HIGH TEMPERATURE , HIGH RELIABILITY INTEGRATED HYBRID PACKAGING FOR RADIATION HARDENED SPACECRAFT MICROMACHINED TUNNELING ACCELEROMETER

(Integrated MCM Sensor)

THIN FILM TECHNOLOGY RADIATION HARDENED MCM

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Abstract-

This paper summarizes and reports a radiation hardened spacecraft high temperature, high reliability Sensor/Circuit Integrated Packaging Technology. Tunneling Accelerometer Integrated Circuitry is the first flight-ready demonstration of electronics hybrid packaging as part of electron tunneling sensor. It is a radiation hardened spacecraft MCM [1] Integrated Circuit (IC) technology/Packaging to operate at elevated temperatures in a 100 Krad (Si) environment. Circuit with the sensor is the first micro-electromechanical system (MEMS) based on electron tunneling principal in a flight qualified Integrated hybrid packaging form. Circuit guarantees automatic tunneling by adjusting tunneling gap (~ 10 Angstroms) at above mentioned environments with minimum power consumption.

1. Introduction

Recently, electron tunneling through a narrow vacuum barrier has been employed in scanning tunneling microscopy (STM) [6] to study the atomic scale structure of surfaces. The tunneling current I has the following dependence on the separation between a pair of metallic electrodes [7]:

$$I = V e^{(-\alpha(\sqrt{Ps}))}$$

Where P is the height of the tunneling barrier, V is the bias voltage, V is small compared to P, and $\alpha = 1.025$ Å^{-1}eV$^{-1/2}$. For typical values of P and s, the current varies by an order of magnitude for each change in electrode separation. This sensitivity to relative position is superior to that available in other compact transducers and creates an opportunity for miniaturization of a broad class of sensors without loss of sensitivity. Integration of this miniaturized micromachined sensors with support electronics in a single integrated hybrid package has been the main effort of this activity.

2. Tunneling Accelerometer Hybrid Module/Packaging:

The Tunneling Accelerometer Sensor Hybrid Module in Figure 1. below

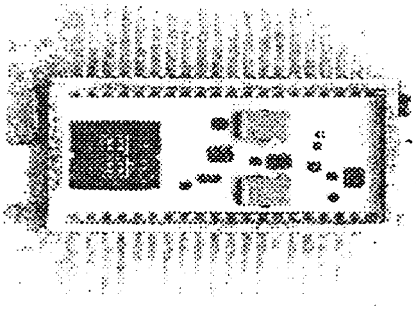

Figure 1. Tunneling Accelerometer Hybrid Module and its packaging

incorporates a mechanical tunneling device and its high temperature reliability electronics control circuitry all integrated on the same substrate within integrated hybrid package.

Substrate for hybrid circuit serves three key functions.[1]

1. Mechanical support for the assembly of the devices
2. Base for the electrical interconnect pattern
3. Medium for the dissipation of heat from devices.

Besides three basic mechanical, electrical, and thermal functions, substrates must meet many other electrical, thermal, physical and chemical requirements such as high electrical insulation resistance, low porosity and high purity, high thermal conductivity, low thermal expansion coefficient, high thermal stability, high degree of surface smoothness and high chemical resistance.

Micro-machined accelerometer is a mechanical sensor which is made by silicon processing using Tunneling Displacement Transducers and are glued to alumina substrate with special, space qualified conductive epoxy. This micromachined tunneling accelerometer uses displacement transducer to detect gravitational force accelerations . The sensor itself consists of a tip and a membrane essential for the tunneling action (see Figure 2). The third electrode (deflection electrode) along with the closed loop operation of the electronics helps to maintain the tunneling action.

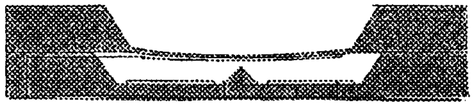

Figure 2. Micromachined silicon Sensor

Maintaining the tunneling action is essential for the detection of any force acting upon the accelerometer membrane. A control voltage is applied to the deflection electrode through feedback control circuit (see Figure 3).

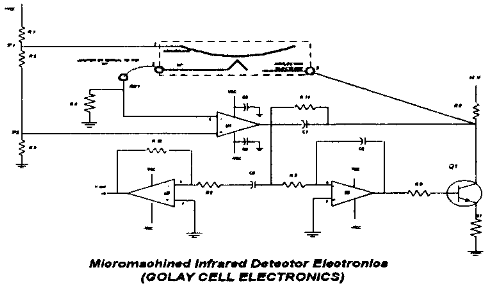

Figure 3 Schematic Diagram of Accelerometer high temperature reliability radiation hardened Electronics

This voltage is large enough to keep the lower membrane within 10 angstroms from the tunneling tip. The result is tunneling current which is detected by the feedback circuit. The control of the deflection electrode voltage is accomplished by a slow integrating action of a long time constant integrator which in turn controls the base of the loop transistor. Controlling the current through the transistor invigorates the servo action and keeps the tunneling action steady [2,3]. The electronic parts in the circuit were chosen to survive 100 Krad (Si) environment.

The advantages to the development of sensor components in silicon include the use of single crystals as raw material, use of photolithography for precision patterning, and use of batch processing techniques to reduce fabrication costs. Micromachining has been used in this case to produce micron scale components with micron scale precision.

In contrast to conventional tunneling devices, the relative position of the electrodes is controlled through the use of electronic servo loop system of electrostatic forces applied between the elements. The electron tunneling displacement transducer, was the first such device to use a quantum mechanical tunneling current to detect changes in separation between a pair of sensor elements [4]. The original devices consisted of piezoelectric actuators supported by complicated mechanical structures. More recently complete tunnel sensors have been fabricated from micromachined silicon components. The separation between the tunneling electrodes is controlled by electrostatic forces between a pair of metallic electrodes .

3. Fabrication:

The Electronics and the packaging have been designed with the other project hardware currently being built in mind, to make the MCM Universal enough to be used on-board of other Spacecraft.[5] Prior to layout and packaging substrate area has been estimated using Parts List which had a list of all discrete devices, transistors, diodes, chip capacitors, and chip resistors and the record of maximum device sizes, value tolerances and power dissipation. Calculations were made for the areas of each circuit element; added the individual component areas and the resulting sum have been multiplied by ten (10). This figure have accounted for the area of the lead pads and all interconnections. The approximate calculations accounted for the total substrate area for a given number of devices.

For the micromachined accelerometer in general the wafers have been polished on both surfaces and are coated with > 0.5um SiO_2 which were patterned by standard photolithography techniques. The wafers were etched in ethylene diamine pyrocatechol (EDP), removing the parts of the silicon wafers not covered by SiO_2 mask. After etching, the remaining oxide was removed in a buffered HF etch. A new oxide layer > 1um thick was then grown on all surfaces of the structure. Gold electrodes were thermally evaporated onto the components of the sensor through shadow masks which have been fabricated by the same micromachining techniques. The SiO_2 has served as a dielectric isolation layer between the metal films and the silicon substrate. Photolithography, micromachining and metallization techniques were used to fabricate the components.

4. Testing

Pre-testing of semiconductor die (transistors and diodes) have been essential for producing MCM circuit with initial high yields. Defective die have been identified and replaced in early stages of MCM assembly. Calculations for initial yields and first rework yield are given below.

Initial Hybrid Yield (Fo). Assuming 20 devices each having 10% probability of failure (P):

$$Fo = (1-P)^{(M)}$$

$$Fo = (1-0.1)^{20} = 0.9^{20} = 12.2\%$$

first rework yield (F1)

$$F1 = (1-Fo)(1-P)^{M1}$$

where M1 is the average number of failures per rework.

$M1 = (M*P)/(1-Fo)$

$1-Fo = -0.112 = 0.878$

$M1 = 20(0.1)/0.878 = 2.28$ average rework failure, therefore

$$F1 = 0.878(1-0.1)^{2.28} = 69\ \%$$

Burn-in consisted of applying power to the circuit while maintaining an elevated temperature of unextended period of time. Raising the ambient temperature and applying power it stresses critical connections and components while accelerating the life cycle of the Hybrid Module.

Burn-in has been a critical step in the screening of Accelerometer Hybrid Module since it has established electrical and thermal conditions that approximate actual operation in a compressed time frame (i.e. burn-in of 160 hours at +70 degrees Celsius is equivalent of a full year of operation at ambient temperatures. In this case semiconductor devices in the HYBRID MODULE were prone to many types of failures, one of which is ion migration, which generally occurs in the passivation layer , or between metal conductors. Chloride or sodium ions are two prevalent forms of ionic contamination.

Positively charged sodium ions under the temperature and bias conditions readily migrate to N-doped regions causing high leakage current and even shorts. Chloride ions tend to migrate to the P-doped material and may cause emitter to collector shorts in NPN transistors. These defects may not be discernible for many months, but the combination of high temperature and power that is provided by burn-in, accelerates the ionic migration without effecting the normal failure rate or the wear-out rate. Wear-out is associated with metal migration, long-term threshold drift, and corrosion. [1]

The Arrhenius Equation governs the reaction failure rate of an electronic device:

$$F = Ae^{(-Ea/KT)}$$

where:
F = failure rate
E_a= activation energy (varies from 0.3 to 2.3 ev; if it is not known, MIL-STD-883 allows the use of a E_a= 1.0ev)
k = Boltzmann's constsnat (8.63 X 10^{-5}ev/K)
T = junction temperature in degrees Kelvin (Desgrees C + 273 = degrees K)

5.0 Discussion:

The Tunneling Accelerometer itself has been exposed to direct gamma radiation with Co-60 radiation source at Total Dose Radiation of 100 Krad(Si) in JPL Radiation Test Chamber along with the electronics supporting the tunneling action. During this process tunneling has been monitored assiduously. Dynamic action of turning the tunneling action 'on' and 'off' while radiating the accelerometer was also performed. In both cases tunneling was not effected by the radiation source.

Hybrid circuit advantages over custom monolithic IC in this case were:

1. Power Packaging
2. Lower nonrecurring design and tooling costs for low to medium volume production
3. Readily adaptable to design modifications
4. Fast turnaround for prototypes and early production (i.e. this particular project had 75 day flight delivery schedule)
5. Higher performance sub-components available, for example +/- 0.1 % resistors, +/- 1% capacitors and low TCR zener diodes
6. Ability to intermix device types of many different technologies, leading to increased design flexibility
7. Ability to rework allows complex circuits to be produced at reasonable yields, and allows a certain amount of repair.

The Integrated Sensor with its power packaging described above has been delivered to be flown on board Space Technology Research Vehicle (STRV-2) for the purpose of demonstrating a tunneling action in space environment.

6. Acknowledgments

The research, design and the development of micro-machined Automatic Tunneling controlled (ATC) Accelerometer and its electronics was performed at Jet Propulsion Laboratory, California Institute of Technology under contract with National Aeronautic and Space Administration. Circuit testing has been conducted at the Microdevices Laboratory (Fig. 4).

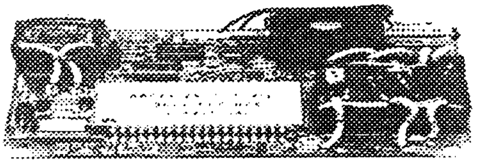

Figure 4. The Tunneling Accelerometer and its support electronics.

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