Sensor Amplifier for the Venus Ground Ambient

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Abstract

Previous Venus Landers employed high temperature pressure vessels, with thermally protected electronics, to achieve successful missions, with a maximum surface lifetime of 127 minutes. Extending the operating range of electronic systems to the temperatures (480°C) and pressures (90 bar) of the Venus ground ambient would significantly increase the science return of future missions. Toward that end, the current work describes the innovative design of a sensor preamplifier, capable of working in the Venus ground ambient and designed using commercial components (thermionic vacuum tubes, wide band gap transistors, thick film resistors, advanced high temperature capacitors, and monometallic interfaces). To identify commercial components and electronic packaging materials that are capable of operation within the specified environment, a series of active devices, passive components, and packaging materials were screened for operability at 500°C, assuming a 10x increase in the mission lifetime. In addition, component degradation as a function of time at 500°C was evaluated. Based on the results of these preliminary evaluations, two amplifiers were developed.

Key words: Venus electronics

1. NASA Requirements and Technology Needs

As illustrated in Figure 1, ambient temperature requirements for missions to Jupiter (350°C) and Venus (480°C) are significantly higher than those for conventional applications on Earth. Since current military and space rated electronics have a maximum use temperature of 125 °C, electronic instruments and systems used for space exploration are traditionally maintained within protective environmental enclosures that allow them to function within their rated temperature ranges of operation, shielding them from the extreme temperatures, pressures and radiation levels of outer space or the dense atmospheres of planets such as Venus and Jupiter.

Unfortunately, maintaining all of the electronics within this protective environment requires significant energy, and under several circumstances limits the mission's science return. Conversely, one could design the entire system to survive within the ambient environment of planets such as Venus. The problem with this solution, however, is that electronics capable of functioning at the desired operating temperatures (+480°C) do not possess the level of complexity available with standard Si electronics that operate within the Mil Spec (-55 to +125°C) temperature range. Therefore, inconsistencies between the level of functionality available in current high temperature electronics capable of operating at 480 C and that required for the complete spacecraft in a Venus landed mission makes such an option unfeasible.

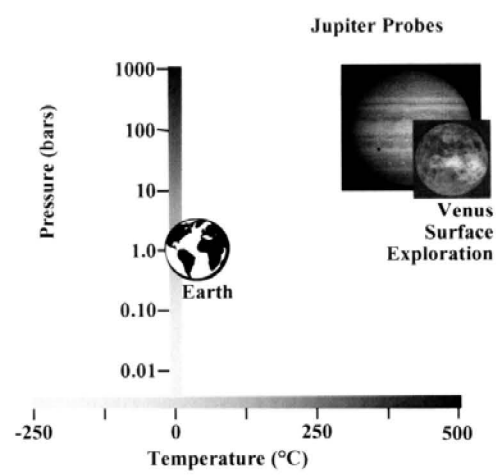

Figure 1. Comparison between high temperature space environments and that of Earth.

Detailed understanding of the capabilities and limitations of specialized high temperature electronic systems allows a third option, which is a craft that

maintains high level, complex, low power electronics within the protective environmental enclosure, while allowing select subsystems to operate within the ambient environment of the planet. This option, as illustrated in Figure 2, minimizes the cost and thermal load required to maintain a large volume of instrumentation at a significantly lower temperature than the ambient environment, while limiting the cost of high temperature electronic development efforts to critical subsystems that do not require complex circuitry.

As illustrated in Figure 2, there are several critical electronic subsystems, including sensor/ actuator systems, data acquisition systems and telecommunications. Regarding sensor, actuator and data acquisition subsystems, the goal is to maintain the required signal conditioning, signal amplification and control electronics close to the sensors and actuators with which they are associated. This reduces thermal leakage through the cabling port on the Lander as well as increasing the signal to noise ratio for the sensors.

Much of the remaining electronics and instruments will need to be protected from the harsh Venus surface environment via a pressure vessel that is thermally controlled using either insulation alone or a combination of active cooling and insulation. Since maintaining heat generating electronic systems within the vessel greatly increases the amount of power required to maintain the desired internal temperature and reduces overall mission lifetime, the development of 500°C electronics will allow the removal of high heat dissipating subsystems, such as signal transmitters for telecom, power converters, and actuator drive electronics from the pressure vessel. Potential technology needs for Venus landed missions are summarized in Table 1.

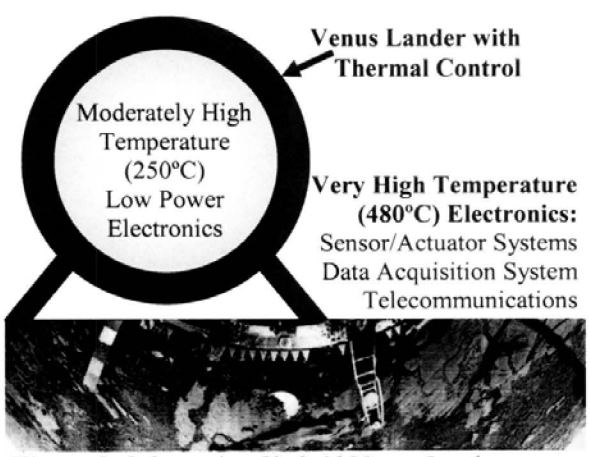

Figure 2. Schematic of hybrid Venus Lander concept.

Table 1. High temperature mission technology needs.

	Venus In-Situ Exploration			
	Short-lived Surface Mission	*Long-lived Surface Mission*	*Extended Surface Mission*	*Sample Return*
	Full science suite	Focused science	Full science suite	
HT Electronics	Low	Very High	Very High	Low
HT Comm. System	Low	Very High	Very High	Low
HT Sample Acquisition	Very High	Very High	Very High	Very High
HT Energy Storage	Low	Very High	Very High	Very High

2. High Temperature Active Device Technologies

As shown in Table 2 and mentioned previously, most commercially available electronic devices have temperature limits far below those required for the Venus environment. Conventional bulk-Si devices can be used only to 200°C, due to a significant increase in leakage current at higher temperatures. For functionality up to 300°C, leakage current may be managed using Si on insulator (SOI) technology, which uses SiO_2 to dielectrically isolate devices on the integrated circuit. Large feature sizes and non-conventional metallizations can be utilized to increase device lifetime. At temperatures above 300°C, wide bandgap semiconductors, such as SiC or GaN, are needed.[1] Alternatively, thermionic vacuum devices (TVD), which can operate in ambient temperatures greater than 500°C, show great promise in potentially being able to withstanding the harsh Venus ambient environment.

Table 2. Summary of temperature limits for current active device technologies.

Electronics Technologies	**Theoretical Semiconductor/ Anode Limit (°C)**	**Practical Device Limit (°C)**
Bulk Si	400	225
SOI	400	300
GaN	900	600
SiC	900	600
TVD	1000	600

2.1 Solid State Devices

Although the theoretical maximum for SiC operation is 600°C, problems with diffusion and oxidation of metal contact layers significantly reduce both operation temperature and lifetime. Some of the primary challenges associated with his technology include the selection of metal layers to reduce diffusion and oxidation, repeatability of SiC growth and metallization processes, and the low level of device integration. To ensure long term survival of SiC active devices, the selection of a proper metal stack that minimizes diffusion, while maintaining a contact resistance that is negligible compared with the device on resistance is highly desired and has been an ongoing topic of research for the last 20 years. Since the most critical Venus high temperature electronics applications involve transmitters for telecom systems and basic operational preamplifiers for sensor and actuator interfaces, the lack of integrated circuits does not prevent the use of SiC in Venus missions.

Since the primary commercial application of SiC devices is that of power circuits, no commercially available devices are designed for small signal applications. Current SiC devices include junction field effect transistors (JFET)s, bipolar junction transistors (BJT)s, and metal-semiconductor field effect transistors (MESFETs). It is also worth noting that current commercial SiC devices were not designed for operation within the desired Venus ambient temperatures. For the purposes of this investigation, such devices were evaluated well out of there defined ranges of operation.

Due to issues such as diffusion, oxidation, and electromigration, devices will degrade with temperature and time. Such degradation must be understood and taken into account when designing systems using these devices. Toward that end, three different SiC device types were evaluated as a function of temperature (25°C to 500°C). In addition, short term aging experiments were conducted at 500°C to verify sufficient operation for the intended mission lifetime. All experiments were performed within a nitrogen purged furnace.

As shown in Figure 3, each device exhibited changes in gain with increasing temperature. SiC#1 exhibited a minimum gain between 200 and 300°C, with a similar gain at room temperature and 460°C (10% increase in gain at the higher temperature). Above 460°C, the gain for this device dropped to 70% of the room temperature value. The other two devices evaluated; however, exhibited between 75 and 85% reduction in gain from their initial room temperature values.

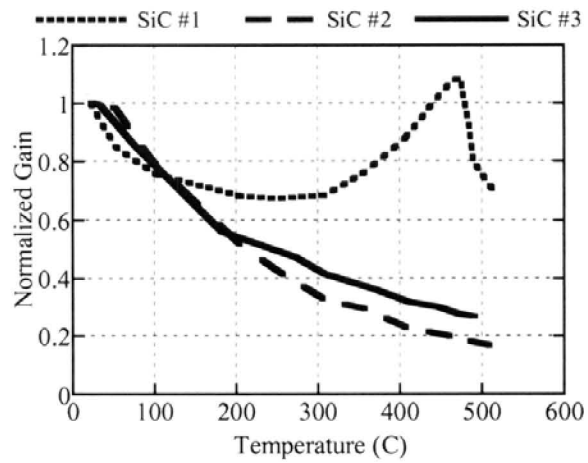

Figure 3. Plot demonstrating the influence of temperature on SiC device performance.

A preliminary short-term life test was performed on SiC#2, with a continuous IV sweep on the device. Since this is a power device, as mentioned previously, and the goal of the test was to determine the effect of temperature on its peak performance characteristics, the device was subjected to a significant amount of power and current. Due to the high stress test conditions, the device failed after less than 24 hours. The test was repeated a second time with similar results. As shown in Figure 4, scanning electron microscopy (SEM) analysis of the failed devices revealed the presence of hillocks and voids, indicating that the device likely failed due to electromigration.

Figure 5 illustrates some of the mechanisms behind the formation of voids and hillocks as a result of electromigration. In addition to the factors shown in Figure 5, issues such as grain structure, temperature gradients, passivation coating selection (adhesion and degradation), surface structure and migration, stress distribution within the metal film, distribution and selection of metal layers, alloying effects, surface roughness, and CTE mismatch among the different layers.[1-2] Although the formation of hillocks and voids within Au films located between TiW and SiO_2 layers has been observed in the absence of current loading,[3] the fact that the unloaded samples survived for more than 200 hours at temperature indicates that electromigration had a significant role in the current evaluation.

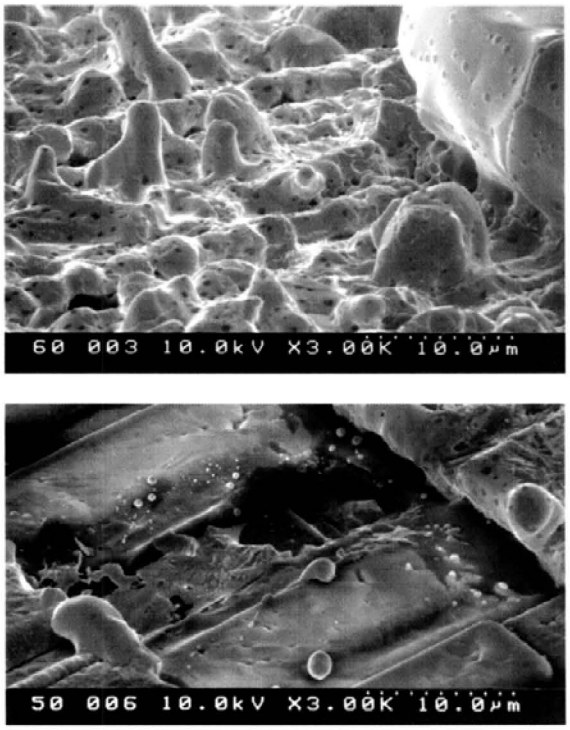

Figure 4. SEM micrograph of a SiC device surface following long-term test at 500°C.

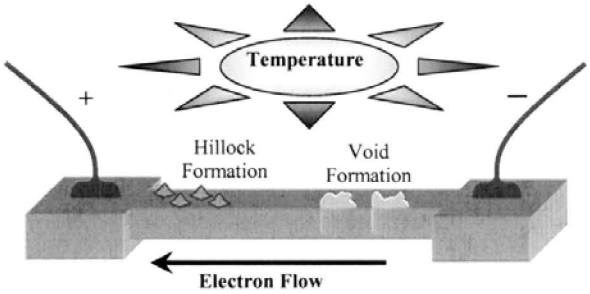

Figure 5. Schematic illustrating the influence of temperature and current density on electromigration.

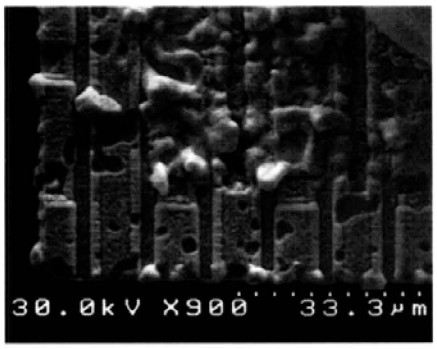

Figure 6. SEM micrograph indicating the presence of voids beneath the passivation and hillocks in unpassivated areas.

Select devices were also evaluated for over 125 hours at 500°C, and the results are summarized in Figure 7. It should be noted that none of these devices was electrically stressed during this evaluation, so that the influence of temperature alone could be determined. For SiC#1, which was not designed for elevated temperature operation, the greatest reduction in gain occurred over the first 30 hours and the device began to stabilize as time progressed further. Conversely, SiC#3, which was designed for elevated temperature operation, exhibited minimal reduction in gain with time at 500°C. This evaluation illustrates the importance of maintaining the proper metal stack for elevated temperature operation.

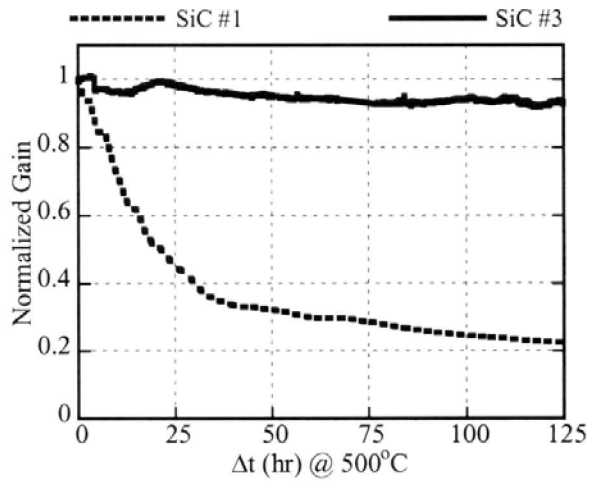

Figure 7. Plot demonstrating the influence of time at temperature on SiC device performance.

2.2 Thermionic Vacuum Devices

Conventional TVDs represent a mature technology with a long history of reliable space operation. A schematic diagram of a TVD is shown in Figure 8. The surface from which electrons are thermionically emitted is called the cathode. To obtain practically useful currents, thermionic emission typically requires temperatures in the range of 500 to 2000°C, depending on the emission material work function. These electrons are then attracted to an electrode called an anode or plate, which is generally maintained at a relative higher voltage potential than that of the cathode. The anode temperature may be anywhere from ambient temperature to greater than 1000°C, depending upon the power being intercepted. The simplest active gridded thermionic electron device is the triode, in which a third electrode, known as the grid, is inserted between the cathode and the anode. Since the grid is generally much closer to the cathode

than the anode, it is typical for the grid to be at a temperature very similar to that of the cathode. Therefore, within the envelope of the vacuum enclosure, gridded vacuum electronics operate at temperatures above 600°C. The maximum ambient temperature of operation for TVDs is primarily set by the vacuum package, or the envelope that surrounds and supports the vacuum environment.

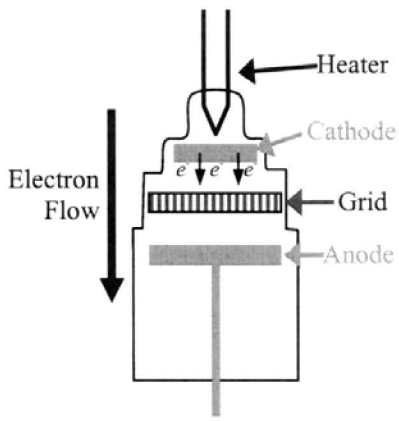

Figure 8. Schematic of a thermionic vacuum device.

As shown in Figure 9, these devices have been demonstrated for operation at temperatures ranging from room temperature to 500°C. In addition, the short term ageing characteristics of these devices were evaluated and the results are summarized in Figure 10.

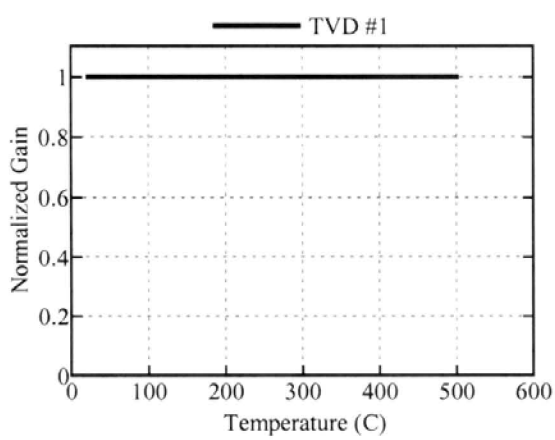

Figure 9. Plot demonstrating the influence of increasing temperature on TVD performance.

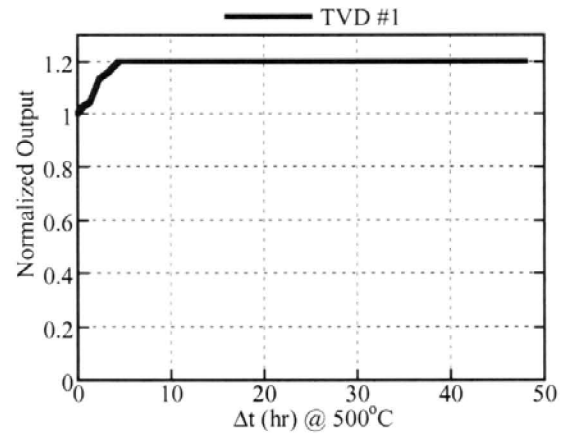

Figure 10. Plot demonstrating the influence of time at temperature on TVD performance.

During testing it was observed that the primary challenge in using vacuum electronics at 500°C involves maintaining the vacuum under these conditions. The vacuum enclosure must be strong enough to maintain its integrity following exposure to such harsh conditions. In addition, the devices must be heated to temperatures greater than the use temperature in order to avoid internal outgassing during use. Therefore, even though the devices have been demonstrated to work well under the desired conditions, they must still be optimized. Further challenges associated with this technology include issues related to higher levels of integration, and power requirements.

3. Passive Device Technologies

The development of passive components has had several significant difficulties. Issues such as drift, thermal stress and diffusion complicate the use of resistors. In addition, general-purpose ceramic capacitors tend to exhibit wide variations in dissipation factor and capacitance with increasing temperature. Unless capacitors and resistors have been designed for high temperature operation, they will likely fail due to packaging problems prior to failure of the parent resistive or capacitive material.

3.1 Resistors

Following a review of available literature, thick film RuO_2 resistors deposited on Al_2O_3 substrates were selected for evaluation. Such resistors eliminate the need for mechanical attachment to substrates, along with the associated failure mechanisms, and minimize failures due to encapsulation instabilities and oxidation, such as seen for TaN thin film resistors. The results of short term ageing experiments are summarized in

Figure 11. The lower resistivity ink exhibited a gradual increase in resistance with increasing time at temperature. Conversely, the higher resistivity ink exhibited an initial dramatic increase, but ultimately seemed to stabilize at a resistance that was about 4% lower than the initial value. Differences in the volume fraction of conductive particles and the softening of the glass binder with time at 500°C may have resulted in the difference in behaviour between the two inks.

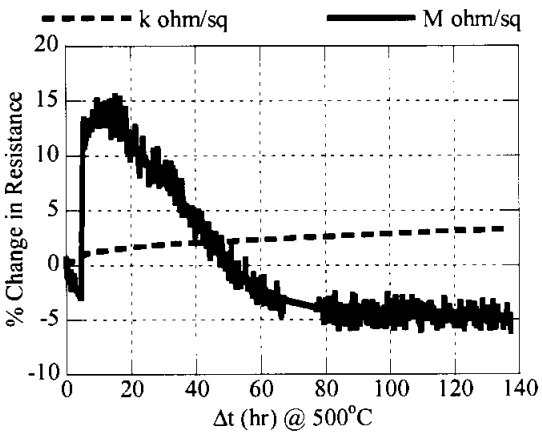

Figure 11. Plot demonstrating the influence of time at temperature on thick film resistor performance.

3.1 Capacitors

Capacitors for high temperature operation are particularly challenging, since they tend to vary in capacitance with increasing temperature. At elevated temperatures, the leakage currents of these capacitors become very high, making it difficult for the capacitor to hold a charge. A selection of potential high temperature capacitors is discussed in Table 3. The influence of temperature on the capacitance and dissipation factors for several of these candidate capacitors is summarized in Figures 12 and 13, respectively. Based on the results of these screening experiments, the most promising candidates for high temperature (500°C) capacitors were found to be NP0 ceramic capacitors and piezoelectric based capacitors.

NP0 capacitors have minimal variation in capacitance with temperature, but unfortunately they exhibit a significant increase in dissipation above 300°C. Piezoelectric capacitors are designed for operation at a specific temperature, and therefore exhibit optimum properties at the desired temperature. Unfortunately, this peak in behaviour can be very narrow with respect to temperature, making the implementation of this technology in actual designs difficult.

Table 3. Selection of high temperature capacitor technologies.

Capacitor	Max. Temp. (°C)	Comments
X7R	≤ 500	Capacitance is a strong function of temperature. High leakage current at elevated temperatures.
NP0	≤ 500	Capacitance is stable up to 500°C with low temperature coefficient of capacitance. Dissipation factor increases above 350-400°C.
Piezo-electric	Design Dependent	Composition selected to peak in capacitance and dissipation factor for specified temperatures. Difficult to implement.
Diamond	> 500	Theoretically useful to > 500°C with stable, high capacitance. Still under development to attain uniform diamond film and stable metal contacts.
Air Gap/ Parallel Plate	> 500	Low capacitance, but stable over entire range of temperature. Very large area capacitors required.

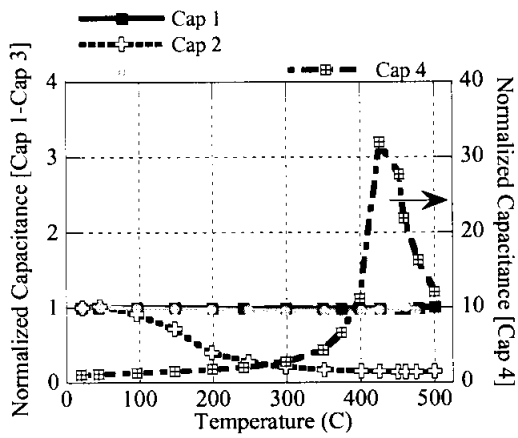

Figure 12. Plot of normalized capacitance as a function of temperature for various capacitor types.

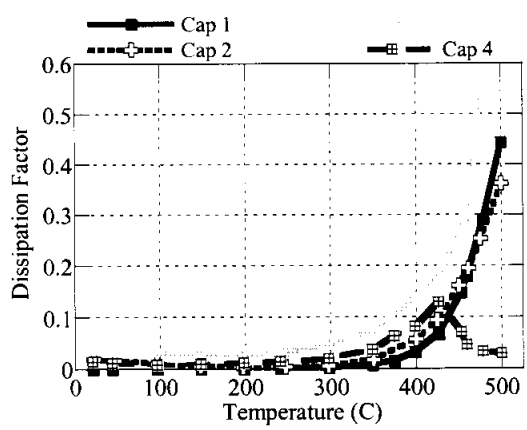

Figure 13. Plot of dissipation factor as a function of temperature for various capacitor types.

Various capacitor technologies, such as those based on diamond and other alternative dielectric materials, are currently under development and may eventually offer excellent properties over the entire temperature range from 23 to 500°C.

4. Electronic Packaging

Failure of electronic packaging at elevated temperatures is dominated by stress distributions between the die and the substrate (coefficient of thermal expansion (CTE) matching between the different layers), degradation of packaging materials, interdiffusion of metal layers, and oxidation. In order to minimize the CTE mismatch between the substrate and the SiC die, while using standard manufacturing processes, SiO_2 thick film substrates were used in the present evaluation. In addition, diffusion issues were minimized through the use of mono-metallic interfaces (Au wirebonds on Au bondpads).

Die attach materials selection is dominated by the following: mechanical attachment to the substrate, electrical connectivity between the backside of the die and circuit traces, and minimization of stresses transferred to the die during power and temperature cycling. In order to minimize stresses at the die attach interface it is important to keep the attachment temperature as low as possible, without compromising high temperature mechanical strength. A list of potential candidate die attach materials is summarized in Table 4. The use of eutectic Au80Sn20 and Au97Si3, along with thick Au layers on the substrate allows attachment at relatively low temperatures, without compromising the high temperature behaviour of the assembly. Au thermocompression bonding allows processing at low temperatures and provides a relatively compliant attach material at elevated temperatures.

Table 4. Selection of high temperature die attach materials.

	Max. Temp. (°C)	Comments
Solders and Brazes		
Au80Sn20	280	Eutectic
Au97Si3	363	Eutectic
82Au/18In	451	Solidus
45Ag/38Au/17Ge	525	Eutectic
72Ag/28Cu	780	Eutectic
Other		
Au thick film paste	> 600	High firing temperature
Au thermo-compression bonding	> 800	Assumes Au to Au interface

5. Sensor Sub-system

A high temperature piezoresistive pressure transducer was used to evaluate the functionality of the 460°C pre-amplifier. Two pre-amplifier circuits are under development using SiC discrete transistors and thermionic vacuum devices. The TVD pre-amplifier was evaluated at room temperature and 500°C; preliminary results are shown below.

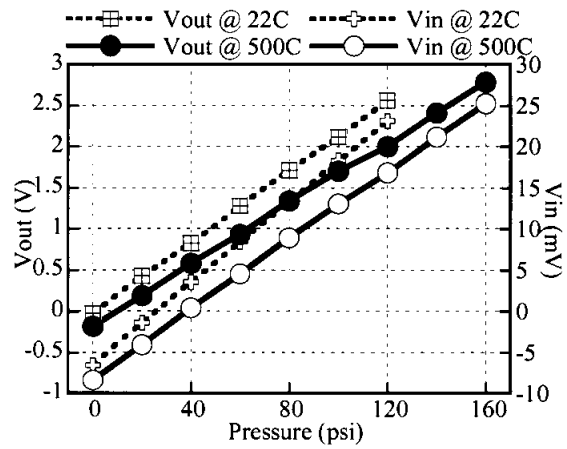

Figure 17. Plot of amplifier.

6. Summary

High temperature electronics can play a key role in Venus missions and deep atmospheric probes. In the present investigation, a sensor amplifier was developed using commercially available sensors, active devices, passive devices and packaging materials. The amplifier was demonstrated to function at 500°C.

7. References

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