A NOVEL SILICON MICROMACHINED CRYOGENIC CAPACITIVE PRESSURE TRANSDUCER

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ABSTRACT

A novel cryogenic capacitive pressure transducer was developed using Silicon micromachining techniques. It employs a flexible Silicon membrane which is sealed to a helium sample chamber with an Indium seal. A thin film capacitor plate is attached to the back side of the membrane. A second thin film capacitor plate is located a short distance away on a fixed Silicon wafer. Pressure variations in the sample cell will flex the membrane thereby adjusting the relative capacitance of the circuit. The membrane can be easily fabricated to precise dimensions, allowing fine tuning of the spacing between the capacitor plates. This allows easy optimization of the sensitivity and dynamic range of the transducer.

INTRODUCTION

Capacitive pressure gauges are extremely useful devices in low temperature science, being conceptually simple, well analyzed and yielding a resolution of up $\delta P/P$ 10^{8}.[1] However, current designs are somewhat complicated to build and not very reproducible. Once the transducer is assembled, then its characteristics can be measured, and if the characteristics are not desirable, one has to essentially rebuild the transducer. Another problem with the conventional design is the degree of parallelism between the capacitor plates and the distance between them, both of which will affect the sensitivity of the device. We developed a new type of capacitive pressure sensor in which the gap between the electrodes can be set precisely to one's specification, allowing tailoring of the starting pressure and dynamic range, while maintaining a high degree of parallelism between electrodes. This new design borrows techniques from integrated circuit fabrication technology to build mechanical structures using a single crystal silicon wafer as the starting material.

DESIGN AND CONSTRUCTION

igure 1 shows a schematic drawing of the transducer. A silicon membrane seals a helium

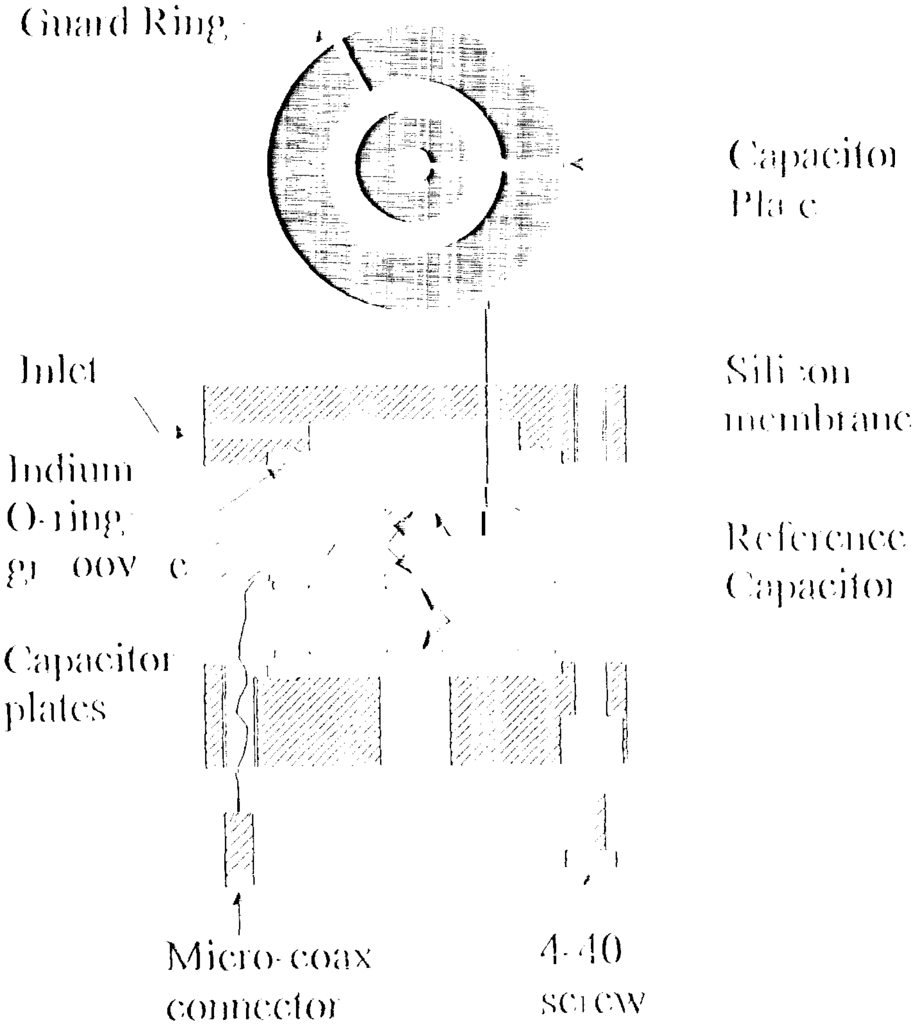

Figure 1. Schematic drawing of the silicon micromachined capacitive pressure tra [illegible]

sample chamber with an Indium O ring. The back side of the membrane has a well etched on it. A capacitor plate is defined inside the well by photolithography and metal deposition. A second identical wafer is placed against the membrane so that the gap between the capacitor plates is given by the depth of the wells. By measuring the capacitance as the membrane displaces due to changes in pressure (relative to ambient pressure, which is close to zero in a cold vacuum can), one can then measure the change in pressure in the chamber. An identical set of wafers can be placed under this first set to act as a reference capacitance, in case a cold reference capacitance is needed. In a preliminary version, a block of Silicon replaced the reference capacitor. The gap between the capacitor plates can be adjusted by timing the etch of the silicon wafers as will be described below. By varying this gap we can tailor the shorting pressure to be close to the pressure to be measured, yielding greater resolution. The trade-off is the dynamic range, which becomes smaller as the pressure to be measured gets closer to the shorting pressure.

The fabrication of the wafers is as follows. One inch wafers polished on both sides are furnished by the vendor. The wafers are then oxidized in a furnace at 1050 C in a flow of oxygen saturated with water vapor. The oxide acts as a mask during the etch step. The well pattern is defined by standard photolithography. The result is a pattern where the oxide is exposed in the regions to be etched and protected by the photoresist in the regions that will not be etched. Reactive Ion Etching with CF_4 is than performed on the wafer, removing the oxide from the regions left exposed by the photoresist mask. After removing the leftover resist in acetone the wafer is placed in the standard anisotropic etch bath (KOH at 95 C). The KOH will etch preferentially the regions without the protective oxide. The etch rate is typically 1μm per minute. For short etch times, the bottom of the well remains optically flat. The remaining protective oxide is removed in Buffered Oxide Etch and the whole wafer is oxidized again in a furnace at 1050 C under a flow of oxygen saturated with water vapor. The capacitor plate patterns are defined by standard photolithography, metal evaporation and lift-off in acetone. The capacitor plates are composed of a bottom layer of Titanium (300Å), an intermediate layer of Platinum (300Å) and a top layer of Gold (3000Å). Notches are cut on the wafers so external contact can be made to the coaxial connectors.

A typical depth of the well is 12μm, yielding a separation between capacitor plates of 24μm. Such small separation yields reasonably large capacitances (a few to tens of pico-Farads) even for small (1.5 mm radius) capacitor plates. Moreover, small capacitance plates ensure that the plates displace with respect to one another while still remaining flat, therefore minimizing the effect of bowing of the plates, which degrades the performance of the transducer. The distance between plates can be controlled to within 1μm. The design also includes a guard ring around the capacitor plates. The guard ring avoids errors in capacitance measurements due to stray capacitances, and they should be always grounded.

The membrane and bottom wafer plates can be replaced if one desires different characteristics, with thicker wafers yielding higher shorting pressures. The fabrication time for a set of wafers is about two days.

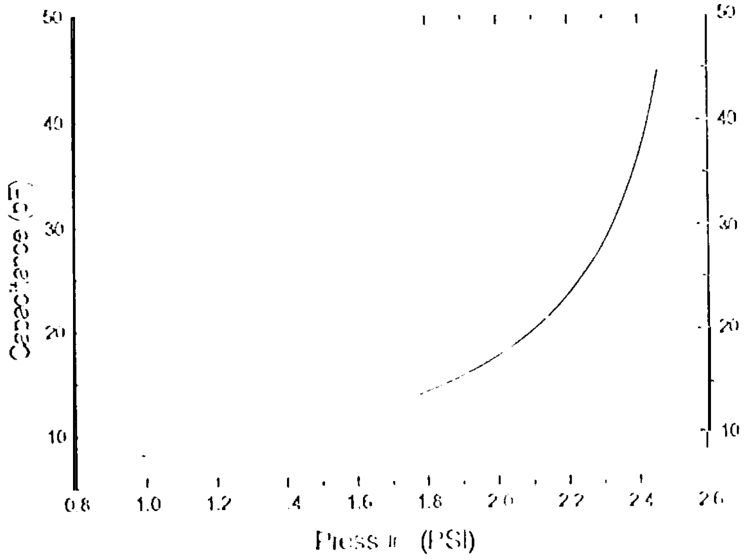

Figure 2 Pressure Transducer Calibration

TESTS AND RESULTS

In order to test the ultimate resolution of the transducer, a preliminary version was built that had a shorting pressure of roughly 2.5 PSI. This allowed us to use our cryostat with a high resolution thermometer to regulate the temperature in the cell to the necessary accuracy to observe the target resolution of 1 part per billion in pressure. Figure 2 shows the calibration of this version of the transducer. The calibration was done by slowly cooling the sample cell which contained liquid helium in equilibrium with its vapor, and passively measuring the temperature in the cell and the transducer capacitance. The pressure is obtained from the vapor pressure of helium at a given temperature.[2] We have used a low temperature valve[3] to isolate the sample chamber from pressure fluctuations due to the temperature gradient along the fill line.

In order to measure the resolution of the transducer, the temperature in the cell was stabilized at 2.75K (vapor pressure = 2.37 PSI) to within 2nK rms using a High Resolution Thermometer (HRT)[4]. The temperature was determined by measuring the temperature dependent magnetization of a paramagnetic salt ($GdCl_3$) placed in a constant magnetic field. Changes in magnetization induce current changes in a superconducting pick-up loop coupled to an RF SQUID. The HRT was calibrated against a germanium resistor. To stabilize the temperature the output of the RF SQUID is used as the input signal for a Linear Research LR130 Temperature controller [5]. While measuring the capacitance, the temperature was changed by 365nK and stabilized to within 2nK rms. After roughly five minutes the temperature was changed backward to the original point and again stabilized to within 2nK rms. This was done several times and the corresponding change in capacitance was recorded. Figure 3 shows typical data. The averaging time for the capacitance measurements was 0.5 seconds. The capacitance measurements were performed with an Andeen Hagerling model 2500A self balancing capacitance bridge.[6] The rms variation of the temperature at each plateau was 2nK.

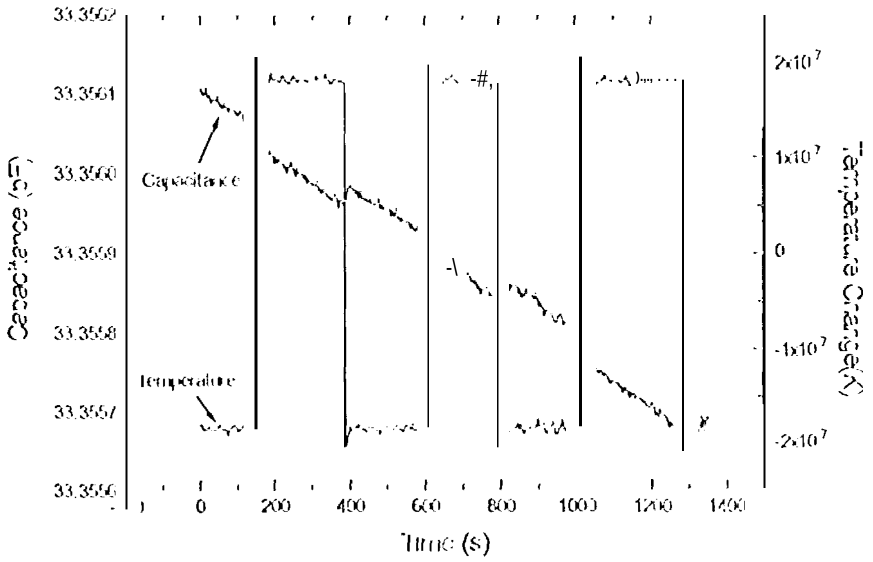

Figure 3. Temperature in sample cell and capacitance as a function of time

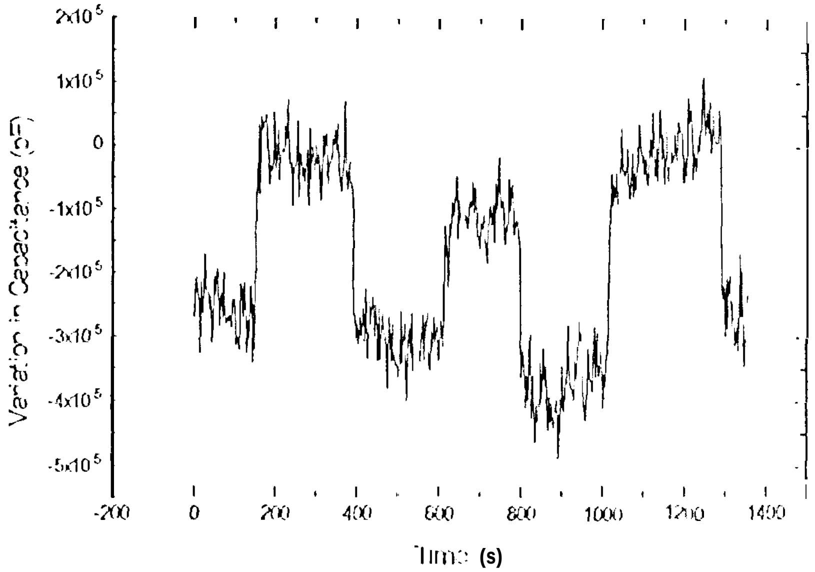

Figure 4. Variation in capacitance as a function of time without the constant drift

The capacitance had a constant drift of -3.25×10^{-7} pF per second. In order to obtain the rms value of the fluctuation in capacitance, this drift was subtracted from the data as shown in Figure 4. The rms fluctuation of the capacitance at each plateau was $\delta C = 3.74\times10^{-6}$ pF. Based on the change in capacitance with the change in temperature, we estimate $dC/dT = 1.79$ pF/K. At this temperature ($T = 2.75$K) the slope of the helium vapor pressure line is $dP/dT = 3.942$ PSI/K^2. The fluctuation of pressure at the plateaus is then $\delta P = 1.8\times10^{-7}$ PSI. This gives a pressure resolution of $\delta P/P = 8\times10^{-8}$. Note that the fluctuation in pressure due to temperature fluctuations is only 8×10^{-9} PSI, more than one order of magnitude smaller. This indicates that the source of fluctuations in capacitance is intrinsic to the transducer. At this time, the cause is still unknown, and further investigation is necessary. One possible source is the measuring setup since, even though the bridge used is self balancing (i.e., it is never run off-balance), the ultimate resolution can still be affected by the cable length. In order to correct that, a cold reference capacitor has to be included in the setup. The next version of the transducer will have this cold reference. The other problem to be solved is the drift in capacitance as a function of time. One possibility that was considered to explain this behavior is the ductibility of the Indium O-ring. It is possible that the O-ring relaxes with time, therefore affecting the pressure that presses the two silicon wafers together and thus the distance between the capacitor plates. To correct this, different O-rings will be tested. The two possibilities considered are gold and kapton. It is possible that a cold reference will also minimize this problem, since the pressure that holds the measurement capacitor together will be exactly the same as the pressure that holds the reference capacitor, therefore canceling the effect.

CONCLUSION

We have designed and built a novel pressure transducer based on silicon micromachining techniques. Preliminary tests show a resolution $\delta P/P \sim 8\times10^{-8}$, roughly one order of magnitude worse than the state-of-the-art and two orders of magnitude worse than our target. An additional problem is a constant drift of the capacitance with time. New versions of this transducer will have a cold reference built in, and possibly a different kind of O ring for sealing the chamber. We believe this will bring us close to the state-of-the-art. In order to achieve a resolution of $\delta P/P$ of 10^{-9}, we believe the length of the leads will have to be reduced, implying the necessity of a cold amplifier.[7] Once this problems are solved, we believe this instrument will be extremely useful and versatile, providing the opportunity of tailoring the desired resolution and dynamic range with great ease.

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