A 15 ATM. PRESSURE SENSOR UTILIZING MICRODISCHARGES IN A 1.6 mm^3 CERAMIC PACKAGE

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ABSTRACT

This paper reports a high-pressure sensor that utilizes differential measurements of pulsed DC microdischarge currents. The microdischarges are created between three photochemically-patterned metal foil electrodes – two cathodes and one anode – within a gas-filled capsule. The external pressure deflects a diaphragm, which also serves as one cathode, varying the inter-electrode spacing. This changes the differential current between the two competing cathodes. The electrodes are fabricated from Ni foil, and separated by dielectric spacers within a micromachined glass cavity. The structures are enclosed within 1.6 mm^3 ceramic surface-mount packages. Devices with 25-µm-thick nickel diaphragms reinforced with 75-µm-thick epoxy provide a sensitivity of 2,864 ppm/psi (42,113 ppm/atm.).

INTRODUCTION

Microscale pressure sensors are potentially useful for mining and subterranean exploration if they can withstand high pressures and temperatures. A variety of optical and electrical microstructures have been proposed for these and various high-pressure and high-temperature applications. Fabry-Perot and other interferometers have been fabricated on the ends of fiber optic cables using a diaphragm to modulate a cavity thickness [1]. A microscale sensor has been fabricated using this technology to measure temperature and pressure [2]. Another sensing technology uses Bragg gratings, which are photo inscribed into fibers and used to trace wavelength shifts caused by strain (or pressure, displacement) and temperature changes [3]. A miniature bulk-modulus-based fiber Bragg grating sensor has been explored for pressure and temperature measurements in petroleum boreholes [4]. Piezoresisitve pressure sensors with diaphragms made from silicon carbide [5], and more recently even Si [6], have been reported that can also operate at elevated temperatures. Sapphire membranes have also been used in this context [7].

Microdischarges, or microplasmas, are miniature plasmas created in gases between electrodes and are used for on-chip chemical sensing and other applications. A discharge-based approach to pressure sensing is of interest because of the wide dynamic range and temperature immunity of the transduction method. Devices utilizing microdischarges are well suited for high temperature operation as the electrons have average thermal energies exceeding 3 eV (34,815 K) [8] away from the cathode. Ions have thermal energies exceeding 0.03 eV above ambient (644 K) in a 23ºC (296 K) ambient environment.

The target pressure range of these sensors is 1-15 atm. These microdischarge-based pressure sensors operate by measuring the deflection of a diaphragm electrode resulting from an external pressure. The diaphragm serves as a cathode and when deflected, the distance between the anode and the deflected diaphragm is affected, altering the current distribution of microdischarges between two cathodes with pressure. Microdischarge-based pressure sensors are fundamentally different than ion gauges, which are not effective at atmospheric pressure because the small mean free path of the created ions, 20-65 nm, makes them difficult to detect at the collector [9].

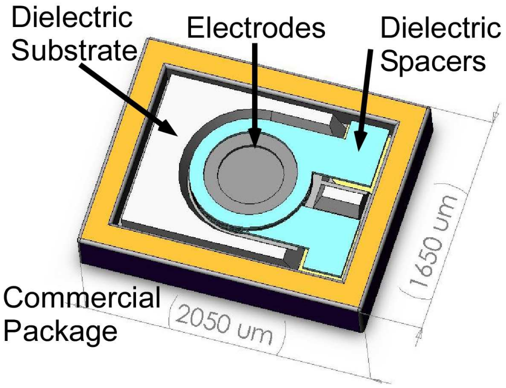

Figure 1: Schematic of device contained within a commercial Kyocera Package.

A microdischarge-based pressure sensor that exploits the variation, with pressure, of the mean free path of gas molecules was previously reported [10]. It uses an unsealed structure fabricated and operated in clean gas environments up to 2.5 atm. and 1,000°C.

This paper describes microdischarge-based microscale pressure sensors that utilizes sealed ceramic packages with a deflecting diaphragm-cathode, a stationary cathode, and an anode. These sensors are laboratory tested in an oil environment. The active volume of these devices is 0.057 mm^3, which is ≈10x smaller than previously reported microdischarge-based pressure sensors, while the targeted pressure range is ≈6x higher. Instead of a multi-cathode arrangement, multiple anodes may be used; however, anode current shows very high dependence on encapsulated gas pressure [11]. This high sensitivity results in relatively small dynamic ranges, thereby limiting the utility of multi-anode configurations.

DESIGN AND OPERATION

A pressure sensor consists of two electrodes enclosed within a commercial package with a dielectric substrate and spacers as shown in Fig. 1. (The third diaphragm electrode seals the package.) A dielectric Pyrex substrate is used within the package to maintain the position and spacing between the electrodes and diaphragm. Each electrode has a single lead for electrical contact to a package feedthrough. Dielectric spacers are used between electrodes to maintain inter-electrode spacing and provide electrical isolation. A microdischarge chamber exists in the center of the package, in a through-hole. A single disk-shaped anode electrode serves as the bottom of the chamber while the center electrode (cathode 1) is torus-shaped, allowing the discharges to exist between the bottom anode and both cathodes. The top cathode is disk-shaped as well, confining the discharges.

The encapsulated microdischarge-based sensors operate by measuring changes in current distribution of pulsed DC microdischarges between an anode and two cathodes. The distal diaphragm cathode (cathode 2) deflects due to external pressure,

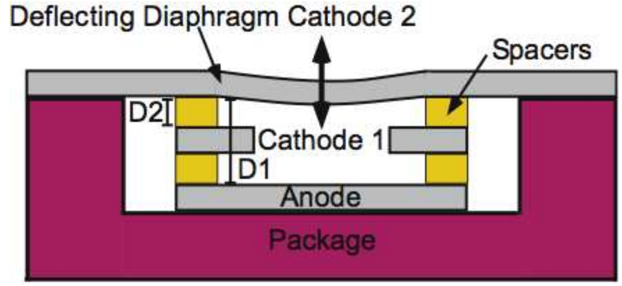

Figure 2: Conceptual image of sensor operation showing the anode, the proximal stationary torus-shaped cathode 1, and the distal diaphragm, cathode 2.

changing the inter-electrode spacing (Fig. 2). To determine the pressure causing this deflection, it is first necessary to separately determine the current in the two cathodes. These current components are denoted as I_1 in the proximal stationary torus-shaped cathode (cathode 1) and I_2 in cathode 2. The differential current, expressed as a fraction of the total peak current, $(I_1 - I_2) / (I_1 + I_2)$, is treated as the sensor output. At lower pressures cathode 2 is less deflected and more current flows through cathode 1, while at higher pressures more current flows through the deflected cathode 2. The readout is thus a displacement measurement for the diaphragm-electrode. An important benefit of using a differential output that is expressed as a fraction of the total is that the exact magnitudes are less important than fractional changes.

The gas pressure in the sealed cavity remains relatively constant because the cavity volume remains relatively unchanged by the diaphragm displacement. The high external pressure causes a great deal of initial displacement and additional pressure variations cause only small displacement changes. These changes can be measured directly using the microdischarge current distribution, but do not alter the internal package pressure significantly. Thus measurements of the internal package pressure are less sensitive than measurements of the diaphragm displacement.

Finite element analysis (ANSYS®) is used for diaphragm design, considering spacer compression and diaphragm deflection. Options range from 25-µm-thick nickel foil for high sensitivity to cold-rolled 125-µm-thick stainless steel for very-high pressure operation. The maximum achievable pressure with diaphragms of specified thicknesses and materials are outlined in Table 1.

Table 1: FEA analysis was performed using ANSYS® software to determine the maximum measurable pressure of sensors utilizing various diaphragms.

Material	**Thickness (µm)**	**Deflection (µm)**	**Max. Stress (MPa)**	**Max. Pressure (psi)**
Nickel	25	0.63	59	100-200
304 SS	25	2.4	215	400-500
60% Hardened 304 SS	125	7.3	1,027	20,000

To control power consumption and parasitic heating in the pressure sensors, pulsed DC microdischarges are used, as opposed to constant DC discharges. A computer controlled, single ended, transformer coupled, gate drive circuit creates the pulses. A current limiting ballast resistor is used in series with the anode, and 100-Ω resistors are used in series with each cathode to measure current.

The basic operation of a DC microdischarge in a sensor is driven through electron and ion transport. The electrons are drawn towards the anode, whereas the positive ions are drawn to the two separate cathodes forming positively charged sheaths around them. Upon cathode impact, the energetic ions eject high energy secondary electrons from the cathodes, which sustain the microdischarges by ionizing additional neutral molecules and continuing the breakdown process. The current in each cathode is composed of a combination of positive ions impacting the cathodes from the microdischarges and secondary electrons ejected from the cathodes upon ion impact. Further away from the cathodes, the current is carried primarily by the faster moving electrons, which cannot reach the cathodes because of surrounding sheaths.

Sensor characteristics such as the sensitivity, pressure dynamic range, and temperature dynamic range depend on a variety of dimensional parameters, including inter-electrode spacing, electrode diameter, and the cathode thickness. (Cathode thickness effects sheath sizes as well as electrode positioning). The sensors are designed to function with an applied voltage of 500 V; altering the voltage results in different sensitivities. A sealed sensor is shown in Fig. 3(a), with a visible bond ring. A scanning electron microscope image of the components within a sensor is shown in Fig. 3(b).

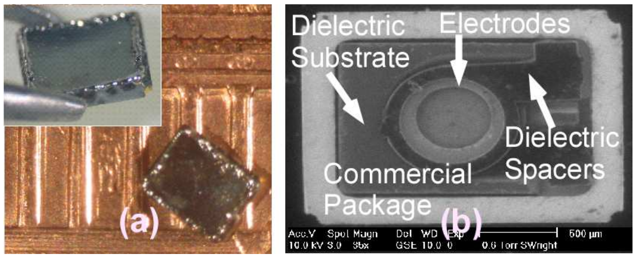

Figure 3: (a) Photograph of pressure sensor on a penny with a laser-welded diaphragm. (b) SEM image of the sensor illustrating the stacked electrode and dielectric spacer layers.

FABRICATION

The sensors are formed by stacking bulk-metal electrodes and dielectric spacers within a dielectric substrate. This substrate is then enclosed in a commercial package by bonding a metal diaphragm to the top of the package, as shown in Fig. 4.

The package used for the sensor is designed for crystal oscillators and has external dimensions of $2.05 \times 1.65 \times 0.5$ mm^3 (Kyocera, Japan). The package has two internal feedthroughs with internal gold-coated contact pads, which are used for the anode and cathode 1. A third gold-coated contact pad on the rim makes electrical contact to cathode 2, the diaphragm lid.

Within the packages a 175-µm-thick-Pyrex substrate maintains the position of the electrodes and dielectric spacers. The sidewalls of this substrate and the recessed area in the center are formed using a micro abrasive jet (MAJ) process, also known as powder abrasive blasting (Bullen Ultrasonics, Eaton OH). The substrates are formed from Schott D263 borosilicate glass due to its

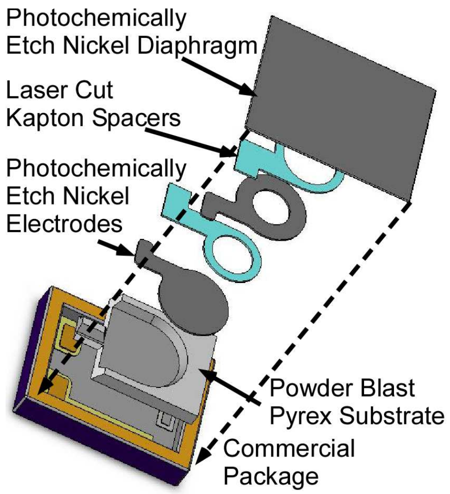

Figure 4: Component integration illustrating stacked electrode/spacer structure within a commercial package before diaphragm attachment.

machinable and dielectric properties. The MAJ process is used because it allows a 100 µm deep recess to be etched into the center of the substrate, in which the microdischarge chamber is housed.

The 25-µm-thick-bulk-foil electrodes have outer diameters of 800 µm and are patterned from nickel for several reasons. Primarily it is robust, inexpensive, easily machinable by micro-electro-discharge machining and photochemical etching, and has a sufficient secondary emission coefficient (i.e. secondary electrons created per incident ion) in a nitrogen ambient.

The electrodes are lithographically patterned and etched from nickel foil using photochemical machining. This process involves coating a thin sheet of metal with photoresist, exposing the resist, and spraying the sheet with a chemical etchant to dissolve the exposed metal. The exposed metal is completely removed, leaving through-holes in the sheet, and the resist is stripped (ChemArt Company, Lincoln RI).

The 25-µm-thick-dielectric torus-shaped spacers serve to electrically isolate the electrodes from one another and from the diaphragm, and to allow microdischarges to be created in the center through-holes. They also define the inter-electrode spacing. Kapton is used due to its dielectric properties and ability to withstand 400ºC temperatures without significant dielectric loss. The spacers are laser cut from a Kapton sheet for precision (Tech-Etch, Plymouth MA).

Electrical contact is made between the nickel electrodes and the gold contact pads of the package by conductive silver epoxy. The epoxy also serves to physically secure the electrodes.

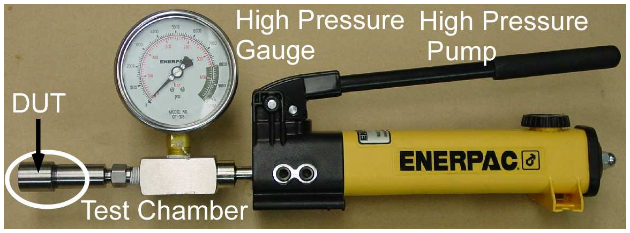

Figure 5: Test set-up used to apply high pressure oil to the sensor.

The diaphragm electrode is bonded to the package using laser welding or solder bonding. When solder bonding, a Sn/Pb foil bond ring is used between the package and diaphragm. These bonding procedures hermetically seal the device within the package. The diaphragm rests on the electrode/spacer stack to strictly define the maximum inter-electrode spacing.

RESULTS AND DISCUSSION

Pressure sensors were fabricated and tested at pressures up to 15 atm. (200 psi) in dielectric oil. Compressed nitrogen was used to pressurize the oil at lower pressures while a hydraulic jack (Fig. 5) was used at higher pressures. Pulses 1 ms in duration with 500 V were applied. The applied voltage pulses resulted in current pulses through each cathode. The transient current peaks were approximately 100-200 µs in duration, with amplitudes of 5-50 mA (25 µJ per pulse), varying with pressure.

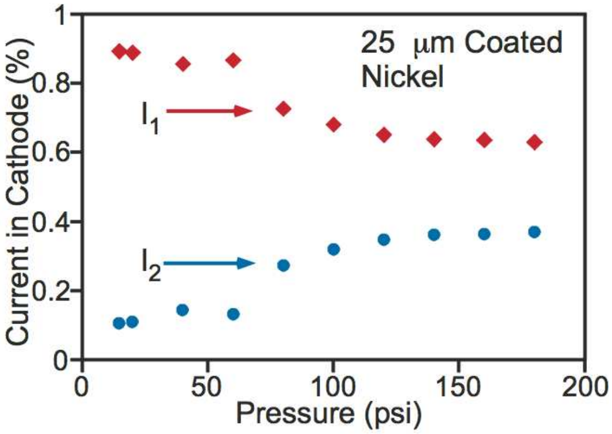

Figure 6: Current distribution between cathodes 1 and 2 in a sensor with a 25-µm-thick nickel diaphragm coated with a 75-µm-thick epoxy layer. Each data point is the average of 100 measurements.

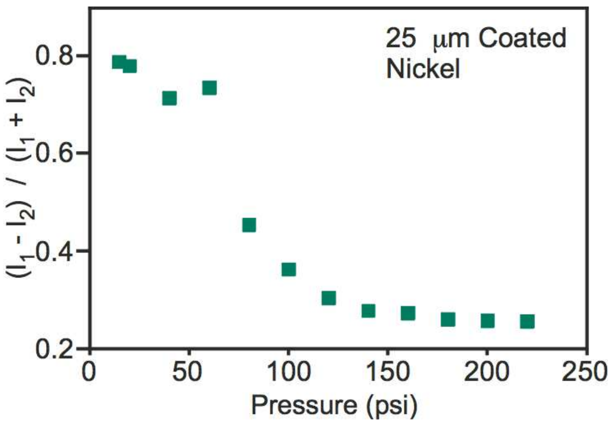

Figure 7: Sensor output as a function of pressure in a sensor with a 25-µm-thick nickel diaphragm coated with a 75-µm-thick epoxy layer. Each data point is the average of 100 measurements. Pressure was measured up to 15 atm.

Pressure was determined by measuring the difference between the fractional current in each cathode. Figure 6 shows the fractional current distribution between cathodes 1 and 2 in a sensor with a 25-µm-thick nickel diaphragm coated with a 75-µm-thick epoxy layer as a function of pressure. This sensor provided a sensitivity of 2,864ppm/psi (42,113ppm/atm.) and operated up to 15 atm. (Fig. 7).

CONCLUSIONS

Encapsulated microdischarge-based pressure sensors have demonstrated an ability to measure pressures up to 15 atm. within oil environments. By utilizing different diaphragm materials and thicker diaphragms, the sensors are expected to operate up to 20,000 psi, as experienced in petroleum exploration and pumping. The electrical nature of the readout avoids an intermediate transduction step that is common to many sensors. The discharge-based transduction provides a large readout that does not require local amplification, although it does require a high voltage (pulsed) power source. The small volume occupied by the sensors could be useful for embedded systems and portable applications.

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REFERENCES

[1] R. Fielder, K. Stingson-Bagby, M. Palmer, “State of the art in high-temperature fiber optic sensors,” *SPIE*, 5589(1), pp. 60-69, 2004

[2] D. Abeysinghe et al., *J. Micromech. and Microeng.*, 12(3) pp. 229-235, 2002.

[3] T. Li, Z. Wang, Q. Wang, X. Wei, B. Xu, W. Hao, F. Meng, S. Dong, “High pressure and temperature sensing for the downhole applications,” *SPIE*, 6757(1), pp. 1-7, 2007.

[4] Y. Zhao, Y. Liao, S. Lai, *IEEE Photonics Technology Letters*, 14(11), pp. 1584-1586, 2002.

[5] A. Ned, R. Okojie, A. Kurtz, “6H-SiC pressure sensor operation at 600°C,” *HITEC*, Albuquerque, NM, pp. 257-260, 1998.

[6] S. Guo, H. Eriksen, K. Childress, A. Fink, M. Hoffman, *IEEE MEMS*, Tucson, AZ, Jan. 2008, pp. 892-895.

[7] S. Fricke, A. Friedberg, T. Ziemann, E. Rose, G. Muller, D. Telitschkin, S. Ziegenhagen, H. Seidel, U. Schmidt, “High temperature (800ºC) MEMS pressure sensor development including reusable packaging for rocket engine applications,” *MNT for Aerospace Applications, CANEUS*, pp. 5p, 2006.

[8] M. Kushner, “Modeling of microdischarge devices: Plasma and gas dynamics,” *J. Phys. D: App. Phys.*, 38(11), pp. 1633-1643, 2005.

[9] C. Edelmann, “Measurement of high pressures in the vacuum range with the help of hot filament ionization gauges,” *Vacuum*, 41(7-9), pp. 2006-2008, 1990.

[10] S. Wright, Y. Gianchandani, *J. Microelectromechanical Sys.*, 18(3) pp. 736-743, 2009.

[11] C. Wilson, Y. Gianchandani, R. Arslanbekov, V. Kolobov, A. Wendt, “Profiling and modeling of dc nitrogen microplasmas,” *J. Appl. Phys.*, 94(5), pp. 2845-2851, 2003.