Micromachined Pressure Sensors and Hydrophones for Extreme Downhole Environments

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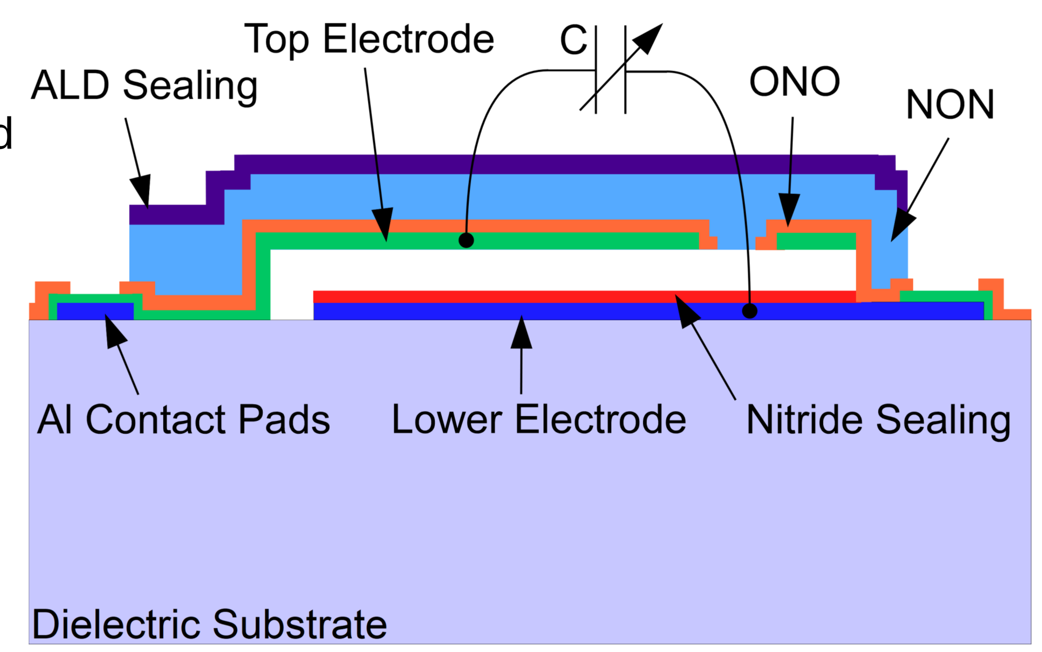
Project Description: This project is directed at robust microsensors for downhole environments. The current phase focuses on highly sensitive capacitive pressure sensors and hydrophones. Designs were optimized using mechanical and electrical FEA. A 6-mask, dielectric substrate microfabrication process is used to fabricate pressure sensors and hydrophones. Pressure sensors with ø100 µm, ø200 µm, and four parallel ø100 µm diameter diaphragms were experimentally tested up to 7,250 psi (50 MPa), showing an average responsivity of ≈135 fF/kpsi, ≈220 fF/kpsi, and ≈490 fF/kpsi, respectively. Hydrophones were designed for high sensitivity and linearity over a wide operating pressure and bandwidth (0 – 2 MHz). The hydrophone array was experimentally tested up to 2,200 psi (15 MPa) showing an average responsivity of 648 fF/MPa (4470 fF/kpsi) with 97% linearity. Hydrophone AC pressure sensing was also tested, showing general agreement with a reference pressure transducer.

1 Fabrication Process Flow

Robust, high-yield process:

- A 6-mask process that has been extensively evaluated, with nearly all fabrication problems investigated and solved
- Low temperature (≤400ºC) process allows for post-CMOS
- Demonstrated multi-design approach by creating static pressure sensor, hydrophone (dynamic pressure sensor)
- Smallest sensors: 125x125 µm² with ø100 µm diaphragm
- *Device* yield above 80% for all high pressure designs



Dielectric substrate:

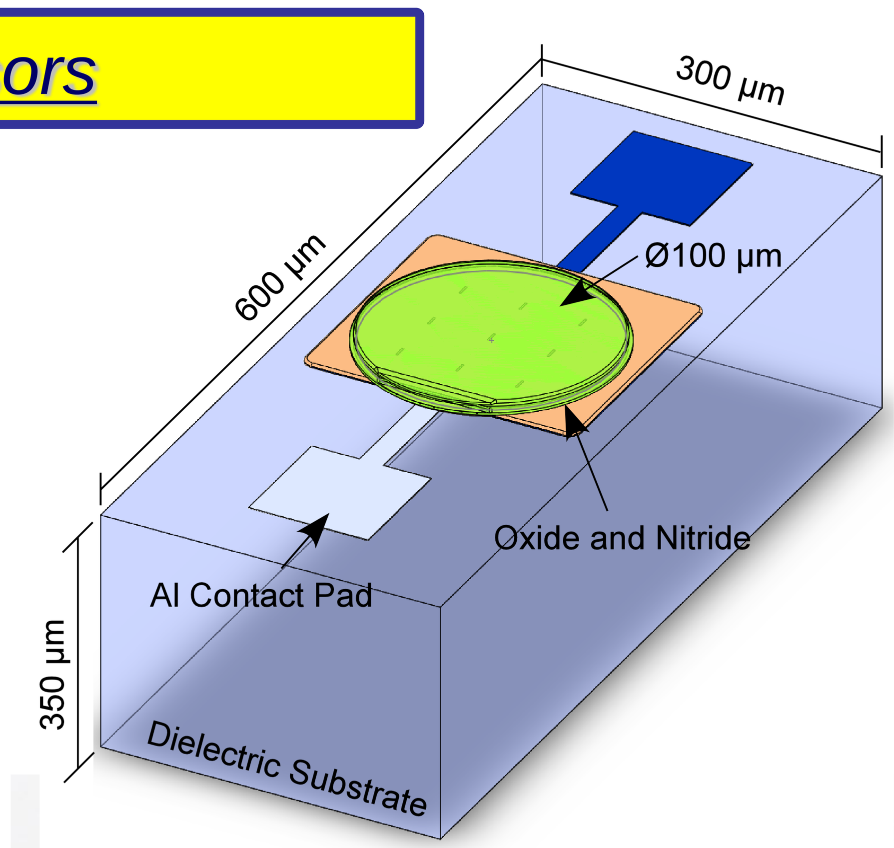
- Near-total elimination of inherent parasitic capacitances
- Dielectric substrate improves TCO and TCS with better thermal expansion match of diaphragm and substrate
- Pure size reduction not necessary for system integration - electronics, packaging much larger than sensor
  - Front-sided contact pads compatible with 3-mm electronic stack

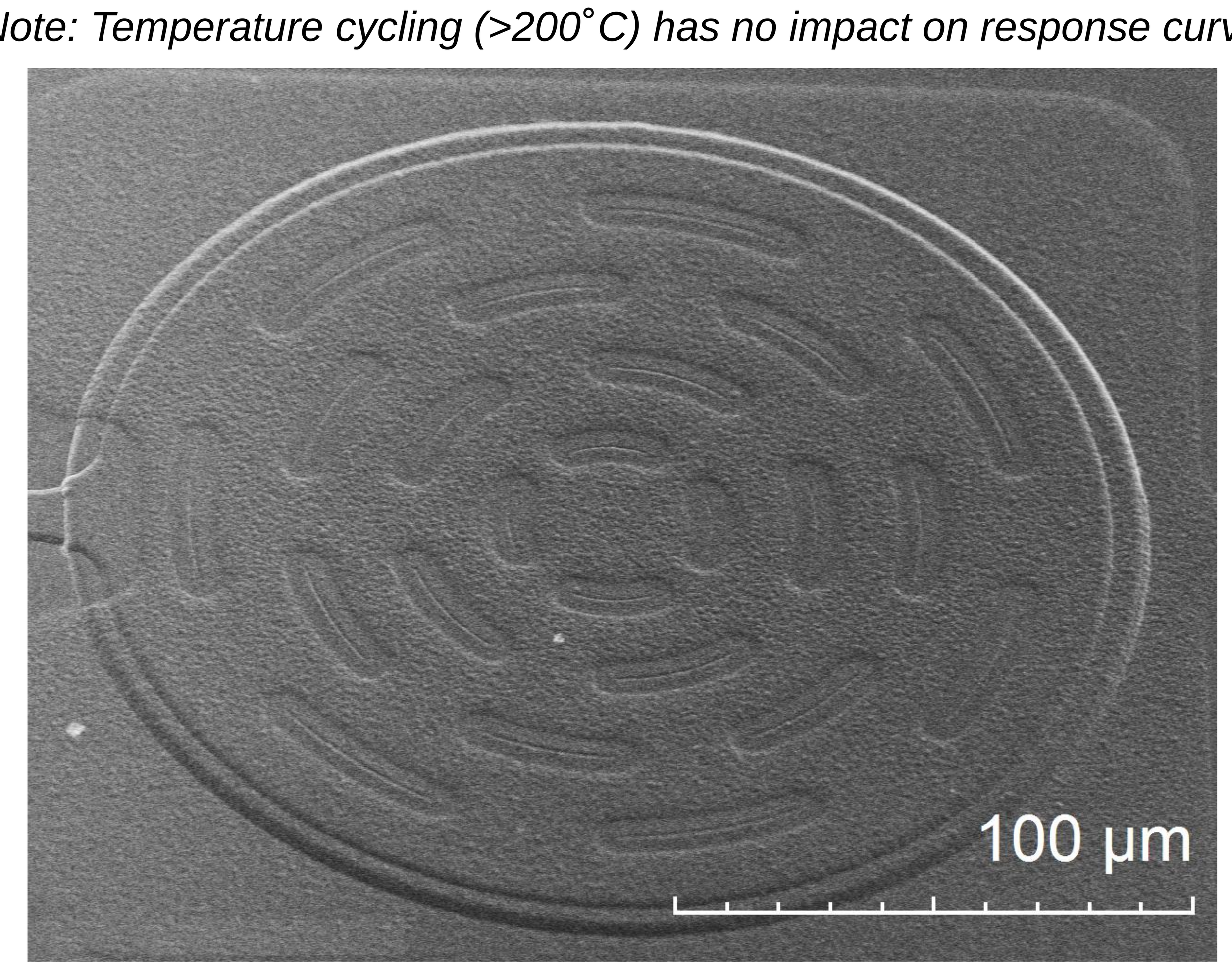
2 Capacitive Pressure Sensors

Capacitive Pressure Sensor Experimental Results

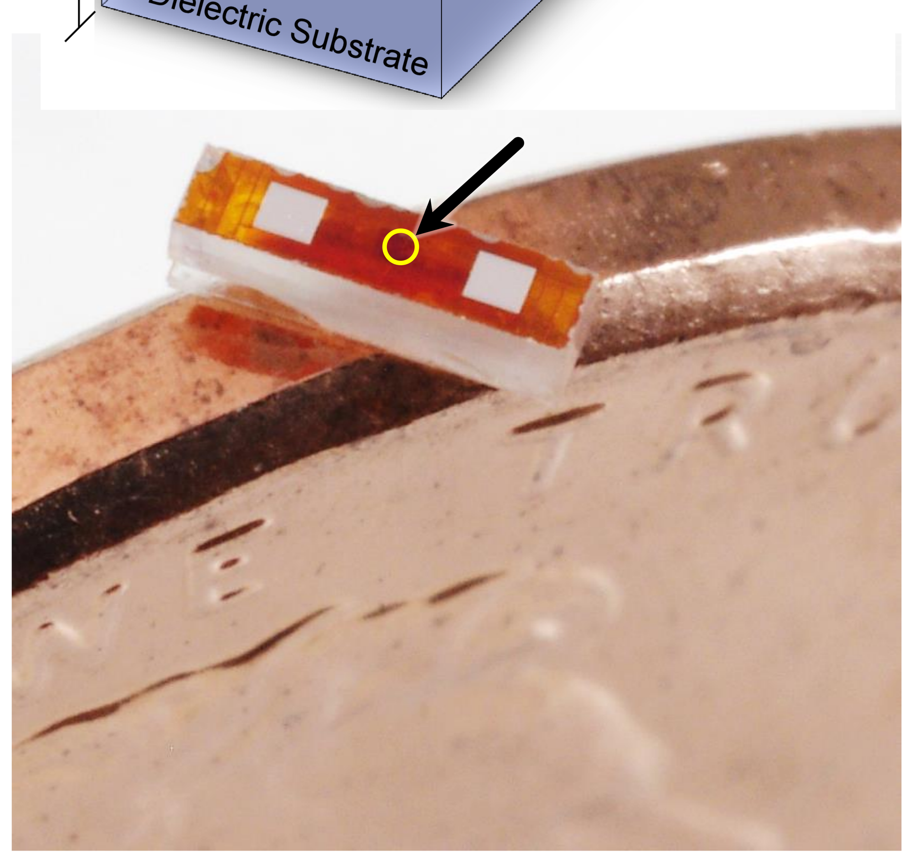
Device under test	C100	C200	4C100
Diaphragm size	ø100 µm	ø200 µm	4 || ø100 µm
Pressure range	0-7.25 kpsi (50 MPa)	0-1.8 kpsi (12 MPa)	0-7.25 kpsi (50 MPa)
Full range △cap.	≈1000 fF	≈1600 fF	≈3500 fF
Full range avg. sens.	≈135 fF/kpsi	≈915 fF/kpsi	≈490 fF/kpsi
Temperature sens.	TCO ≈ 276 ppm/°C (Inc. parasitic capacitances)		

Note: Temperature cycling (>200˚C) has no impact on response curve





SEM image of ø200 µm diameter device



ø100 µm device on US penny coin

3 Capacitive Hydrophone Sensors

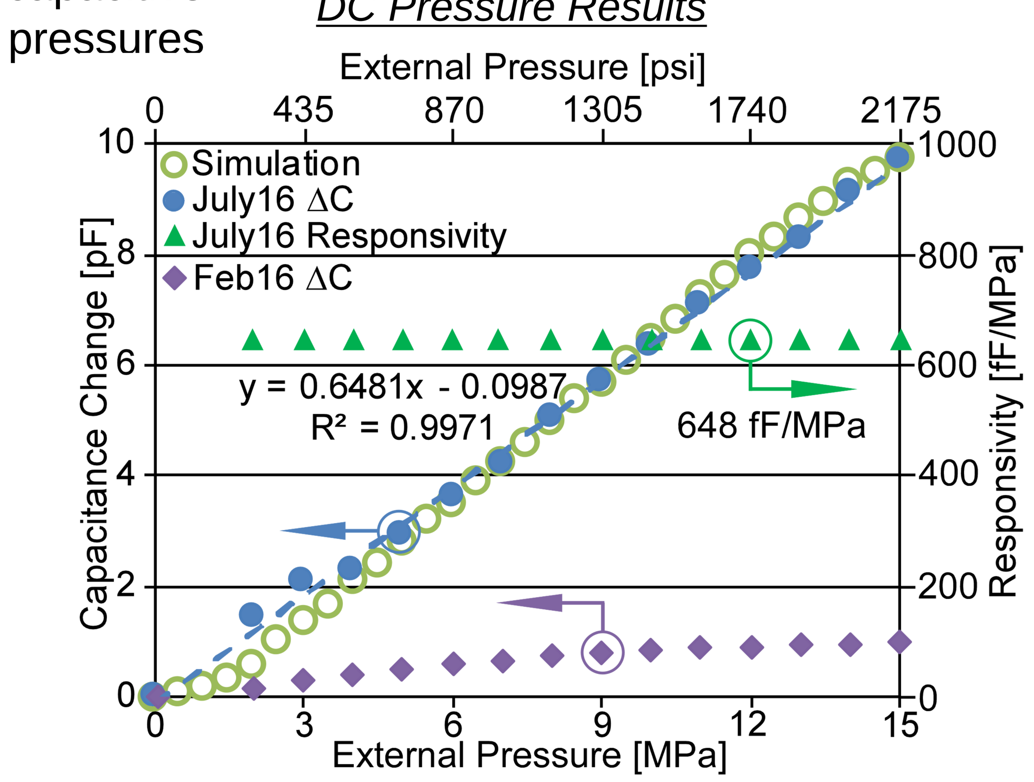
Motivation

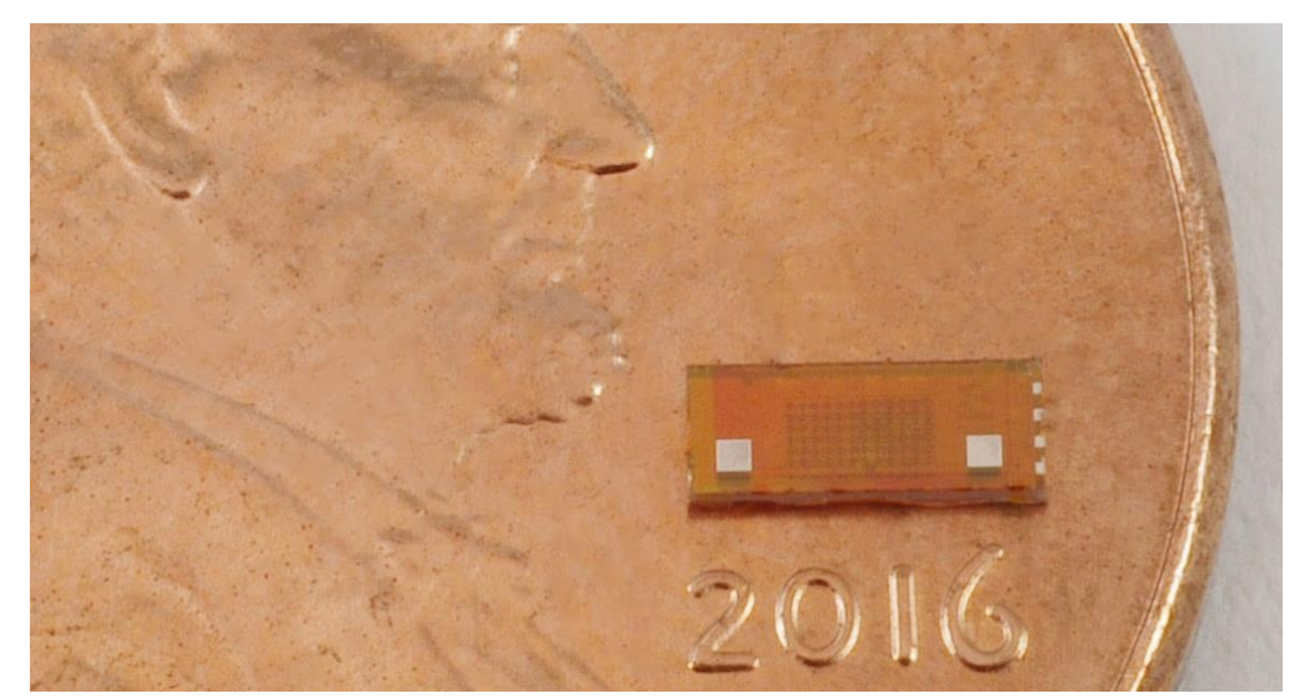
- Conventional hydrophones for high hydrostatic pressure environments compromise low frequency dynamic range and responsivity by using piezoelectric elements
- High pressure is conventionally accommodated by hydrostatic balancing, which leaves device susceptible to shock waves
- Capacitive touch mode sensing allows for pressure overloading, but does not provide highest responsivity
- A new capacitive architecture is proposed that exploits the non-linearity of capacitive sensors in order to deliver high responsivity over a large range of external pressures

Experimental Methods and Results

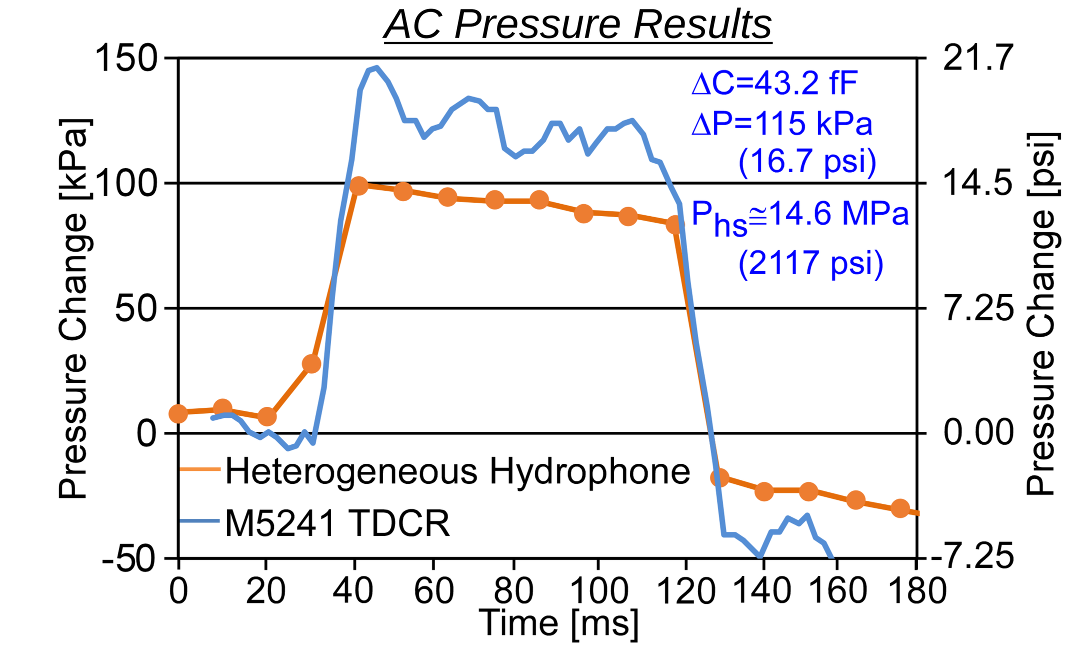
- AC pressure waves created by a piezoelectric actuator
- Commercial pressure transducer is used as a reference
- Hydrophone readout is done with AD7746 C-to-D converter
- DC pressure measurements show a ΔC of 9.7 pF over a 0-15 MPa dynamic range with a linearity of 97%
- Maximum pressure resolution estimated to be 0.23 psi when integrated with ELM microsystem
- Hydrophone bandwidth is simulated to be approximately 0-2 MHz with no lower frequency bound
  - *Also operates at DC pressure*
- AC amplitude of the hydrophone response tracks the small signal pressure wave regardless of applied DC pressure

DC Pressure Results



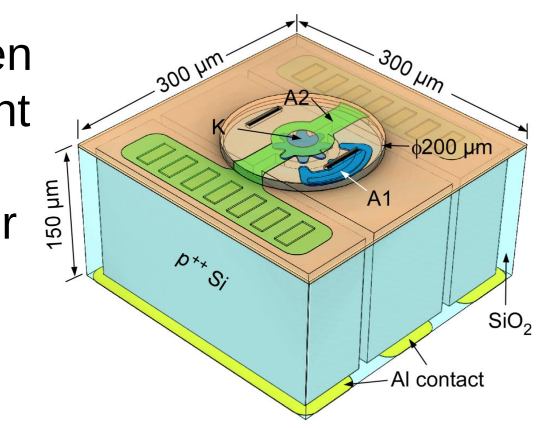


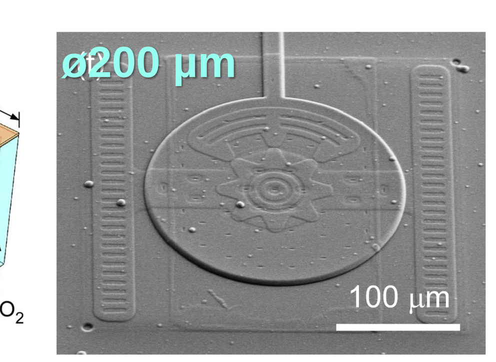
AC Pressure Results



4 Silicon Substrate Plasma Microdischarge Sensor

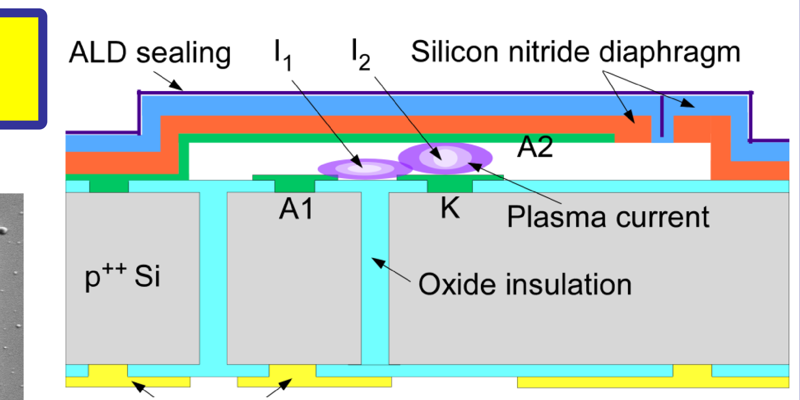
- As diaphragm deflects, current between K and A2 increases while K - A1 current remains constant
- Surface micromachined single Si wafer
  - Doped Si for electrical routing
- Ring A2 and spiked A1 & K
  - Optimized from plasma modeling





$$I_{out} = \frac{I_2 - I_1}{I_1 + I_2}$$

C. K. Eun, X. Luo, J.-C. Wang, Z. Xiong, M. Kushner and Y. Gianchandani, "A microdischarge-based monolithic pressure sensor," Journal of Microelectromechanical Systems, vol. 23, pp. 1300-1310, 2014.



Experimental Results

Pressure range	0–120 psi (0.8 MPa)
Discharge voltage	250 V
Full Range Sens.	≈1125 ppm/kPa

WIMS²

Acknowledgement

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Published Work

X. Luo and Y. B. Gianchandani, "A 100 µm diameter capacitive pressure sensor with 50 MPa dynamic range," Journal of Micromechanics and Microengineering, vol. 26, 2016.

Patent Pending

Non-provisional utility patent on plasma and capacitive sensors submitted on June 20th, 2014