ELSEVIER

Sensors and Actuators 83 (2000) 142–149

SENSORS AND ACTUATORS A PHYSICAL

www.elsevier.nl/locate/sna

Packaging a piezoresistive pressure sensor to measure low absolute pressures over a wide sub-zero temperature range

J. Kurth Reynolds [a,*], David Catling [b], Randel C. Blue [c], Nadim I. Maluf [d], Thomas Kenny [a]

[a] Mechanical Engineering Department, Stanford University, Stanford, CA 94305-4021, USA
[b] NASA Ames Research Center, Mountain View, CA 94035, USA
[c] Jet Propulsion Lab, Pasadena, CA 91109-8099, USA
[d] Lucas NovaSensor, Fremont, CA 94539, USA

Received 28 June 1999; received in revised form 25 November 1999; accepted 9 December 1999

Abstract

The packaging, calibration, and testing of a commercial silicon fusion bonded piezoresistive pressure sensor for a Martian deployment are described. Detail is provided on the sensor mounting and electronic instrumentation required for this environment. Flight testing procedures and the residual errors for packaged pressure sensors are presented. Pressure and temperature hysteresis are investigated as sources of this error. The data illustrates the potential high performance of off-the-shelf silicon fusion bonded piezoresistive pressure sensors, which are carefully packaged, instrumented, and individually calibrated.

Keywords: Piezoresistive; Calibration; Die attach; Hysteresis

1. Introduction

NASA has recently initiated a series of low-cost, short development time missions, which are intended to speed the infusion of commercial technologies into spacecraft. An example of this is the Deep Space-2 (DS-2) Microprobe mission launched in January of 1999 with the Mars Surveyor Lander [1]. Such probes may be used to monitor meteorological parameters such as barometric pressure, and our research was directed at packaging pressure sensors in a manner suitable for incorporation onto the probes. The probes drop ballistically to the planets surface from an interplanetary trajectory and slow during entry, but still experience a shock of $\sim 100{,}000 \times g$ upon reaching the surface. This shock and other environmental conditions favor the use of miniature sensors. However, scientific requirements are so demanding that off-the-shelf micromachined pressure sensors are not accurate enough, especially given the mean atmospheric pressure on Mars of ~ 6 mbar.

Silicon piezoresistive sensors represent a significant fraction of all commercial micromachined sensors. The basis of this technology is the piezoresistive strain gauge, implanted on the surface of micromachined silicon structures, and measurable with simple instrumentation amplifiers and off-chip electronics. The simplicity and robustness of piezoresistive sensors makes them an ideal candidate for the DS-2 mission, though they are generally regarded as ‘‘low-performance’’ devices because of large scale-factor and offset temperature coefficients that limit their accuracy.

To overcome known problems with piezoresistive pressure sensors, we implemented a novel mechanical package to minimize transmission of stress from the substrate to the sensor. We utilized a monolithic temperature reference to calibrate the pressure signal. Instrumentation electronics were miniaturized using simple hybrid circuitry. Digitized data and resulting calibrations are fit to a third order functional surface, and the residual errors of subsequent calibrations are calculated. Further data was collected on the source of the residual errors, and the effectiveness of sensor burn-in. This investigation has focused on the basic performance limitations of piezoresistive sensors, and the following conclusions can be extracted for a generic MEMS audience.

* Corresponding author. Tel.: +1-650-723-9098; fax: +1-650-723-3521.
E-mail address: kuthr@stanford.edu (J.K. Reynolds).

0924-4247/00/$ - see front matter
PII: S0924-4247(00)00294-6

- The error in commercial piezoresistive sensors due to package-induced stresses, which lead to un-calibrated errors and drift, can be minimized over a wide temperature range. Such errors are not unique to piezoresistive sensors, and must be accounted for in all instruments.
- Individually calibrated, strain isolated piezoresistive sensors are suitable for low absolute pressure and low temperature applications.
- Piezoresistive sensors are generally more accurate than realized, and should be considered for many lower pressure applications, due to their ease of fabrication and simple sensing circuitry.

2. Sensor deployment and operation

This pressure sensor package is designed to be delivered on board a microprobe, which descends as a single stage from atmospheric entry at an interplanetary velocity of 7 km/s to impact and deployment. An aeroshell orients and slows the probe, but shatters when the probe strikes the surface with a velocity of ~200 m/s. The sensor experiences a peak shock of ~100,000 $\times$ g with a bandwidth greater than 1 kHz when it decelerates in the top 10–30 cm of the Martian surface [2]. The sensor must reliably survive this type of deployment with minimal effects on sensor performance. Sensors previously deployed on Mars are based on relatively large metal diaphragms and clearly could not meet this goal.

The Martian temperature environment is extreme relative to Earth, because it has a thin atmosphere and no oceans. The average pressure is less than 1% of Earth's, and has significant daily and yearly changes in pressure as shown in Fig. 1. This makes all manner of sensing more difficult, and measurements of pressure particularly so. To resolve less than 0.05 mbar hourly pressure change, and accurately report daily changes of under 1 mbar in the presence of temperature swings greater than 50°C is problematic [3]. Previous missions provided extra power to continuously heat sensors, which removes their direct sensitivity to temperature, and also lowers the effect of external temperature cycling on the long-term stability of the sensors.

Though piezoresistive sensors would clearly also benefit from such temperature regulation, continuous power was not available in the Mars Microprobe design. A peak of less than 65 mW was available for all electronics integrated with the sensor and an average power of only 2.5 mW was allowed. In a typical sampling strategy, the pressure sensor and associated electronics would be activated for only ~2 min each hour after deployment for a number of samples (~16) to be stored and later transmitted. Approximately 90 s of this is warm-up and stabilization time for the sensor with individual samples taking only ~1 s. Longer continuous measurements could be done with ~100 continuous pressure samples in less than 3 min out of an hour and still maintain a duty cycle of less than 5%. Pressure samples would be returned to Earth periodically via an orbital relay around Mars. Measurements at a single site would allow comparisons with previous data such as that from NASA's Viking and Pathfinder Landers [4]. A time series of such measurements would allow the characterization of the atmosphere, facilitating quantitative comparisons with the terrestrial climate [5].

3. Instrument

3.1. Substrate mounting

The instrument substrate mounting is crucial to the survival of the sensor and electronics through deployment. Each IC, including the pressure sensor die, is recessed into a ceramic substrate as shown in Fig. 2. Short aluminum wire-bonds, less than 250 μm long from die to substrate, were chosen for their high strength to weight ratio. This stiffness minimizes the risk of breakage and shorting, but can allow strains developed during impact or due to temperature fluctuations to stress the die at the bond pads and cause sensing errors. Each surface mount resistor and capacitor is secondarily bonded to the substrate with a filleted non-conductive epoxy.

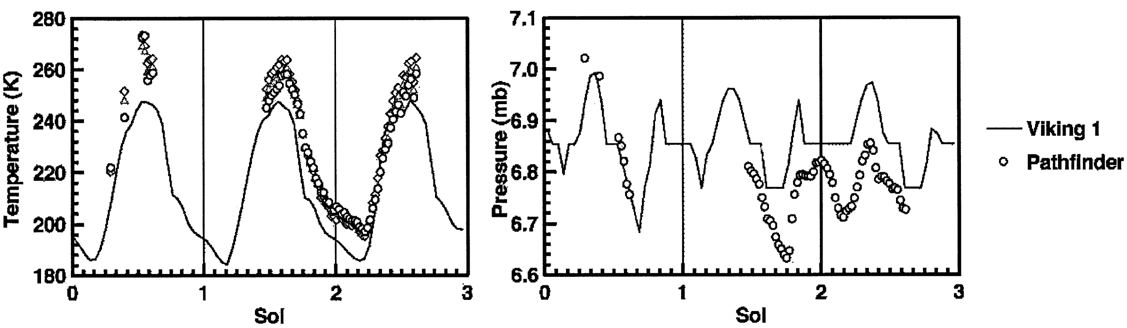

Fig. 1. Martian summer weather data is taken by Pathfinder and Viking over 3 Martian days (Sol: 24 h 39 min).

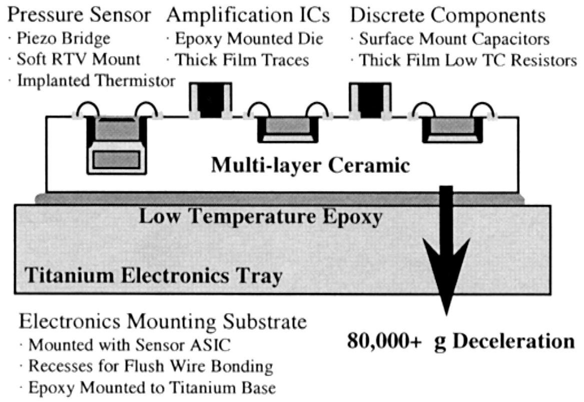

Fig. 2. The schematic diagram of the instrument substrate shows how components were mounted to survive deployment and thermal cycles.

A multi-layer ceramic substrate serves to isolate the die and electronics from the worst impact and thermal stresses. In turn, the substrate is mounted with Hysol 9309, a low-temperature epoxy, to the titanium electronics tray. The size and weight savings of the hybrid technology should not be over looked. It allows seven ICs with more than 50 passive elements to be routed, mounted and recessed in only 5 cm^2. This in turn allows a minimal five wire digital and power flex-cable interconnect between a substrate sensor ASIC and the telecom electronics. The digital signals are carried over a serial bus to control and communicate the pressure sensor signals.

3.2. Die attach

Mounting of the pressure sensor into the ceramic substrate as drawn in Fig. 3 is crucial to minimize strain on the piezoresistive die. Since the pressure sensor itself is a strain transducer, stresses coupled by the mount cause errors and must be minimized. At the same time, the sensor must remain laterally caged by the mount during impact and damped of the higher frequency components. If the die is allowed to deflect too far laterally or vertically, wire-bond failure is likely. The wire-bonds themselves experience significant impact forces so they also cannot be made too long. The caging, damping, and strength of the mount designed for deployment must be balanced with the forces on the die after deployment. Here the packaging strains associated with deflections of the Titanium mount from impact, which can be as large as 1% must be mitigated. The thermal strains caused by differential thermal expansion of the silicon and RTV over 100°C are also approximately 1%, and are difficult to minimize simultaneously [6,7].

The normal procedure for mounting piezoresistive sensors is a silicone soft die-attach. In this case, however, a specialized silicone with a glass transition below −115°C must be used to isolate the pressure sensor at Martian temperatures. Moreover, vacuum compatibility with other instruments must be considered. One of the few satisfactory choices is GE-RTV 566 [8]. Although its compliance falls with temperature, it retains elasticity below the −80°C temperatures required. In analytical models it provides five orders of magnitude of strain relief from thermal mismatch, but this is accomplished by using a very thin die attach layer of only ∼25 μm of RTV to a secondary substrate. Unfortunately, this thickness of RTV alone connecting directly to the ceramic substrate would not provide the same level of isolation needed for package strains. These simple models assume that the elastic modulus of silicon ($E_{Si} = 190$ GPa) is much greater than that of the RTV ($E_{RTV} \approx 250$ MPa) and that only stresses due to bending moments are considered [9]. More complex FEM models have been developed in ANSYS, and are being evaluated with data from specially fabricated experimental die to discover and minimize the remaining error sources.

The design constraints led to the adoption of a multi-layer isolation scheme. A secondary silicon substrate isolates the sensor from the package impact stress and minimizes any thermal coefficient mismatch with the RTV. This allows a fairly large fillet to secure the ceramic and secondary substrate, while the thinner silicone die-attach connects the two silicon die. This was not an optimal solution, sensor isolation could be improved most by fabrication on a significantly thicker single substrate, and by using lower modulus adhesives. However, this was not an option with commercial die in Martian deployment conditions. Assembly further constrained the design thickness of the RTV films. A thickness of ∼25 μm was the minimum possible by controlling the volume deposited, and ∼250 μm was the maximum thickness, which allowed robust wire bonding. The stresses developed at the pad/wire-bond interface may be an issue, as the post curing temperature treatments certainly are. The temperature of the substrate after calibration is limited to 50°C, because re-flow of the RTV appears to cause significant offset drift.

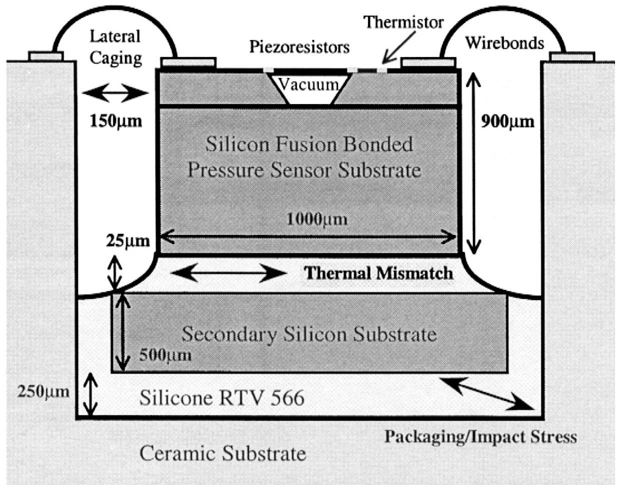

Fig. 3. The schematic diagram shows the sensor thermal and impact strain isolation mounting with dimensions.

Table 1
Specifications of a typical piezoresistive pressure sensor compared to the DS-2 requirements

Sensor attribute	Requirements	Specifications
Offset (mbar)	< 2.0	< 50
Range (mbar)	> 14	1000
Temperature coefficient (mbar/100°C)	< 2.0	40
Resolution (mbar)	< 0.05	unspecified
Accuracy (mbar)	< 0.5	< 5
Power (mW)	< 3.0	3–5

3.3. Sensor selection

To meet the requirements of the DS-2 mission in a 1-year development cycle, only commercial piezoresistive pressure sensors were considered. Their small size, wide availability, and simplicity of instrumentation were key. Also important was the long studied and well-characterized behavior of these sensors. Judging from the specifications of commercial pressure sensors, it was apparent that mission needs could only be met with significant improvement (see Table 1) [10].

These specifications are for minimally tested lots, and an individual sensor can have greatly improved characteristics. In particular, fully packaged offsets of less than 5–10 mV are reasonable, along with reductions in the specified offset temperature sensitivity by a factor of 10 or more. These two attributes, in addition to a full visual inspection, form the basis of our selection. More than 90% of the remaining temperature sensitivity of piezoresistive sensors is stable enough that it can be calibrated out. Of course, intensive calibration of each sensor is then required, but this is standard NASA procedure for flight instruments. Reduction in lot specified errors of one to two orders of magnitude is possible by selection, correction, and calibration. Just as important, NASA can now realize future commercial improvements in piezoresistive sensor performance.

3.4. Instrumentation

A simplified instrumentation diagram is presented in Fig. 4. Both temperature and pressure sensor bridge signals are pre-amplified and bandwidth limited before digital conversion. The piezoresistive pressure sensor bridge is amplified 100 × with an AD621 low-drift single-supply instrumentation amplifier. Then the bridge offset (±10 mV) is corrected before the signal is further amplified in a second bandwidth limited stage (~ 1 Hz). The offset correction voltage is generated by a variable band gap reference available and selectable by the same sensor ASIC which controls power and communicates digitized signals to the probes microcontroller and telecom system. The reference can set the instrumentation amplifier offset between 0 and 4.8 V in 32 steps by the ASIC. Electronic offset correction of the pressure sensor is crucial, because Martian pressure signals on the bridge are only ~ 1 mV/10 mbar or 1/10th of a typical device offset. In this case, the digitally controlled band gap scheme brings the effective offset down to less than 0.5 mV after mounting. This could also allow the microcontroller to change the offset for operation at different pressure ranges.

The calibration temperature sensor is composed of a single monolithic and matched, but electrically isolated resistor implanted at the same time as the piezoresistors. It is placed well away from the pressure strained regions near

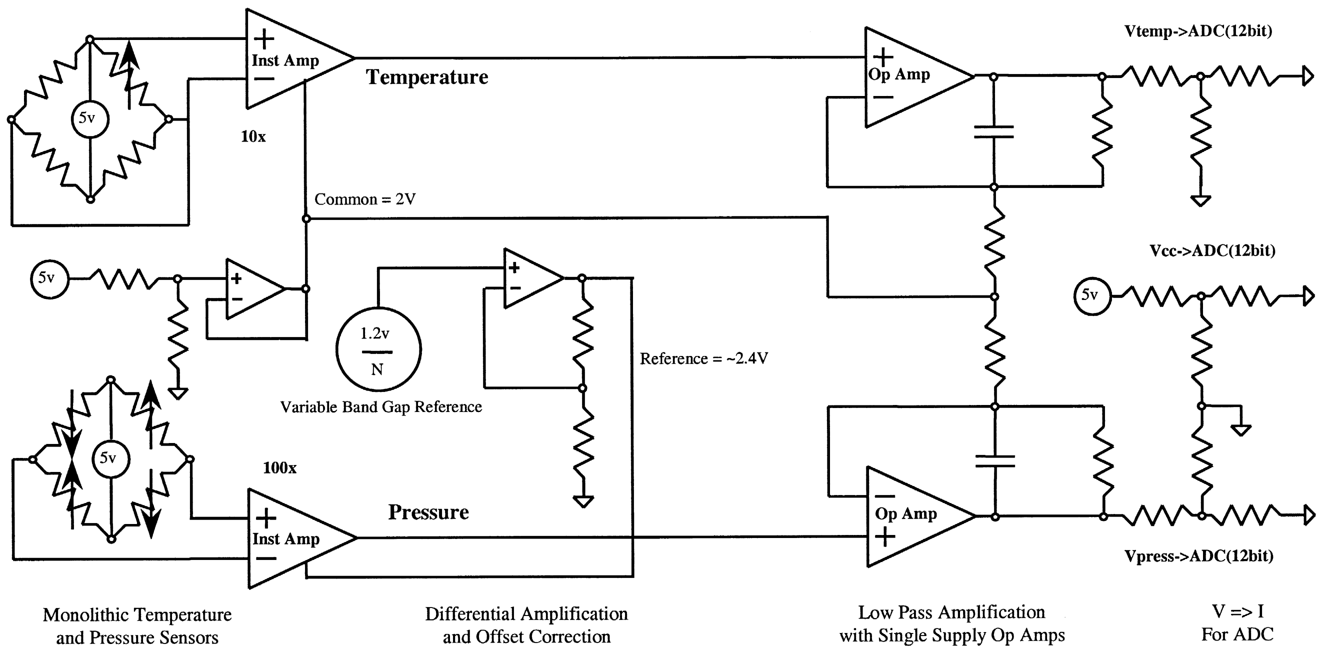

Fig. 4. A simplified instrumentation diagram for the pressure sensor electronics shows the signal amplification and conversion paths.

the pressure sensing resistors, and is supported by the bulk of the die. This element is placed in an external bridge of low TCR resistors. The variable 5 kΩ resistor has a temperature coefficient of ∼2000 ppm/°C. The bridge yields ∼1 mV/°C direct output, and provides the most accurate measure of sensor temperature for calibration. When amplified 10×, this sensor has a resolution of 0.1°C and is stable to 0.5°C, and because of its relatively large signal, offset correction is unnecessary. The amplified and digitized output allows calibration down to the accuracy and stability of the pressure sensitive bridge.

Once amplified, the signals are converted using a current sensing analog to digital converter. It is important to note that the digital conversion and single supply voltage place significant limitations on the circuitry. Only ∼10 bits of accuracy are available. This limits dynamic range and makes offset correction, low drift, and stable amplification circuitry critical. The excitation voltage on the sensor is also monitored because power and voltage constraints prevent regulation. During calibration, it also provides a measure of the ADCs offset and scale factor temperature sensitivity against the sensor ASIC's own monolithic temperature sensor. The results are remarkably stable since few commercial electronics other than Mil-Spec are even specified below −40°C.

4. Calibration apparatus

Calibration of the Martian pressure sensor requires a fairly sophisticated vacuum and data acquisition system. The sensor must be cycled accurately many times in temperature and pressure. This requires closed loop operation, which can be difficult in pressure systems, especially when static pressures are desired. Any flow through the chamber could cause an unknown pressure differential. Therefore, independent fill and evacuation control systems must be implemented rather than a simple differential pumping method. Temperature is also controlled closed loop. Each of the analog signals internal to the sensor must be logged, as well as, the digitized information from the sensor ASIC. Of course, the controlled temperature and pressure in the chamber are also sampled.

To sense the true static pressure in the chamber two NIST traceable MKS Baratrons are used, which cover the range from 0 to 1 bar with an accuracy of 0.01 mbar and the Martian pressure range with an accuracy of 0.001 mbar. Measurements are made more than an order of magnitude more accurately than the sensor is expected to be capable. An accurate substrate temperature is not as crucial since a monolithic temperature measurement is made for calibration purposes, but stable temperature is highly desirable for simplified analysis. This is achieved by using a closed-cycle CryoCooler capable of 170 K operation and an OFHC copper cold stage with integral 50-W heaters in closed loop temperature control with a NIST traceable RTD. This allows stable temperature regulation accurate to less than 30 mK.

The internal analog signals on the pressure sensor substrate are measured with an 8-channel/16-bit National Instruments ADC, and the digital SPI bus is controlled using an integrated ISA PC card. All of these are controlled through a LabView interface which allows automated setup and data taking even for the extremely large data sets required for calibration.

5. Results

5.1. Calibration

For this mission a series of calibrations and tests have been run to allow Martian conditions to be simulated and accurately repeated. Fig. 5 shows this data intensive operation: ∼60,000 samples are taken over six temperatures and 28 pressures. Digitized sensor resolution is determined from the 1σ deviation binned at each sample point. The sensor is swept up and then down in pressure sampling pressures at even separations. Static pressure is controlled to 0.001 mbar at each point over the range of 0–13.3 mbar. This process is repeated at each temperature starting from 290 going to 190 K and back up. Temperatures are held constant to 20 mK for more than 6 h as the pressure data is taken. Once the temperature cycles back to 290 K and pressure cycles back to zero, the chamber is vented, returning the sensor to atmospheric pressure. The entire 36-h calibration process is then repeated. ''Burn-in'' effects have been noted and results after multiple cycles have asymptotically lower offset shifts up to ∼8 cycles. A calibration consists of the last two of these runs, taken over 72 to 96 h.

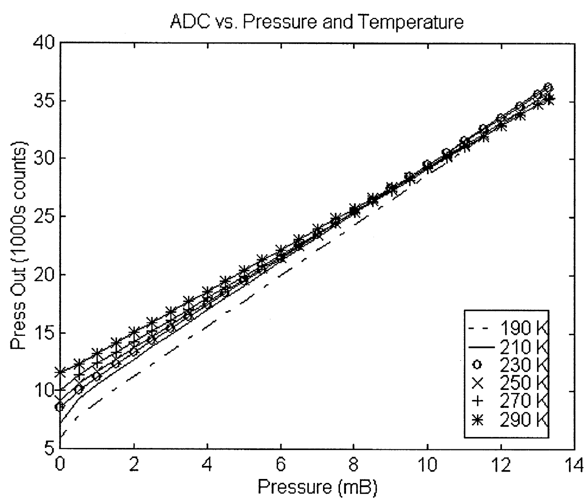

Fig. 5. Pressure sensor output is linear as both temperature and pressure are swept in the chamber, but both offset and scale factor shifts can be seen.

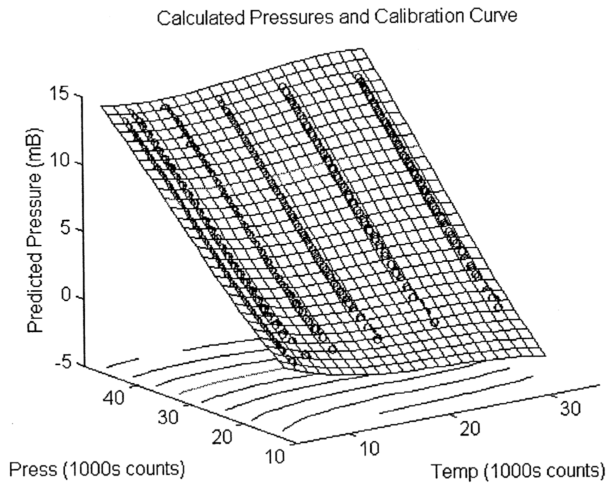

Fig. 6. Measured chamber pressures superimposed on a third order curve fit from a previous calibration of the digitally converted sensor signals at those pressures show very good agreement.

To interpret the calibration data, MATLAB is used to generate a 3-D polynomial least squares curve fit from the measured temp/pressure data to the actual pressure as shown in Fig. 6. Optimal χ^2 is achieved with only third order fits. To determine the sensor accuracy and repeatability, a 3-D difference plot is generated from the actual chamber pressure and those predicted by a calibration using the fitted curve of the same sensor in the previous run. Typical residuals are shown in Fig. 7 to be ~ 0.3 mbar, an acceptable accuracy for the mission.

While these final fully integrated tests were run, each subsystem was tested for impact survival. A series of 18 pressure sensors mounted on ceramic substrates were fired from an airgun at 140–200 m/s to simulate the Mars deployment. Although other failures did occur, the only two impact failures of the pressure sensor were due to mishandling in assembly or deployment. Ceramic substrates with mounted die and surface mount devices were also electrically tested without failure. Finally, two calibrated microprobes were deployment tested in air-gun impact simulations. Though an offset shift corresponding to ~ 0.3 mbar absolute pressure has been observed, these also survived without failure.

5.2. Hysteresis

Initial experiments with the pressure sensor indicated that temperature hysteresis would be a dominant source of error. Repeated calibration measurements showed that succeeding runs were typically more stable than those that preceded them. Before delivery, it was not possible to examine these effects in detail. Since then, more careful measurements of both pressure and temperature cycles have been made. The hysteresis effects are quite small in comparison to the full-scale range of the sensor and fits to the sensor response and difference plots must be made to observe the errors.

First, a device at a constant 300 K was pressure-cycled four times from 10 mbar to 1 bar, or near Martian pressures to approximately Earth's atmospheric pressure. What is most striking is the nearly precise linear fit of bridge output to actual pressure seen in Fig. 8. The hysteresis plot that follows in Fig. 9 shows that there is no measurable error caused by pressure cycling. The bridge output scale factor of 87 mV/1000 mbar shows the pressure hysteresis error from the sensor to be less than 0.06 mbar. The medium term drift of the sensor bridge maintained at a constant temperature and pressure over 10^6 s is only 10 μV or ~ 0.1 mbar, but this could easily explain the shift in a pressure hysteresis experiment which takes several days.

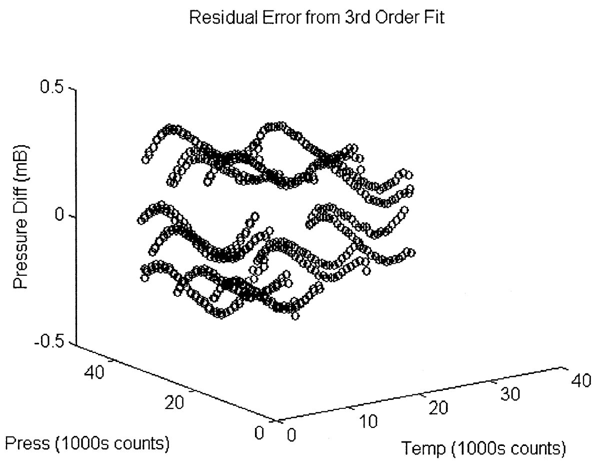

Fig. 7. A difference plot of measured chamber pressures from those predicted based on ADC outputs and a previous calibration curve fit shows that calibrations are stable to better than 0.5 mbar, but that offset shifts cause small third order errors in the prediction.

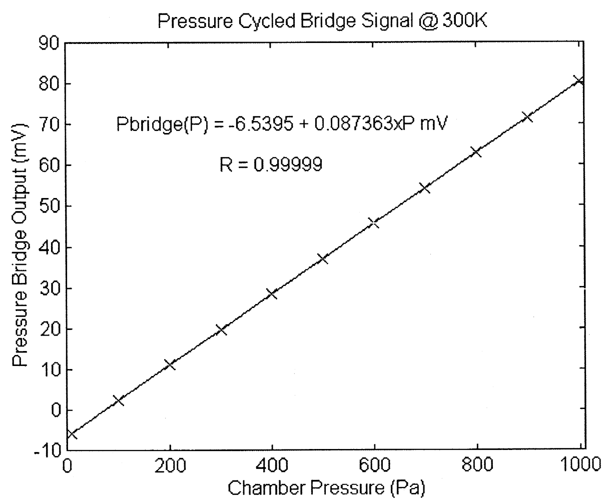

Fig. 8. A pressure-cycled piezoresistive bridge signal at 300 K fits a linear regression very well.

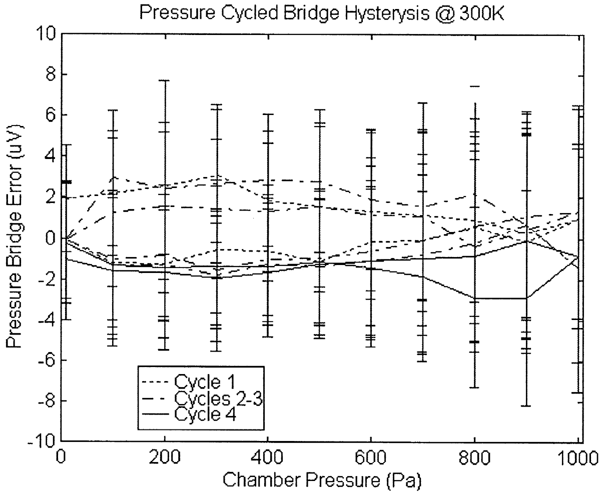

Fig. 9. Hysteresis of a pressure-cycled piezoresistive bridge signal at 300 K is less than the standard deviation and corresponds to ~0.03 mbar.

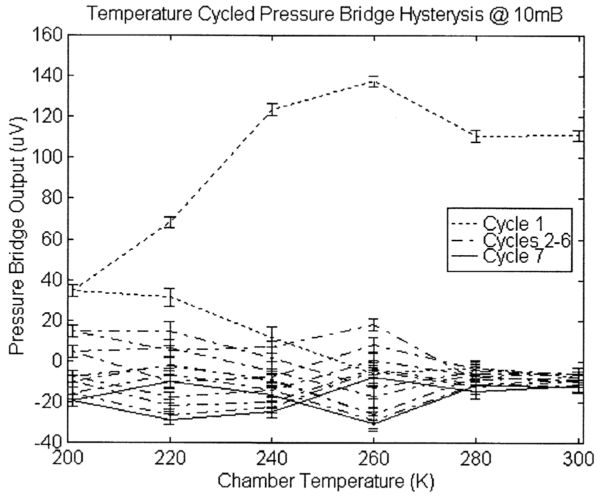

Fig. 11. The hysteresis of a temperature-cycled piezoresistive bridge signal at 10 mbar is more than 100 μV and corresponds to more to more than 1 mbar of offset.

The same device was also cycled 100°C seven times. This has become the first step in the calibration of any device after assembly. The quadratic fit of the bridge output with temperature also appears quite good in Fig. 10, but an error of 110 μV is apparent in the hysteresis plot, and corresponds to an error of more than 1 mbar. To measure the temperature hysteresis in a previously cycled and calibrated device, it was subjected to a relatively high temperature of 60°C. Raising the temperature of the mounting above 50°C causes sensors to drift rapidly. This sensor was temperature-cycled from 200 to 300 K, holding at each temperature for more than 4 h, until hysteresis was minimized as seen in Fig. 11. An initial offset slowly anneals out as the sensor ''burns in.'' Significant errors during temperature cycling still occur, but are reduced in magnitude and of random direction. The stability of this burn-in is being studied, but appears to last months at room temperature and below.

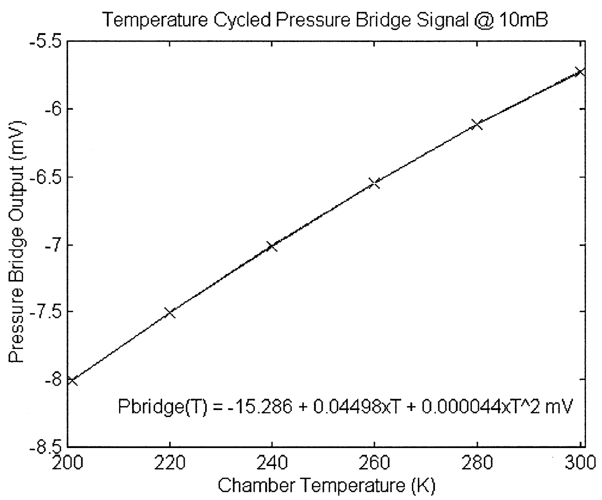

Fig. 10. A temperature-cycled piezoresistive bridge signal at 10 mbar is shown with its quadratic fit.

6. Conclusions

The motivation of this work was to produce a miniature low-power pressure sensor capable of measuring Martian pressure fluctuations and surviving a high-*g* deployment. The data presented show the accuracy of a calibrated piezoresistive pressure sensor in Martian conditions to be better than ± 0.5 mbar, with a resolution of 0.05 mbar to be achievable. This compares well to the barometric sensors used in the Viking mission to Mars. These sensors had a digitized resolution of 0.088 mbar (see Fig. 1), and although the stability once on Mars was apparently quite good, the uncertainty in the absolute pressure after deployment was as large as 1 mbar. The improved variable reluctance pressure sensor used for NASA's Mars Pathfinder resolved better than 0.001 mbar with an accuracy of 0.03 mbar. However, this instrument had a mass of approximately 500 g and consumed almost 250 mW of continuous power [4]. We have approached the precision of these much larger sensors using an off-the-shelf and ultra-calibrated pressure sensor using less than 30 g and drawing an average of less than 3 mW.

This type of calibration is possible with a wide range of piezoresistive sensors, if sufficient strain isolation can be achieved from packaging and temperature related stresses. Improvements in accuracy of an order of magnitude can be achieved. Even large temperature coefficients of offset and scale-factor can be corrected, if temperature is measured monolithically. Individual calibrations add to the cost of such a device, but allows them to compete in the domains of larger and much more expensive sensors. Companies are starting to market ASIC for just this purpose [11].

Furthermore, the strain isolation techniques used are also suitable for other sensitive pressure sensors in the Martian environment, which may use different sensing approaches such as capacitive [12] or resonant sensors.

Acknowledgements

Thanks to Steve Manion and Rick Berard of JPL, and Gertjan ''Sparky'' van Sprakelaar of NovaSensor for their helpful discussions of sensor instrumentation. This work was supported by the NASA New Millennium Program. Travel expenses provided by the NSF, DARPA, and the Transducers Research Foundation.

References

[1] S. Smrekar, D. Catling, R. Lorenz, J. Magalhes, M. Meyer, J. Moersch, P. Morgan, J.R. Murphy, B. Murray, M. Presley-Holloway, A. Yen, A. Zent, The Mars Microprobe Mission, J. Geophys. Res. (1999) in press.

[2] S.A. Gavit, G. Powell, The New Millennium Program's Mars Microprobe Mission, in: Proceeding of the 2nd IAA International Conference on Low-Cost Planetary Missions, April 16–19, 1996, 1996, Paper # IAA-L-0906.

[3] D. Kaplan, Environment of Mars, NASA Technical Memorandum 100470, LBJ Space Center, Houston, TX.

[4] A. Seiff, J.E. Tillman, J.R. Murphy, J.T. Schofield, D. Crisp, J.R. Barnes, C. LaBaw, C. Mahoney, J.D. Mihalov, G.R. Wilson, R. Haberle, The atmosphere structure and meteorology instrument on Mars Pathfinder Lander, J. Geophys. Res. 102 (E2) (1997) 4045–4056, February 25.

[5] R.M. Haberle, D.C. Catling, A micro-meteorological mission for global network science on Mars: rational and measurement requirements, Planet., Space Sci. 44 (11) (1996) 1361–1383.

[6] Q.A. Shams, R.L. Fox, E.E. Adcock, S.K. Kahng, A cryogenic multichannel electronically scanned pressure module, Proc. 38th Int. Instrum. Symp. (1992) 773–791.

[7] S.K. Kang, J.J. Chapman, Piezoresistive silicon sensors in cryogenic environment, Proc. 35th Int. Instrum. Symp. (1989) 663–671.

[8] GE-Materials Data Sheet RTV-566.

[9] W.C. Young, Roark's Formulas for Stress and Strain, 6th edn., McGraw-Hill, New York, 1989, pp. 117–119 and 446–447.

[10] Lucas NovaSensor Application Note 1, Stability and Thermal Hysteresis of Silicon Pressure Sensors, September 1996. Currently available from http://www.novasensor.com/tour/pdf/app1.pdf.

[11] EXAR 7707 Data Sheet.

[12] D.C. Catling, High-sensitivity silicon capacitive sensors for measuring medium-vacuum gas pressures, Sens. Actuators, A 64 (1998) 157–164.

Biographies

J. Kurth Reynolds received the BS degree in Physics from Caltech, and is pursuing a Ph.D. in Mechanical Engineering at Stanford University. He is currently investigating a variety of pressure sensors for future NASA Mars missions. He has worked with micromachined sensor systems and a variety of fabrication, sensing, modeling, and characterization methods for more than 10 years, including work at the Microdevices Laboratory at the Jet Propulsion Laboratory.

David Catling received a BSc (Honors) degree in Physics with Astrophysics from the University of Birmingham, UK in 1990, and a Ph.D. in Atmospheric Physics from the University of Oxford in 1994. He is at present a research scientist employed by the SETI Institute, in residence at NASA Ames Research Center. Current research interests include planetary atmospheres, planetary geochemistry, and NASA missions to Mars. Dr. Catling is a member of NASA's Mars Microprobe Mission Science Team.

Randel C. Blue received a BS in Electrical Engineering from the University of Texas at Austin and an MS in Electrical Engineering from USC. He works at the Jet Propulsion Laboratory as an Instrument Team Leader on the DS-2 Mars Microprobe Mission and now as a Project Element Manager for Avionics on the Europa mission.

Nadim I. Maluf is Manager of Advanced Technologies at Lucas NovaSensor, and Consulting Professor of Electrical Engineering at Stanford University. He received his Ph.D. in Electrical Engineering from Stanford University in 1991.

Thomas Kenny is an Assistant Professor of Mechanical Engineering at Stanford University. He received his degrees in Physics from UC Berkeley, and worked at the Jet Propulsion Laboratory after graduation. At Stanford, he leads a research group that makes use of silicon microfabrication techniques to build inertial sensors, infrared detectors, and force-sensing cantilever beams.