High Temperature Inertial Navigation Sensors, Electronics and Packaging for reliable 300°C Operation

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Abstract

Conventional oil and gas drilling measurement while drilling (MWD) systems are typically designed to operate at temperatures <200°C. To increase the efficiency of drilling unconventional geothermal wells, downhole MWD tools are needed that can operate in the unique thermal challenges encountered in enhanced geothermal systems (EGS).

GE demonstrated a 300°C downhole navigation system. The system utilizes GE's internally developed state-of-the-art MEMS multiple ring Gyroscope (MRG), and a high temperature gyroscope control and readout application specific integrated circuit (ASIC).

The MRG, ASIC and associated high temperature, high reliability packaging were integrated to demonstrate the performance and functionality of the gyroscope across the temperature range from room temperature to 300°C. Specialized long-term capable high temperature test platforms were developed to enable the characterization and testing of the gyroscope system and utilized to validate application-relevant lifetime capability.

Key words

High Temperature Electronics, Geothermal MWD tools, High temperature sensors, MWD Navigation sensors, MEMS gyroscopes.

I. Introduction

Extracting the geothermal resource requires drilling into formations with bottom hole temperatures (BHT) 260-350°C [1]. MWD tools utilized to survey wells and enable directional drilling are currently limited to 200°C operation. MWD utilization in higher temperature wells drive significant non-productive time (NPT) due to the need to trip out of the well, circulate fluid to cool the well, survey on a wireline, and trip back into the hole. Additionally, high temperature environments negatively impact the reliability of the MWD tools, and require the allocation of more tools per well, resulting in added cost. To support the high temperature orientation sensing needs in geothermal wells, GE has developed a MEMS based gyroscope that can operate at 300°C for extended duration. MWD tools traditionally use 3-axis accelerometer and magnetometer to measure inclination and azimuth. Magnetometers are susceptible to magnetic interference which limits survey accuracy. Academic publication on magnetometers operating up to 250°C exist [2]—but demonstrate the physical limitations of the technology—as heat degrades sense element magnetization. To address this gap, GE developed a 300°C MEMS gyrocompass for geothermal drilling[3]. Gyroscope-based orientation directional tools measure the earth rotation rate vector to calculate azimuth [4]. GE's MEMS MRG, Silicon-on-Insulator (SOI) readout and control electronics ASIC and the associated passives were integrated on a high temperature, high reliability packaging and tested for continuous operation at 300°C over extended duration. The test approach and results are presented in this study.

II. Subcomponent evaluation

Prior to testing of the integrated gyroscope system, subcomponent testing was conducted to validate functionality across the temperature range and assess feasibility for long term operation at 300°C. Short term testing of the MEMS MRG resonance and quality factor was conducted from room temperature to 600°C and shown to maintain functionality [5]. The MRG was further tested unbiased for 2412 hours at 300°C and measured periodically over 9 intervals within the test time with no significant change of performance observed over the test duration [5].

The MRG control and readout SOI ASIC was tested for performance from 25°C to 300°C. The test setup is shown in Fig. 1.

Fig. 1 ASIC setup with 300°C chamber, probe connections to test system (outside chamber), and test equipment

The ASIC's primary function is to provide the bias and drive excitation signals to the MRG and read back the sensed parameters though a transimpedance amplifier analog front end circuit. The ASIC functionality and noise floor were measured. The ASIC has two readout channels to detect the drive and the sensed signal with the drive readout channel operating at a lower gain than the sense readout one. The ASIC noise floor over temperature is summarized in Tab. 1 for both high gain and low gain input channels.

Tab. 1ASIC AFE noise over temperature

Temperature	Sense Channel (10X Gain)	Drive Channel (1X - Gain)
25°C	1.3uV/√Hz	2.8uV/√Hz
100°C	1.5uV/√Hz	3.1uV/√Hz
200°C	1.8uV/√Hz	4.3uV/√Hz
300°C	2.2uV/√Hz	5.2uV/√Hz

III. Packaging approach

To support the extended duration at 300°C testing, a custom AlN ceramic substrate was designed and fabricated. The MRG, ASIC, and passive components (resistors and capacitors) were then attached to the board with high temperature capable die attach. The MRG and ASIC inputs and outputs (IOs) were electrically connected to the substrate using wirebonds. The ceramic substrate connects to a conventional temperature data collection interface board through an edge connector. The high temperature ceramic test board is shown in Fig. 3. The ceramic board required two interconnect layers which utilized printed gold thick film materials with a printed dielectric layer in between to provide electrical isolation. A gold sintering paste was utilized for the ASIC and MRG die attach, and aluminum wedge bonds were used to electrically connected from the device pads to the ceramic board.

The passive components were attached utilizing a CuSn transient liquid phase (TLP) paste. Gold terminated capacitors and Gold-Platinum terminated resistors were identified to support the long duration testing at 300°C. Lack of availability of the gold (Au) terminated capacitors within the project timeframe necessitated a switch to Tin terminated capacitors instead. Initial testing showed an increased risk of poor adhesion, but also indicated that thicker layer of the CuSn TLP paste can improve the attach reliability.

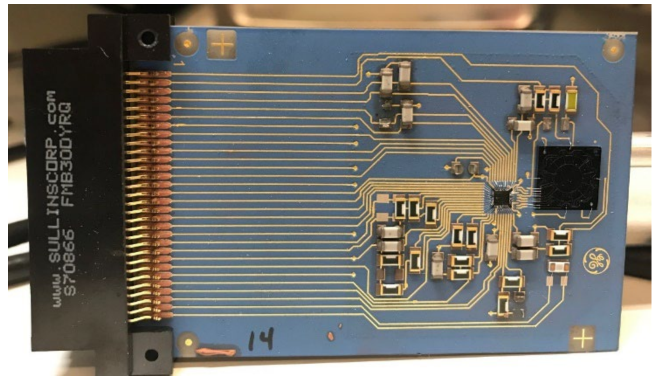

Fig. 2 Assembled 300°C capable ceramic board

Upon the completion of the board assemble, visual and Xray inspects were conducted prior to testing. In particular, since some of the interconnects on the board were routed under some of the passive components, Xray provided a means of inspecting those areas ad verifying that no shorting has occurred between the conductive trace and the adjacent component pads. An example of the obtained Xray images can be seen in Fig. 2.

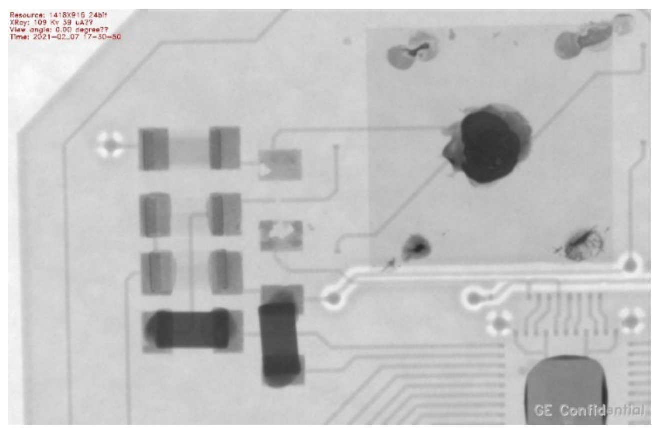

Fig. 3 Xray inspection of completed high temperature boards

IV. Test platform design

Supporting long-term testing at 300°C, the test platform needs to enable holding multiple test parts at temperature while simplifying instrumentation wiring. Additionally, since the gyroscope output is a function of rotation rate, a means of rotating the test board while it is at temperature and wired to the data acquisition system is highly desirable. A test configuration utilizing a hotplate was selected. The hotplate was placed on a rotating platform to enable in-test rotation of the test parts. Prior to start of testing, the temperature uniformity at the surface of the hot plate was assessed to determine the effect on part-to-part temperature difference during testing. Initial mapping of the temperatures on the hotplate showed approximately 80ºC temperature drop between the center of the hot plate and the corners. An approach was devised that enabled the placement of four test board symmetrically around the hot plate to minimize board to board variations. Four RTD temperature sensors were placed at the locations of the test articles and temperature data was collected, The temperature variation was reduced to less than 50ºC as can be seen in Fig. 4. Further reduction was achieved by implementing a heat spreader which resulted in ~16ºC spread between the samples with all four samples achieving a minimum of 300ºC as shown in Fig. 5.

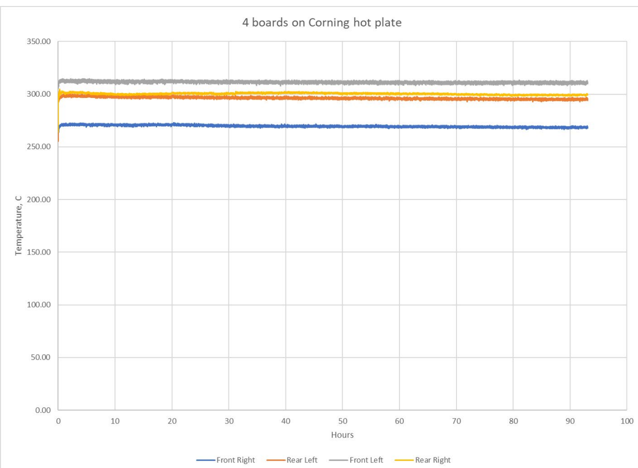

Fig. 4 Temperature spread between 4 test samples

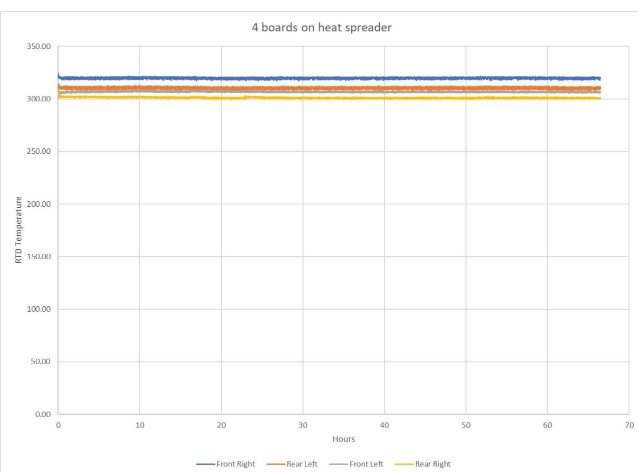

Fig. 5 Reduced temperature spread with the addition of a heat spreader

To facilitate the data acquisition functions needed for testing the ceramic board was connected to a data collection interface board though an edge connector. The edge connector allows for consistent connection to the test board and eliminates the need for making individual connection to the test article which can be complex and error prone. The test board and data collection interface configuration is shown in Fig. 6. As the data collection interface board is only utilized in instrumentation and is not part of the system under test, it was designed and built with conventional temperature electronics. The ceramic test board was designed with a long interconnect region to allow for temperature drop from 300°C at test portion that contains the ASIC, MRG and supporting electronics to <100°C at the data collection board.

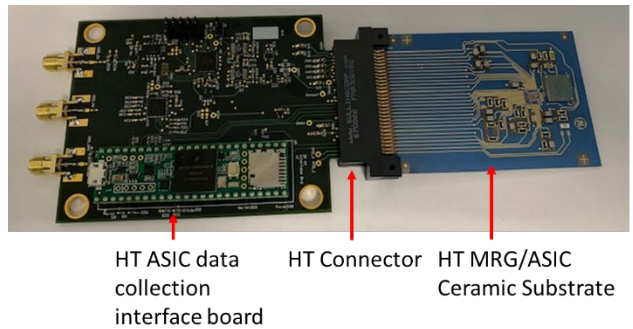

Fig. 6 Test board configuration for testing over temperature

A funcitonal block diagram of the test configuration is shown in Fig. 7.

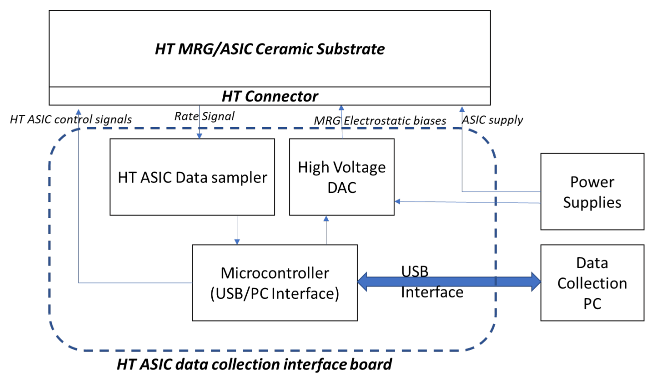

Fig. 7 Test configuration block diagram

The data collection interface board iperforms a data sampling/digitization function and conveys the data to a data acquisition computer over a USB link. The complete test system in Fig. 8 shows the hotplate with the test boards assembled on top, and the supporting power supplies and measurement instrumentation.

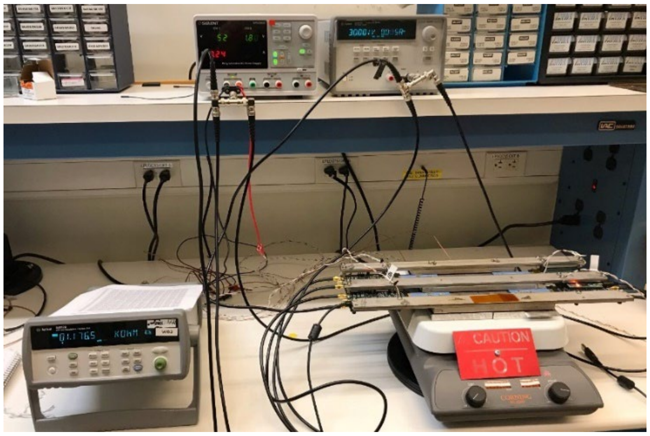

Fig. 8 Integrated MRGT and ASIC test setup

V. Test results

The test articles were powered and driven continuously through the duration of the test, but data acquisition was only performed periodically during testing. At each test interval, key measurement parameters including the scale factor, quality factor, resonance frequency, tuning and bias voltages were recorded along with test duration. Two initial measurement was conducted and utilized as baseline, one at room temperature and one at 300°C.

The 300°C test results are shown in the Fig. 9, Fig. 10 and Fig. 11. The center frequency and quality factor are both measures of the quality of the MRG and its ability to maintain its resonance characteristics. The scale factor is an end-to-end measure of the system under test that is the electrical output in response to a rotation rate input. The units for the scale factor are in millivolt/degree-per-second.

The test was started for each board at a time as it became available, and therefore the accumulated hours per board is different for each of the three test boards.

The measurement results are summarized in Fig. 9, Fig. 10, and Fig. 11. And show that within the measurement period over which the three boards accumulated 520, 877 and 972 hours respectively, the device and electronics maintained consistent performance.

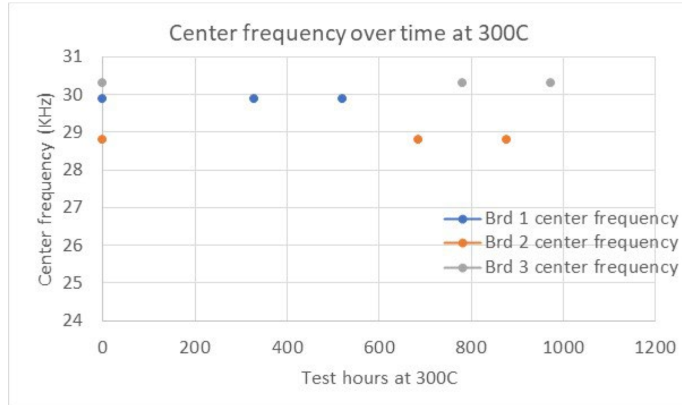

Fig. 9 Center frequency over time for each of the three test boards

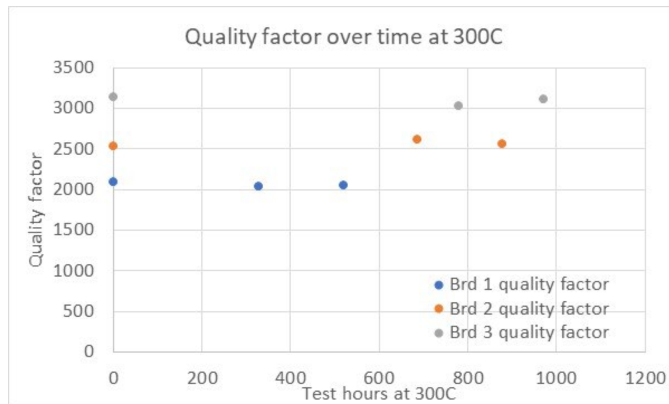

Fig. 10 Quality factor over time for each of the three test boards

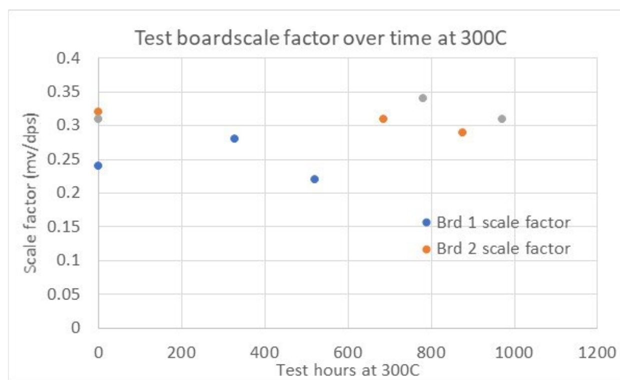

Fig. 11 Scale factor over time for each of the three test boards

The following test interval was conducted when the three boards had accumulated 1529, 1855 and 1980 hours, at which point all three test articles exhibited failures.

Failure analysis was conducted on the test boards as well as the low temperature data acquisition boards. Failures were observed on the digital to analog converters (DAC) utilized on the data acquisition boards. The DACs were replaced and subcomponent testing on the high temperature board was conducted to assess the operational state of the ASIC and the MRG after extended duration operation at 300°C. Subcomponent testing verified that the ASIC drive signal was still active and that the MRG when driven externally was showed similar resonance and quality factor behavior as prior to testing. Further probing of the test board revealed that some of the capacitors (including the coupling capacitors between the ASIC drive output and the MRG drive inputs had lost adhesion to the circuit board. Upon repairing the capacitors on one of the three test articles, a board retest was conducted at room temperature, which showed full system functionality. Fig. 12 transfer function shows the resonance characteristics of the MRG as well as the drive and readout functionality of the ASIC.

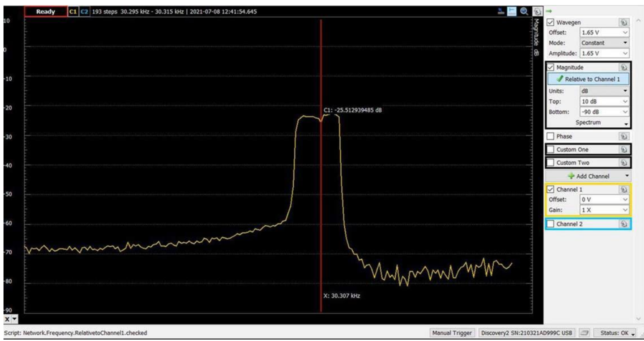

Fig. 12 Post-repair transfer function results

VI. Conclusion

The testing validated that the integrated system can operate for extended periods of time at 300°C. The lifetime was limited by attach failures in the Sn terminated capacitors. The active components (the SOI ASIC and the MEMS MRG) showed no signs of degradation during the testing.

The ceramic circuit board with printed dielectric and multiple conductor layers performed as intended and functioned for the duration of the testing.

Au-Pt terminated resistors didn't exhibit attach failures. Future testing will include the evaluation of alternate attach materials and processed to support long -term reliable high temperature attach to support the Sn terminated passives. Temperature aging and sheer testing will be conducted and evaluation of the attach reliability will be assessed as compared to that for the Au Au/Pt terminated parts with the CuSn TLP attach material.

The testing conducted demonstrated a high temperature MEMS based gyroscope and electronics for high temperature downhole applications. The demonstrated temperature-lifetime shows fundamental capability to meet temperature and lifetime needs of the geothermal drilling community,and demonstrated a downhole navigation sensing approach that extends the operating temperature and ameliorate the effects of magnetic interference of todays state of the art magnetometer based systems.

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Disclaimer

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