HYBRID A/D CONVERTER FOR 200°C OPERATION

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ABSTRACT

This paper describes the design and development of a high performance hybrid 12 bit analog to digital converter, which will operate reliably at 200°C. A product of this type was found to be necessary in areas such as geothermal probing, oil-well logging, jet engine and nuclear reactor monitoring, and other applications where the environments may reach temperatures of up to 200°C. This product represents an advancement in electronics as it proved the operation of integrated circuits at high temperature, as well as providing information about both the electrical and mechanical reliability of hybrid circuits at 200°C. Because the circuit design of the A/D converter involved both digital and linear circuitry, this produced an opportunity to evaluate the performance of both technologies at 200°C. Initial mechanical failure modes led to researching more reliable methods of wire bonding and die attachment. The result of this work was a 12 bit A/D converter which will operate at 200°C with .05% linearity, 1% accuracy, 350 µSec conversion time, and only 455mW power consumption. This product also necessitated the development of a unique three metal system in which aluminum wire bonding is done utilizing aluminum bonding pads, gold wire bonding to all gold areas, and employment of a nickel interface between gold and aluminum connections. This sytem totally eliminates the formation of intermetallics at the bonding interface which can lead to bond failure.

INTRODUCTION

Recently the electronics industry has been made aware of the need for electronic components and systems which will operate at temperatures as high as 200°C. These applications include geothermal probing, oil well logging, jet engine and nuclear reactor monitoring and other hostile environments where the temperature may reach 200°C or higher. In some of these applications, as in oil well logging and geothermal probing, it is necessary to transmit data through long lengths of cable which run from deep into the earth to the surface.[1] These applications are where a high temperature A to D converter becomes highly desirable. Transmitting low level analog data over a long distance such as this would be very difficult without introducing significant extraneous errors. Through the use of an A to D converter it becomes possible to take outputs from strain gauges and thermocouples, convert them to "ones" and "zeros" and then transmit this data digitally to the surface.

ADVANTAGES OF HYBRIDS

An A to D converter can be fabricated in many different forms such as a module, printed circuit board, or hybrid circuit. Hybrid reliability at 125°C has been proven to be excellent through many thousands of hours of qualification tests. This reputation makes hybrid technology a wise choice for 200°C operation. A hybrid circuit can contain several different I.C.s in one small package, which is advantageous in applications where space is limited.

A TO D CIRCUIT DESIGN

An A to D converter proved to be a challenging product to design and evaluate at 200°C due to the fact that little information concerning the different types of components and their properties at high temperature was available. Passive components, such as resistors and capacitors and active components including transistors and integrated circuits required extensive analysis and evaluation. The final A/D design employs both linear and digital circuitry.

In the design of the MN5700, reliability was considered of prime importance. Two factors that significantly effect the reliability of any circuit are power and level of complexity. Research in high temperature electronics has shown that the rate of aging, those factors that produce changes in parameter of key components, will approximately double with each 10°C temperature rise.[2]

For a hybrid circuit the substrate temperature will increase as the power consumption increases. As a design goal the typical substrate to ambient temperature rise was not to exceed 10°C. The 32 pin double PIP Package, selected primarily for its form factor, has a typical substrate to ambient rise of 27°C/Watt.[3] Thus to keep this rise under 10°C, the typical power consumption was limited to 311 milliwatts. To reduce the complexity, as few I.C.s were used as possible.

There are several different approaches to A to D conversion which are currently used. The MN5700 uses the successive approximation method. This allows a converter to be made using few components and has good characteristics in speed, resolution, and accuracy. A successive approximation A to D converter consists of four sections, D to A converter, reference, comparator, and successive approximation register (SAR). See Figure 1. Each of these sections will be discussed showing the design considerations for 200°C operation.

D to A Converter

The D to A section of the MN5700 utilizes a voltage switching R-2R ladder network. The switch is CMOS and connects each leg of the ladder either to ground or a reference voltage. See Figure 2. A CMOS switch was chosen because of its low power consumption and evaluations showed it to be reliable at 200°C.

Reference

The reference circuit shown in Figure 3 consists of a temperature compensated zener diode and a dielectrically isolated op-amp. The zener was found to be accurate to about 10ppm/°C from 25°C to 125°C. From 125°C to 200°C the temperature coefficient increased to 40ppm/°C. Figure 4 shows a graph of zener voltage vs. temperature.

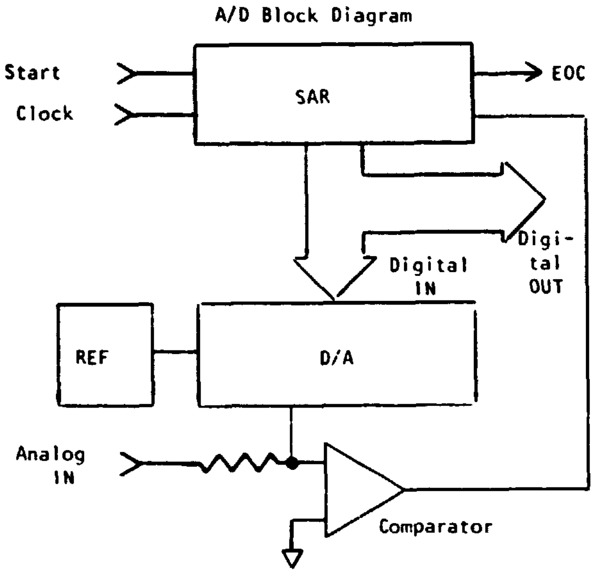

FIGURE 1

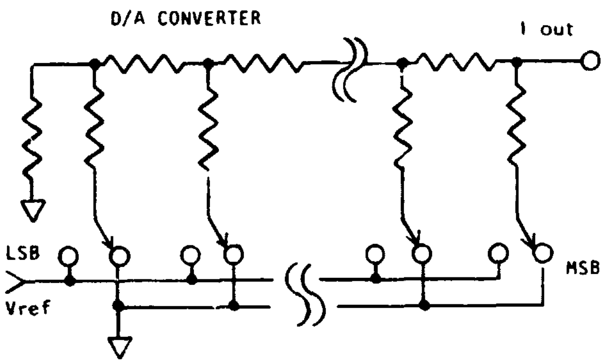

FIGURE 2

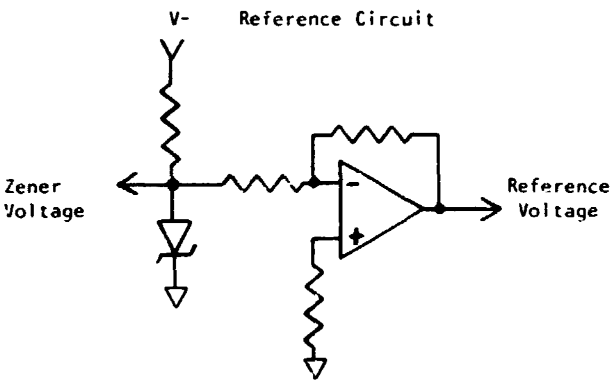

FIGURE 3

Research and evaluation showed that a dielectrically isolated op-amp was the best choice for 200°C operation. Most silicon bipolar I.C.s use junction isolation between transistors. These types of circuits show transistor interaction at 200°C.[3] I.C.s which are manufactured using dielectric isolation have the active areas separated by an insulating layer of material. This reduces transistor interaction and also reduces leakage current to the substrate under high temperature conditions.[4]

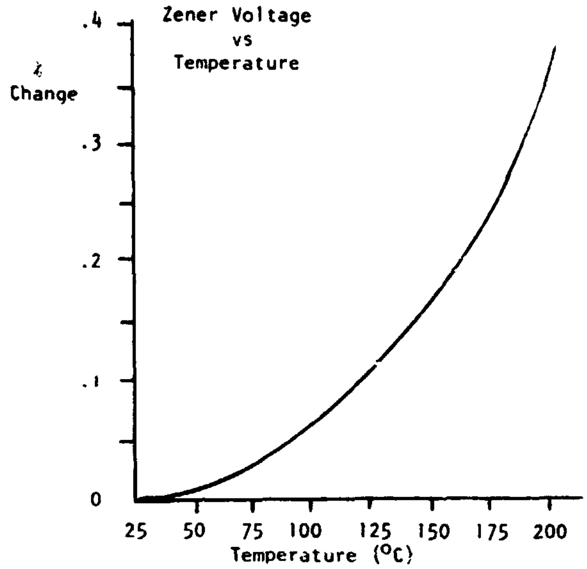

Figure 4

The change in the reference voltage at 200°C was found to be typically .2%. The circuit was evaluated to see why the change in reference voltage was less than the change in zener voltage. Evaluation showed that the offset of the op-amp had its largest change between 150°C and 200°C, as shown in Figure 5 This change was in the opposite direction to the drift of the zener, and therefore the accuracy of the reference became the difference of the two.

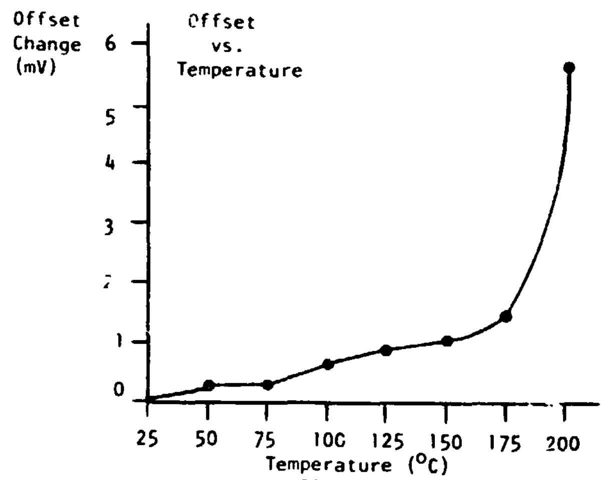

Figure 5

The central component of the D to A circuit is a resistor network. The network used is a thin film chip using nickel-chromium resistors deposited on silicon. The change in resistance over temperature will determine the accuracy and linearity of the device. An absolute change in resistance results in an accuracy change and a change in resistor ratios will result in a linearity change. The graph in Figure 6 shows typical changes in resistance from 25°C to 200°C. Figure 7 shows changes in resistor ratios. In order to meet design requirements of ±1/2 LSB to the 10 bit level, the resistor ratios must track to better than ±.05% from 25°C to 200°C.

The thin film resistor chip also has the advantage of being actively laser trimmed. This results in an A to D which will meet all specifications without any external adjustments. Any external components added would be another source of error when raised to 200°C.

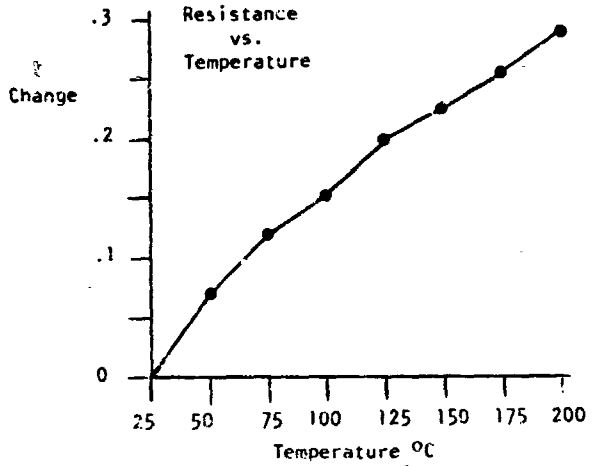

Figure 6

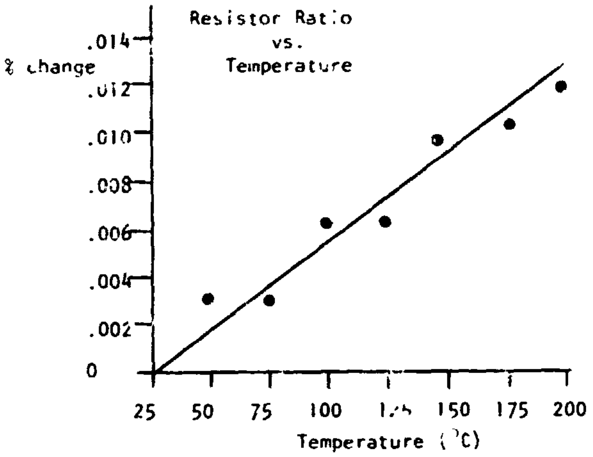

Figure 7

Comparator

In most hybrid A to D converters, the comparator is a single I.C. chip. These are usually bipolar devices. Tests done on most available bipolar I.C.s indicated they were not the most reliable choice for 200°C operation. This is due to the problems of junction isolation previously stated. Because of this, a comparator was designed using a dielectrically isolated op amp and discrete transistors which operated reliably at 200°C.

Successive Approximation Register

The SAR used in this design is a CMOS I.C. This was chosen because of the good characteristics of CMOS at high temperatures and the low power consumption. CMOS I.C.s have been constructed which were functional at 300°C for over 1000 hours.[6] While leakage current on CMOS devices operating at 200°C may be large when compared to +25°C operation, their voltage thresholds do not change appreciably. Thus devices operated from low impedance sources work very reliably at 200°C.

ELECTRICAL TEST RESULTS

The first prototype units were evaluated for conformance to the 200°C specifications. Test results showed that these performed as expected. These units were then put on a 200°C burn-in with frequent monitoring to observe changes or shifts that occured. After approximately 25 hours, large shifts were seen in linearity and accuracy. The cause of a shift such as this indicated a change in resistors or a change in the output resistance of the switches. The parts were burned-in longer and catastrophic failures were seen. Visual inspection showed that gold ball bonds were lifting off of the aluminum pads on the I.C. chips.

BONDING FAILURES

The bonding failures which occured at the aluminum/gold interface arose from the formation of an intermetallic compound at that point. As the time at high temperature increases, these compounds do not exhibit sufficient mechanical strength to insure bond integrity. As a result, the bonds have a tendency to break and cause an open circuit.

DEVELOPMENT OF METALIZATION SYSTEM

It was concluded that the most reliable hybrid could be fabricated if all wire bonding was done to similar metals. This was a problem because available I.C. chips use aluminum bonding pads, while the substrate, resistor chips, and posts have gold bonding areas.

To accommodate this bonding scheme, a substrate was needed with both gold and aluminum bonding areas.

Three Metal-Metalization Process

In order to construct the type of substrate described, it was necessary to use three metals - gold, aluminum, and nickel. The gold is used for conductor runs and bonding areas, and the aluminum is used only for bonding areas, at the I.C. chips. The aluminum bonding pads sit on top of gold pads, but have a layer of nickel in between the gold and aluminum layers to act as a diffusion barrier, which eliminates the formation of intermetallic compounds.

Figure 8 depicts the major process steps. Starting with a wholly metallized Al_2O_3 ceramic plate (Fig.8a) a gold conductor pattern is defined using standard photo lithographic and etching techniques (Fig. 8b). Next a nickel layer and an aluminum layer are vacuum deposited (Fig.8c). Finally, the aluminum pads are formed by selective removal of unwanted film (Fig. 8d).

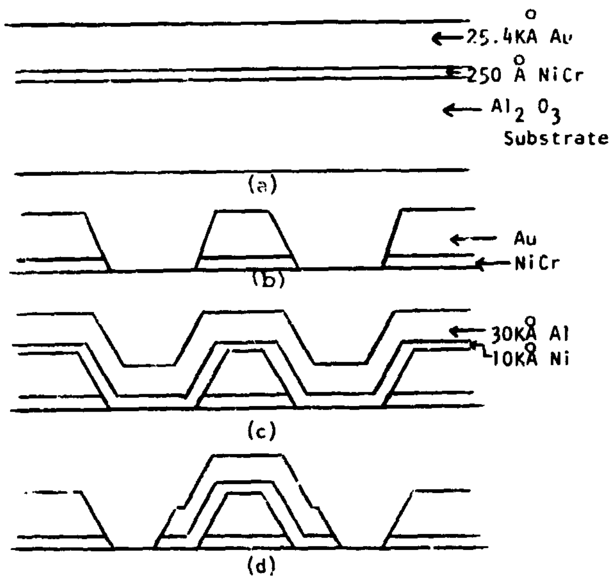

Figure 8

The process steps, thicknesses, and material selection have been chosen on the basis of compatibility with present fabrication techniques, as well as performance criteria.

Au/Ni/Al Substrate Evaluation

For evaluation purposes, a substrate was made which had a pattern allowing gold and aluminum wire bonding to be done between pins of a hybrid package. Connections were made which consisted of 26 bonds (13 wires) between pins of the package. The bonds consisted of aluminum wire on gold pads, aluminum wire on aluminum pads, gold wire on aluminum pads, and gold wire on gold pads. The aluminum pads were deposited on gold using a nickel barrier as described in the previous section. The resistance was measured between the pins of the package at various intervals of 200°C bake. This measurement included the bond resistances along with the resistance through the aluminum/nickel/gold interface. Figure 9 shows a graph of change in resistance versus time at 200°C for the four different bond interfaces. It can be seen that the best results are obtained when bonding is done between similar metals.

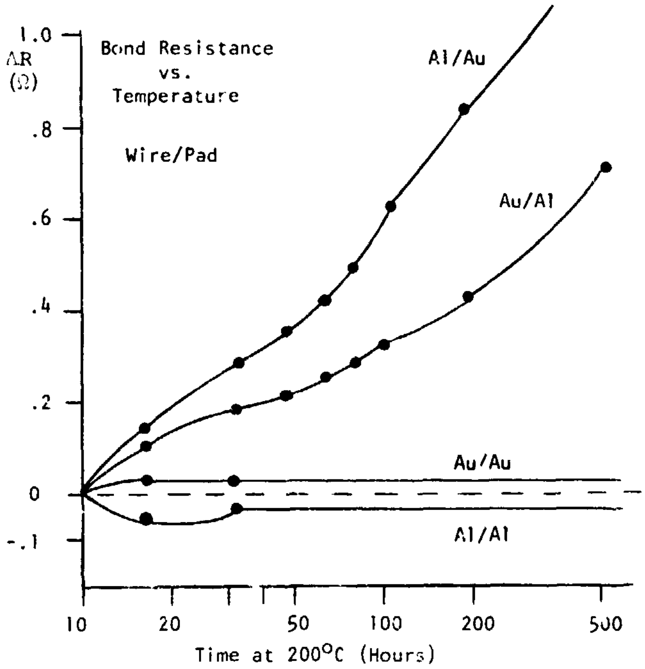

Figure 9

Figure 10 shows a section of the substrate used in the MN5700. The shaded areas indicate aluminum pads which are properly located for aluminum wire bonding to the I.C. Chip.

Other Failure Modes

The next group of catastrophic failures were seen in the 500-750 hour range. When these units were inspected, it was seen that some of the epoxy mounted chips had lifted off the substrate and caused some bonds to break. This was corrected by using a different type of epoxy with better high temperature characteristics. Evaluation of this epoxy after 1000 hours at 200°C showed little or no degradation in its bonding and adhesive characteristics.

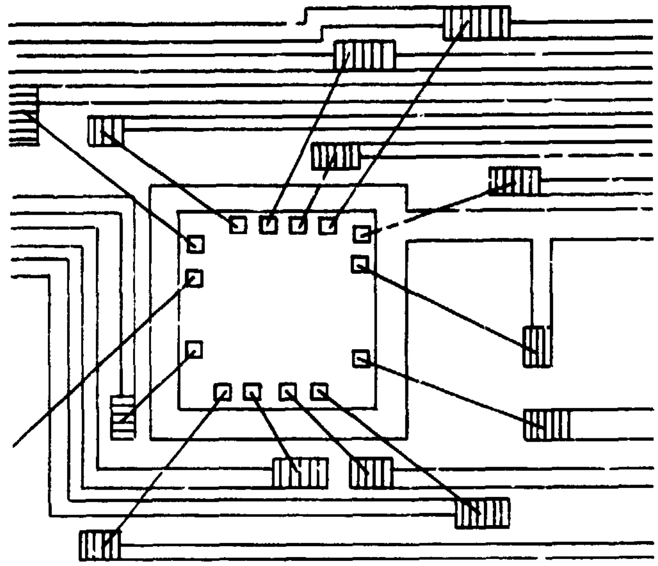

Figure 10

CONCLUSIONS

Tests have shown that units will operate reliably and remain within 200°C specifications in excess of 500 hours. Beyond 500 hours, some units will exhibit a slow shift in linearity and accuracy. This appears to be caused by resistor aging and changes in the characteristics of the CMOS switches in the D/A section. Life tests have shown that most units remain within specification in excess of 1000 hours. Tests have also shown that most catastrophic failures and units with large shifts will show up in the first 24 hours of operation at 200°C. To help assure reliability, all units are tested, burned-in for 24 hours at 200°C, and retested.

All 200°C specifications are also guaranteed at -55°C. The MN5700 is available with high reliability screening according to MIL-STD-883 for Military/Aerospace Applications.

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