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VERY HIGH TEMPERATURE SILICON ON SILICON PRESSURE TRANSDUCERS

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SUMMARY

A silicon on silicon pressure sensor has been developed for use at very high temperatures (1000°F). The design principles used to fabricate the pressure sensor are outlined and results are presented of its high temperature performance.

INTRODUCTION

The small size and wide frequency response of piezoresistive silicon pressure sensors has made them the first choice for wind tunnel and aerospace development programs. Most of the silicon pressure sensors are fabricated by diffusing the strain gage pattern into a silicon diaphragm. Such a construction relies on the reversed biased P/N junction for its electrical isolation. The strong temperature dependence of the P/N junction leakage currents has limited the maximum temperature to about 400°F. Piezoresistive silicon strain gages are capable of operating to a considerably higher temperature than 400°F. In order, therefore, to realize the full high temperature potential of silicon pressure sensors, it is necessary to use a fabrication process that did not rely on P/N junctions for isolation.

MECHANICAL PROPERTIES OF SILICON

To be useful at high temperatures, a piezoresistive silicon strain gage should have the following properties:

1) It must have good stable mechanical properties at the maximum operating temperature.

2) The piezoresistive coefficient should be sufficiently high that signal conditioning does not become a problem. If the strain gage is to be used over a wide temperature range, then the temperature coefficient of the gage factor should be such that it can be temperature compensated.

3) It must be possible to bond the strain gage to the structural member. In the case of a pressure transducer, this will usually be a diaphragm.

The mechanical properties of silicon have been fairly well studied at moderate temperatures. The published data at high temperatures is not extensive. The most often quoted is due to Pearson, Read and Feldmann (reference 1). The three authors showed that at a high enough temperature silicon no longer behaves like a brittle material. They showed that above 1000°F (approximately) silicon was able to yield and that the yield stress fell rapidly with increasing temperature. For the purpose of this paper, the interesting results from the paper of Pearson et al is the relative useful strength of silicon at high temperature. This is shown on Figure 1 as the percentage decrease in the strength of silicon as a function of temperature. (This figure is taken from the results plotted in Figure 5 of Reference 1). The change of ordinate from absolute to relative values was done because Reference 1 was concerned with whiskers of silicon which are known to have a higher strength than bulk silicon.

To use Figure 1 to determine the potential maximum working temperature for a silicon strain gage mainly involves a judgement as to the maximum "safe" operating stress. For pressure transducer manufacturers this basically involves determining proof pressure and burst pressure. In both cases, manufacturers are usually conservative so that a reduction in the strength of the silicon of 30% is probably acceptable. In which case, from mechanical considerations, silicon can be assumed to be usable up to 1100°F.

Perhaps the second most important mechanical property of a strain gage is its Young's modulus. Data are available on the room temperature stiffness coefficients (Reference 2) but not much data are available on the temperature dependence. Based on comparative studies a "best guess" for the reduction in Young's modulus at 1100°F from its room temperature value is of the order of 5%. This figure, if correct, is an acceptable reduction for a silicon strain gage.

PIEZORESISTIVE PROPERTIES OF SILICON

Having acceptable mechanical properties at high temperatures does not, of course, make a material a useful strain gage. It must also have an acceptable gage factor (GF). Potentially this should not be a problem with a silicon strain gage. By the proper choice of doping levels gage factors of >100 can be achieved at room temperature. Even if this were to be reduced by 80% at high temperatures it would still leave a very workable GF of 20. As is well known in the strain gage field, a high piezoresistive coefficient (high GF) is accompanied by a high (negative) temperature coefficient of GF (TCGF) and vice versa (References 3 and 4). As a consequence of this (crude) correlation between GF and TCGF it follows that two silicon strain gages which had different GF at room temperature could have the same GF at some higher temperature. If the two gages were to be used only at this higher temperature, then as far as the GF is concerned, it would not matter what the doping levels were. Pressure transducer users are rarely so easily satisfied. They invariably require the transducer to operate over a range of temperatures; usually the higher the permitted maximum temperature the wider the temperature range requested. In which case the choice of doping levels and hence GF and TCGF becomes more important.

It is generally true that the higher the doping level, the more linear the temperature effects on the strain gage parameters. This allows the strain gage parameters to be easily temperature compensated. If the quest is for high GF, then the non-linear temperature characteristics can be accommodated over a moderate temperature range. This is invariably done by the use of non-linear temperature sensitive components which must experience the same temperature as the strain gages. This is acceptable so long as the non-linear temperature sensitive component can operate over the required temperature range. This use of non-linear strain gage components becomes a major problem as the upper temperature limit is increased.

Kulite has always used degenerate doping levels so as to ensure the optimum linear temperature characteristics. Over even moderate temperature ranges, this has the advantage that passive temperature compensation techniques could be used where the temperature compensation components (resistors) need not be at the same temperature as the piezoresistive strain gages. Over moderate temperature ranges (300°F) the merits of high or low doping levels are debatable. This is not the case as the temperature range is extended upwards. A limit will be reached where it is no longer possible to obtain non-linear temperature compensation components. At this upper temperature limit degenerate doping offers significant advantages.

SILICON ON SILICON SENSOR

So far the discussion has been concerned with the mechanical and electrical properties of silicon strain gages for use at high temperatures. For pressure transducer applications the chosen strain gages must be fixed to some structural member, the strain of which varies with pressure. The most popular structure used for pressure transducers is some form of rigidly clamped thin section plate. At high temperatures bonding of the strain gages to the pressure diaphragm is a problem.

This is not an easy problem to solve. First, there is the difficulty of achieving good adhesive strength at high temperatures. Secondly, there is the potential problem in the mismatch of the thermal expansion coefficients between the strain gages, adhesive and diaphragm. The most appealing way to overcome the above problems would be to use silicon as the diaphragm and diffuse the gage pattern into the diaphragm. This naturally is the now standard method of manufacturing piezoresistive pressure sensors. This approach overcomes all of the problems due to bonding and mismatch of thermal expansion. Unfortunately, the gages are isolated from the silicon diaphragm (and each other) by the P/N junction formed during the doping process. Although great improvements have been made in the leakage currents of reverse biased P/N junctions, they all ultimately fail at high temperature because of the intrinsic exponential temperature relationship. The maximum working temperature, while still retaining adequate isolation, is around 400°F.

The Kulite approach to the high temperature problem was to stay as close as possible to the ideal design. That is of using silicon gages bonded to a silicon diaphragm but without the inherent problems of adhesives. Figure 2 shows a section through a Kulite silicon on silicon pressure sensor (Reference 5). The pressure sensitive diaphragm is formed by etching mono crystal silicon. The built in edges of the silicon diaphragm are anodically bonded to a relatively massive piece of glass. The thermal expansion coefficient of this glass base matches that of silicon. The anodic bond is a molecular bond so that the structure is mechanically stable over a very wide temperature range. The top surface of the silicon diaphragm is coated with a thin insulating layer of glass and the piezoresistive strain gages are anodically bonded to the thin glass layer. Four gages are bonded so as to form a fully active Wheatstone bridge. The silicon strain gages are thus isolated from the silicon diaphragm by the glass layer. The anodic bond between the strain gages and the glass results in the whole structure being held together by molecular bonds. This structure approaches the optimum that can be achieved for a high temperature piezoresistive silicon pressure sensor.

For the silicon pressure sensor described above to be useful as a pressure transducer, it must be housed in some suitable pressure fixture with some means of making electrical connections. The transducer housing need not be large because all that it will contain is the silicon sensor (size approximately .05 inch cube) and the electrical connections. There will not be any compensation components as none are suitable for operation at very high temperatures. The size of the transducer is, therefore, determined solely by the pressure and electrical connections. For very high temperature operation the most suitable electrical cable is the metal clad mineral insulated type, so this was the type chosen. One style of the Kulite very high temperature pressure transducer is shown in Figure 3.

TEST RESULTS

This section presents results obtained from tests on about 200 very high temperature transducers employing the silicon pressure sensor described above. These covered full scale pressure ranges of 40 to 100 psia. The results are presented in terms of the most important pressure transducer parameters. These are the temperature induced changes in the sensitivity, offset and resistance of the strain gage bridge.

The overall nominal span (sensitivity) shift with temperature (Figure 4) was -3.8%/100°F referred to room temperature (RT). The nominal RT spans were 20mV/volt so that at 1000°F the outputs were 13mV/volt. Even with degenerate doping levels the span shifts over a 920°F temperature range had significant non-linearity. The same is true of the zero shifts (Figure 5) but the overall zero shift of just 5% up to 1000°F is an excellent achievement. Such a relatively low zero shift is a good demonstration of the high temperature stability of the silicon on silicon pressure sensor. The temperature coefficient of resistance (TCR) of the silicon on silicon sensors was approximately 10.8%/100°F and is reasonably constant up to 1000°F (Figure 6).

Temperature compensation using a remote resistor network is nominally a linear temperature correction. It does, however, introduce its own (positive) non-linearity the size of which increases with increasing temperature range. The slight increase in TCR with temperature shown by Figure 6 does compensate for this to some extent; but then the (negative) increase in the TCGF (Figure 4) is detrimental. The performance that can be obtained with the silicon on silicon pressure sensors using passive temperature compensation is shown by Figure 7. Although perfect temperature compensation can be achieved at the temperature extremes, the span has a +6% error at mid temperature and the offset has an error of -1%. By choosing to compensate at two intermediate temperatures, the errors can obviously be halved to give ±3% span error and ±.5% offset errors. It is possible to eliminate the above non-linear temperature error by using computer correction techniques. This involves the usual approach of storing the calibration constants of the pressure sensor at various temperatures and, by measuring the sensor temperature, applying the appropriate correction. This is made easier for a piezoresistive pressure sensor because the high TCR enables the strain gages to be used to measure temperature as well as pressure.

CONCLUSIONS

From the tests which have been performed and reported upon here, there is no doubt that silicon on silicon pressure sensors are capable of a remarkably good performance up to very high temperatures. Silicon on silicon pressure sensors should considerably extend the upper temperature range for making both static and wide bandwidth dynamic measurements. Having extended the temperature range for piezoresistive pressure transducers up to 1000°F using silicon, work is already being done to extend the upper limit by using silicon carbide (Reference 6). A note of caution must, however, be sounded. The objective of developing miniature pressure sensors for very high temperature operation is to supply a tool for aerospace test engineers. Although the life at 1000°F of silicon on silicon pressure sensors is being extended, it is not intended for production use at 1000°F. Even the most optimistic models would predict a very low reliability at 1000°F.

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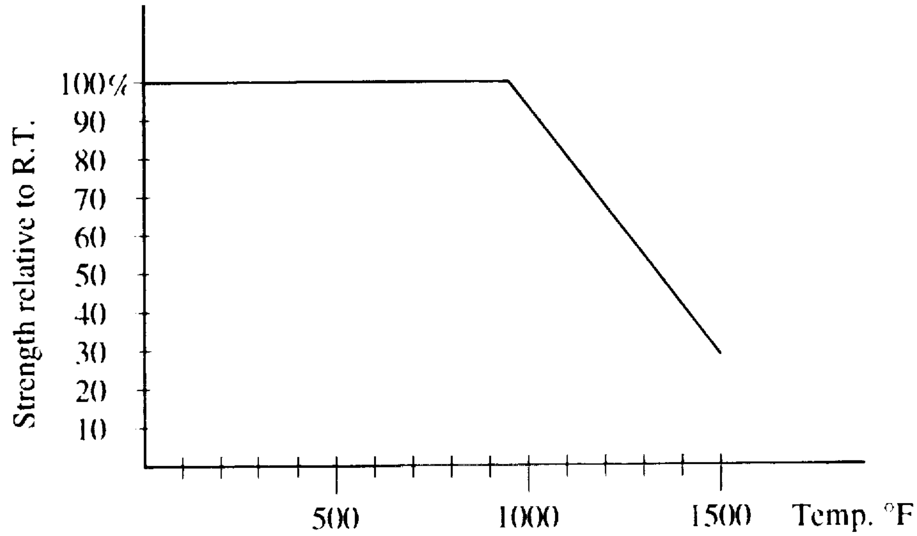

Figure 1. Temperature dependence of the strength of silicon. (Adapted from Fig. 5 of Ref. 1).

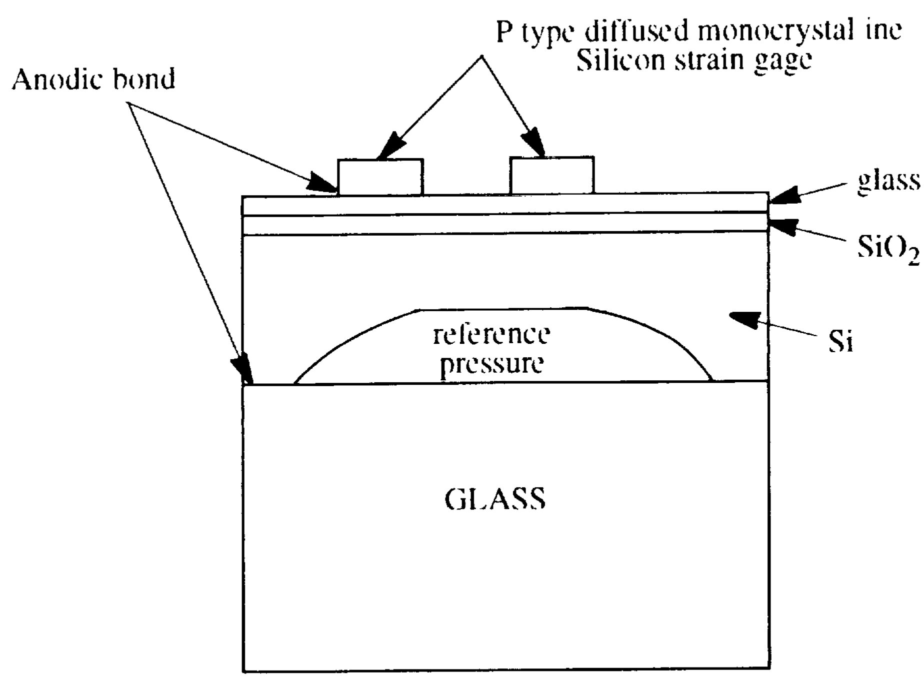

Figure 2. Schematic section of a Kulite silicon on silicon pressure sensor.

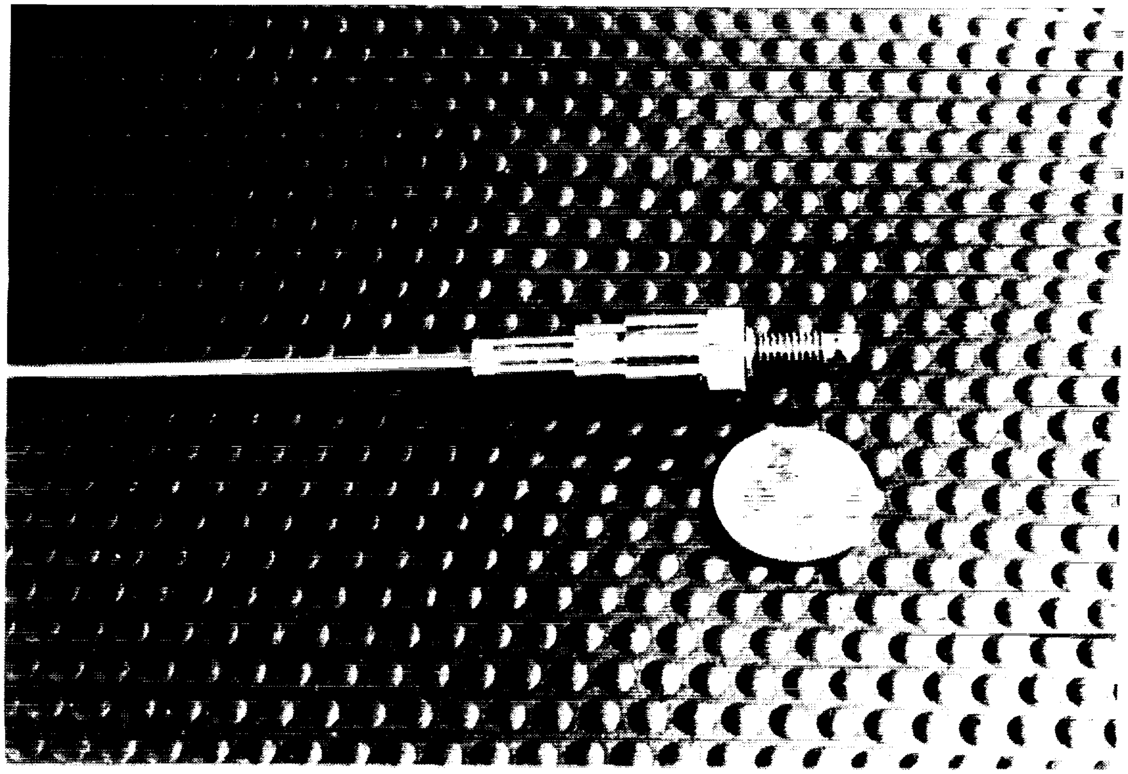

Figure 3. Photograph of one style of Kulite very high temperature pressure transducer.

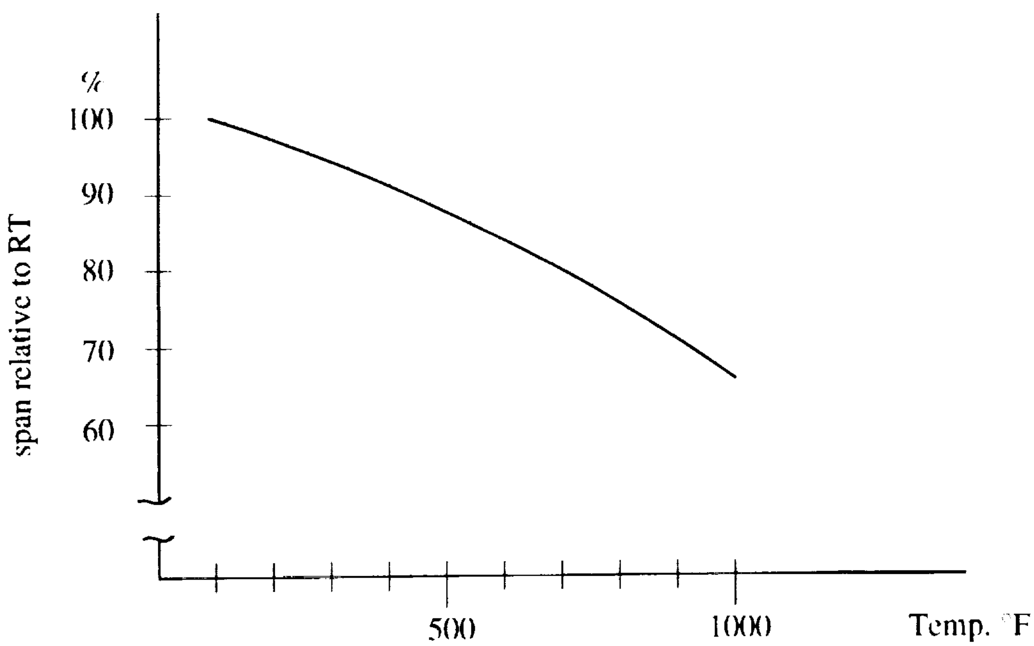

Figure 4. Temperature dependence of span output for a silicon on silicon pressure sensor.

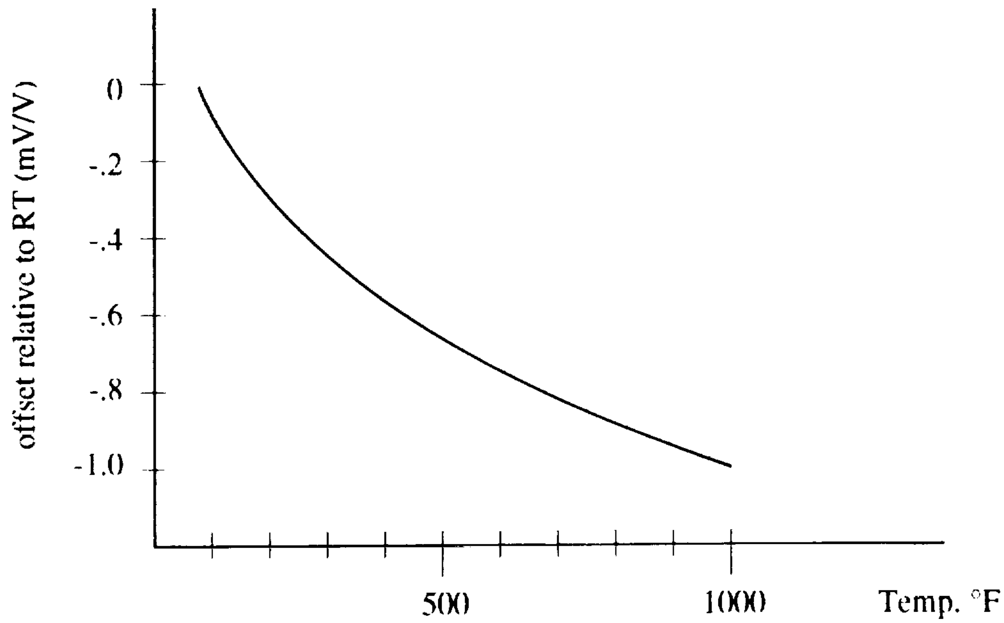

Figure 5. Temperature dependence of zero output for a silicon on silicon pressure sensor.

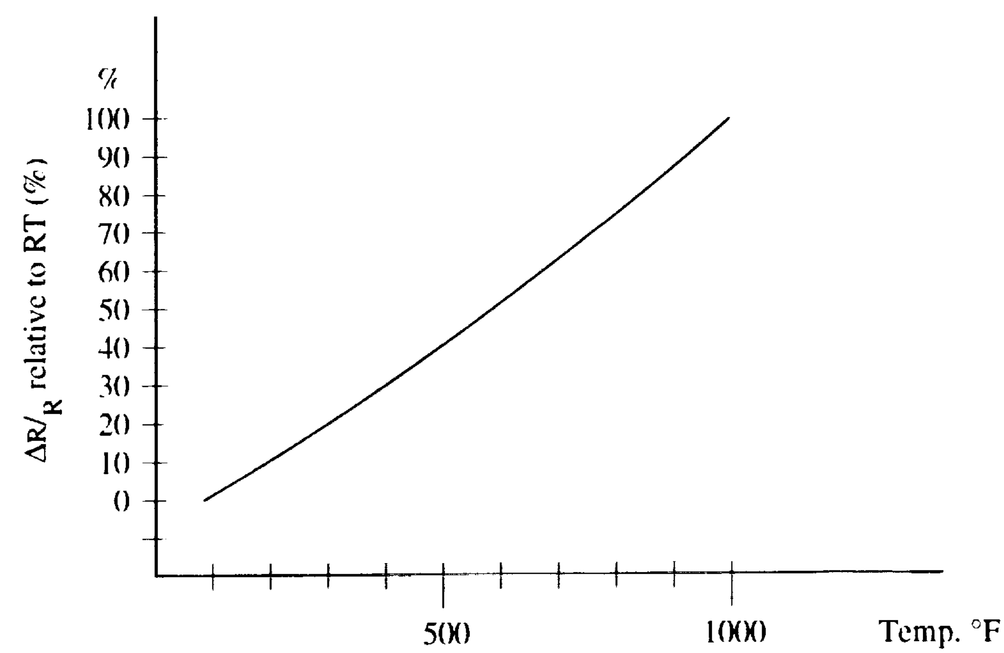

Figure 6. Temperature dependence of resistance for a silicon on silicon pressure sensor.

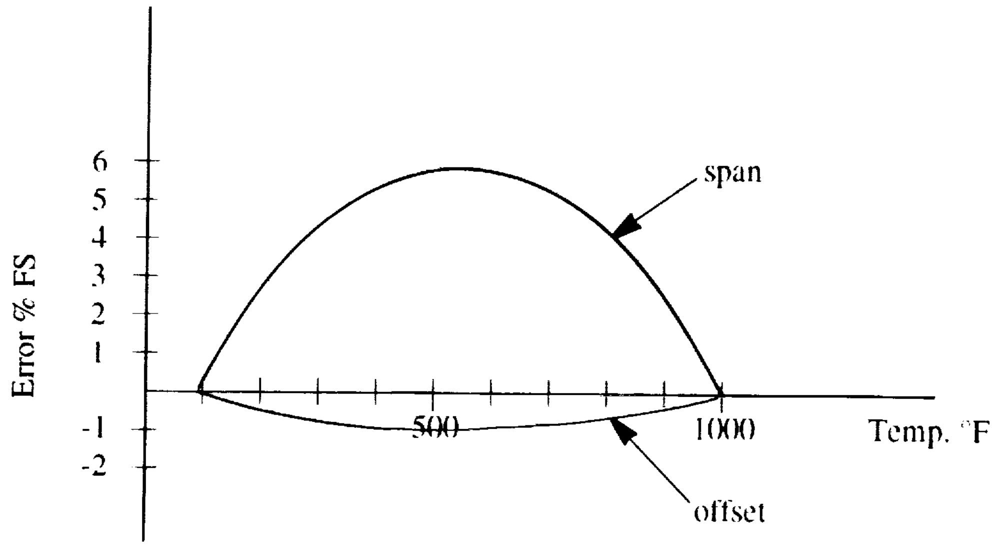

Figure 7. Span and offset errors for a passive temperature compensated silicon on silicon pressure transducer.