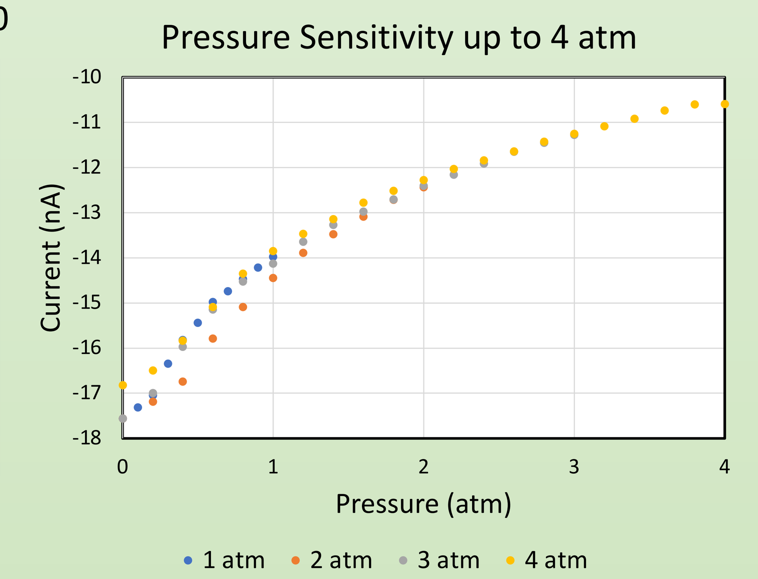

Fig 4b. Current upon 0–4 atm pressure from four trials going up to different pressures on the same device at −200 mV. At 1 atm, each step increased by 0.1 atm and for the rest of the pressures, each step increased by 0.2 atm.

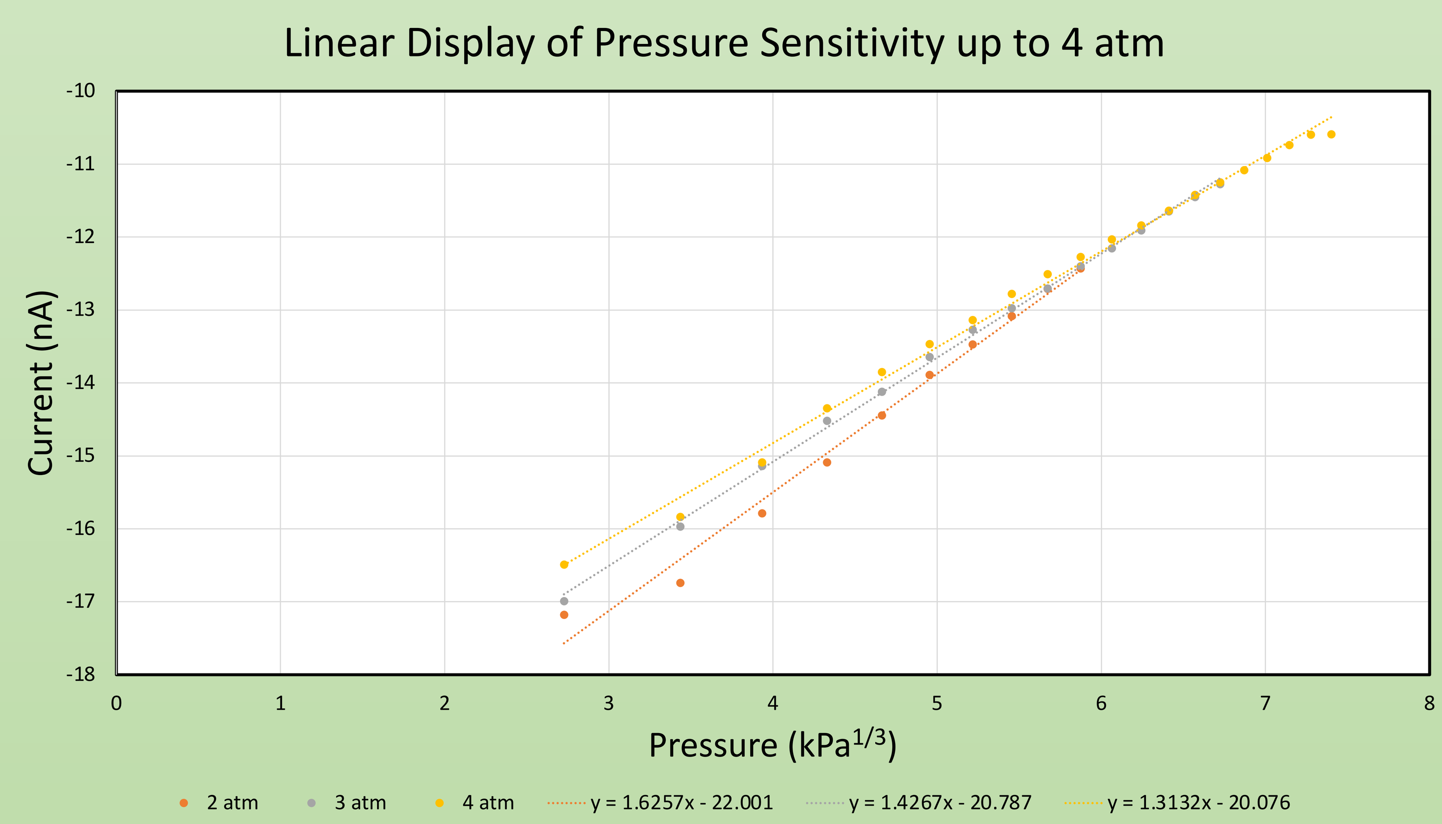

Fig 4c. Experimental result on current with respect to $kPa^{1/3}$ with linear trendlines labeled on the bottom. Each trial goes up to different pressures on the same device at −200 mV. Each color corresponds to one individual trial.

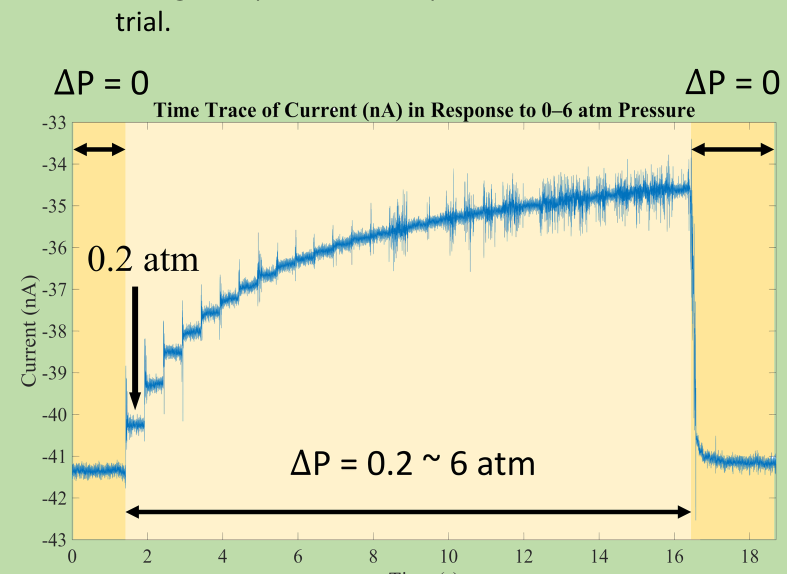

Fig 5a. Time trace of the ionic current through the system in response to 0–6 atm pressure ramp at −200 mV with each step increasing by 0.2 atm.

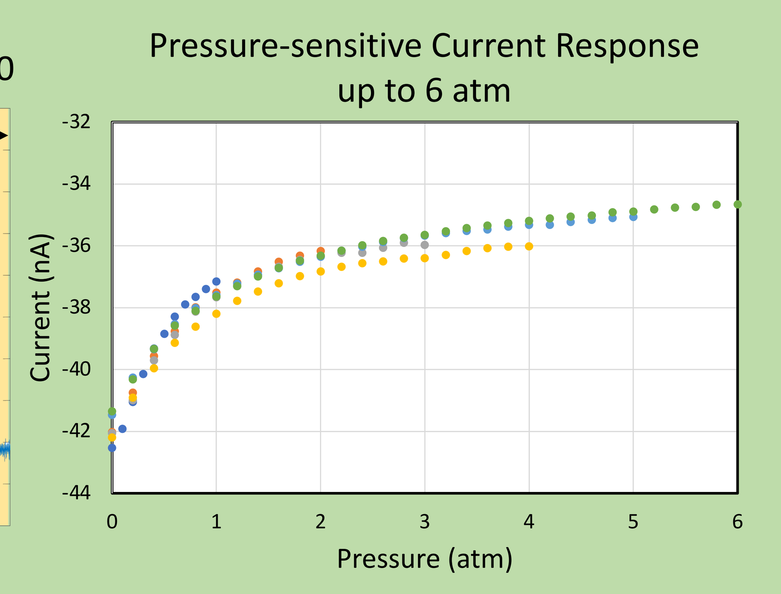

Fig 5b. Current upon 0–6 atm pressure from six trials going up to different pressures on the same device at −200 mV. At 1 atm, each step increased by 0.1 atm, and for the rest of the pressures, each step increased by 0.2 atm.

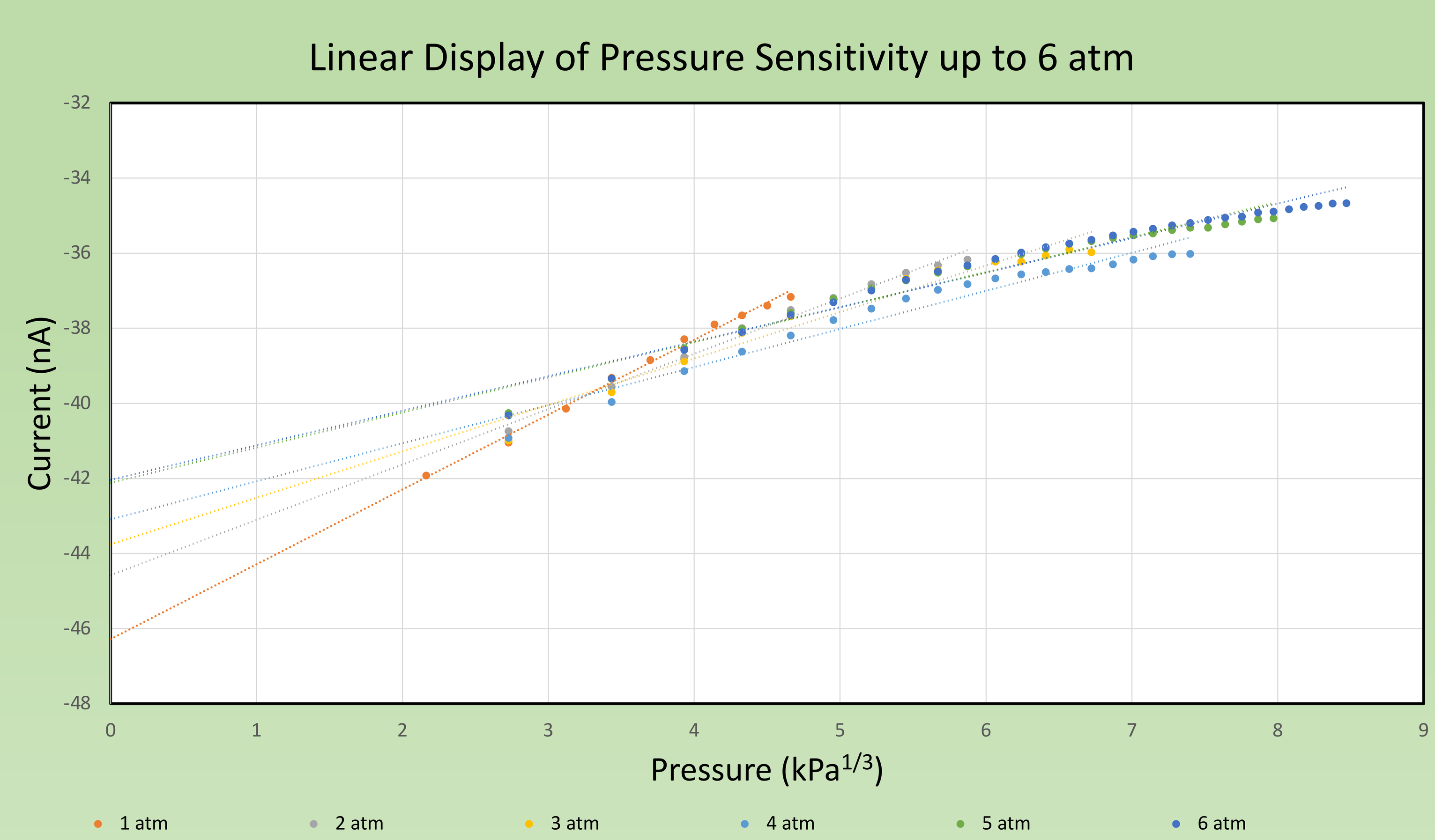

Fig 5c. Experimental result on current with respect to $kPa^{1/3}$ with linear trendlines labeled on the bottom. Each trial goes up to different pressures on the same device at −200 mV. Each color corresponds to one individual trial.

Future Applications

Current issues:

- Current device blows off at higher pressures
  - 7 atm and above
- Susceptible to blockage from epoxy due to proximity of the edges to the nanopore.

For us to apply further to various fields:

- Created a new device holder
- Redesigned our chip dimensions to 1 cm x 1cm to reduce imperfections in our current design

Future experiments with our new design promise to yield more consistent results with a wider pressure range.

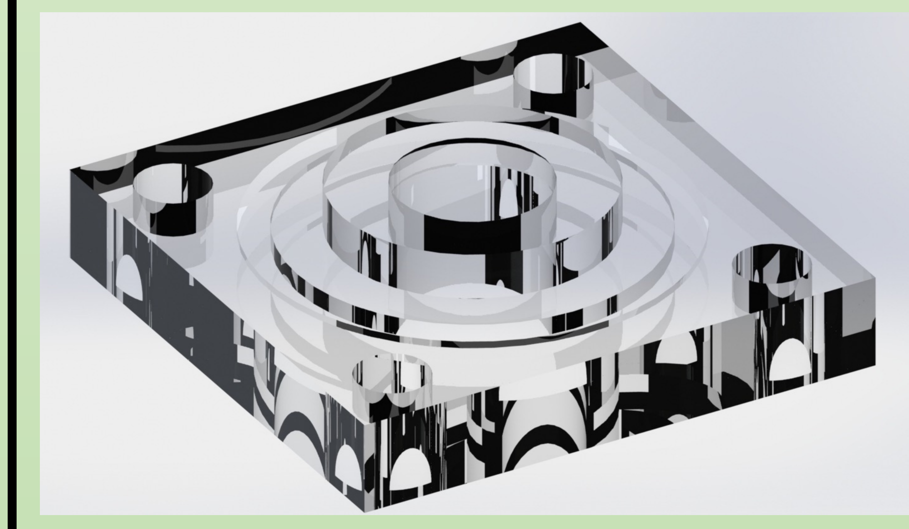

Fig 6a. 3D model of the top cover of chip holder.

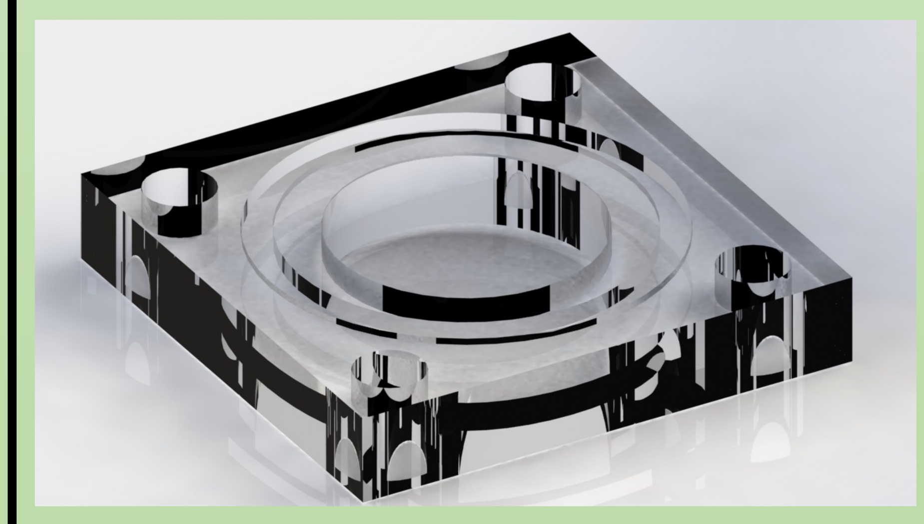

Fig 6b. 3D model of the bottom cover of chip holder.

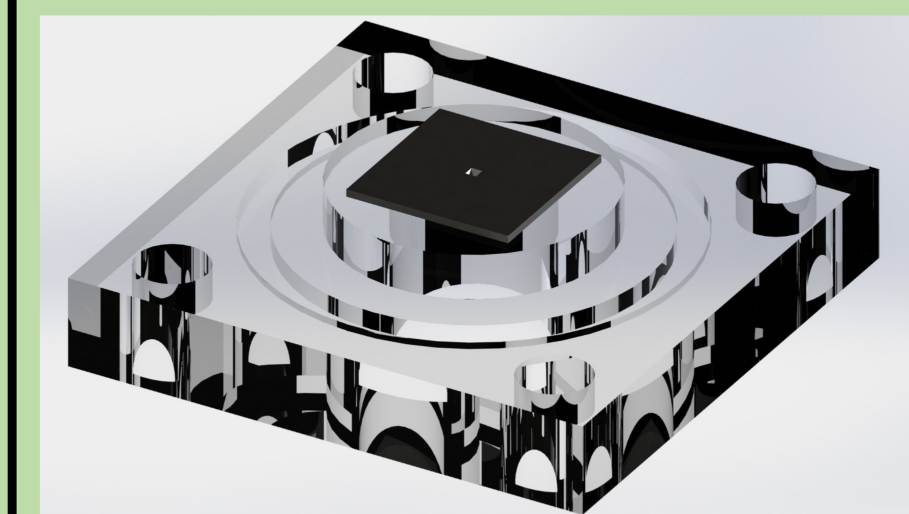

Fig 6c. 3D model of the top cover of chip holder with chip.

References

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