LASERLITH CORPORATION
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"Improved Directional Drilling Technology for the Bakken Formation"

Final Report
February 28, 2011

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Project Summary

It is imperative to bring reliable, domestic hydrocarbon reserves on-stream to help the United States reduce dependency on foreign oil. Hence, the Bakken Formation, with estimated reserves at 200-400 billion barrels of oil, is a critical national asset that needs to be developed to its maximum capacity. At present, only 1%-3% of Bakken reserves are anticipated to be recovered due in part to limitations with existing oilfield technology, including limitations in the accuracy of existing directional drilling technologies. The current technology, magnetometers, cannot be significantly improved since the errors are introduced by external sources.

Gyroscopes are inertial sensors that measure rate of rotation (in °/sec or °/hr) without reference to external coordinates. MEMS vibratory gyroscopes are based on Coriolis acceleration, which arises in a rotating frame of reference and is proportional to the rate of rotation. The gyroscope is forced to vibrate (typically using inter-digitated comb drives) in the sense axis at its characteristic resonant frequency. When subjected to angular rotation, the vibrating mass feels Coriolis acceleration in the direction orthogonal to the drive direction and axis of rotation. This motion in the sense direction is directly proportional to the rate of rotation and is typically measured using capacitive sensing.

The intent of this project is to increase the efficiency of horizontal drilling in the Bakken Formation by including the use of miniature gyroscopes in the drilling assemblage. The result of the project will be a prototype miniature MEMS gyroscope demonstrated at temperatures typical in the drilling environment. In particular, high-temperature shock-resistant MEMS gyroscopes enable the directional sensor to be positioned next to the drill bit, resulting in more accurate navigation, and reduction in drilling cost and time.

The project started with a basic MEMS gyroscope design to perform temperature sensitivity analysis and to study the effects of the high temperatures typically encountered in the down-hole environment. FEA modelers were used to study thermal-structural interactions and modal response at a temperature of 200°C. The results were used to develop an optimized gyro for the requirements set by the end user. The resulting final design provides a multi-fold sensitivity increase, as compared to the initial gyroscope design. Two iterations of MEMS gyroscope processing have been completed.

A closed-loop control circuit was developed and is responsible for oscillating the gyroscope's drive mass while simultaneously detecting any movement from the sense mass. The circuit outputs a signal proportional to the rotation rate sensed by the gyro. It must be able to detect small capacitance changes in the sense combs, correct for errors such as quadrature and the Coriolis offset, and keep any electrical noise to an absolute minimum.

A custom test chamber was built that can be heated up to 200°C simulating the drilling environment. The test vacuum chamber has feedthroughs to connect a power supply and receive signals from the sensor. It will be connected to a vacuum pump to reach UHV levels and mounted to a motor capable of rotating at a rate of 0.25°/min.

The operation of the control circuit and the gyroscope has been verified. The signal from the mechanical sensing element has demonstrated features typical of an operating gyro. Approximately 75% of the test effort is completed. The next step will be to test the gyro in the vacuum test chamber and then measure performance in a high temperature environment.

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Non-Confidential Background Information

It is imperative to bring reliable, domestic hydrocarbon reserves on-stream to help the United States reduce dependency on foreign oil. Hence, the Bakken Formation, with estimated reserves at 200-400 billion barrels of oil, is a critical national asset that needs to be developed to its maximum capacity. At present, only 1%-3% of Bakken reserves are anticipated to be recovered due in part to limitations with existing oilfield technology, including limitations in the accuracy of existing directional drilling technologies. The current Measurement While Drilling (MWD) technology, magnetometers, cannot be significantly improved since the errors are introduced by external sources.

Gyroscopes are inertial sensors that measure rate of rotation (in °/sec or °/hr) without reference to external coordinates. MEMS vibratory gyroscopes are based on Coriolis acceleration, which arises in a rotating frame of reference and is proportional to the rate of rotation (Figure 1). The gyroscope is forced to vibrate (typically using inter-digitated comb drives) in the sense axis at its characteristic resonant frequency. When subjected to angular rotation, the vibrating mass feels Coriolis acceleration in the direction orthogonal to the drive direction and axis of rotation. This motion in the sense direction is directly proportional to the rate of rotation and is typically measured using capacitive sensing.

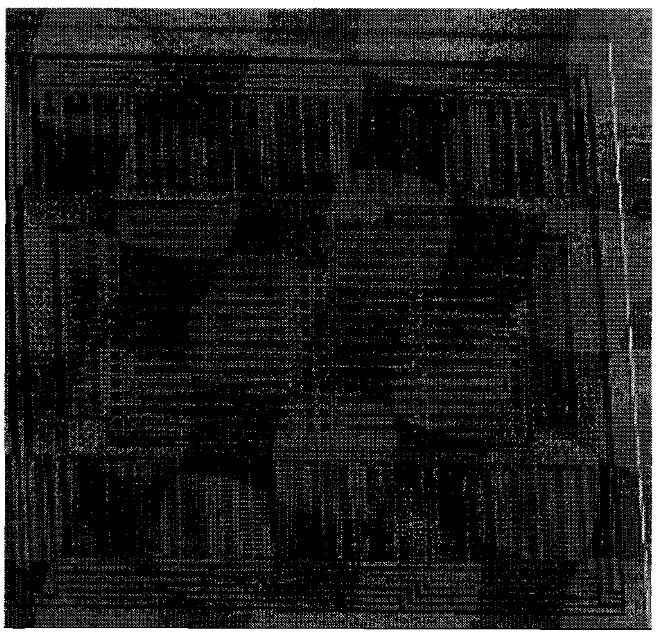

Figure 1. An example of a MEMS gyroscope.

A MEMS gyro can significantly reduce drilling time for casing window cutting applications, intermediate radius re-entry applications and steering applications.

For the Casing Window Cutting application, Baker Hughes has estimated that adding a gyroscopes to the current MWD tool can save approximately $35,000 per well based on avoidance of the cost to plug back and re-drill (Table 1)[1].

For the Intermediate Radius Re-entry application, Baker Hughes has estimated that $115,000 per well can be saved based on net rig time savings and avoiding the need to plug back and re-drill the sidetrack (Table 2)[1].

For steering applications, a direct cost savings cannot be estimated from eliminating the need to plug back and re-drill. However, improved accuracy will lead to a reduction in drilling time. In particular, directional measurement errors will accumulate from magnetometers whereas gyroscopes do not.

Table 1 — Wireline Gyro Replacement Example

Casing Window Cutting	Wireline	MWD Gyro
Drilling Rig Daily Rental Rate	$60,000	$60,000
Directional Drilling Daily Rental Rate	$10,000	$10,000
Gyro Orienting (during 2 days)	13 hours	1 hour
Cost to Cut Window (during 2 days)	$140,000	$105,000
Rig Time Saved		12 hours
Window Cutting Savings		$35,000
Total Savings/well		$35,000

Table 2 — Wireline Gyro Replacement Example

Intermediate Radius Re-Entry Kickoff	MWD Alone	Steering Gyro *	MWD Gyro
Drilling Rig Daily Rate	$60,000	$60,000	$60,000
Directional Drilling Daily Rental Rate	$10,000	$10,000	$10,000
Window Cost	$75,000	$75,000	$75,000
Drilling Time	1 day	1-1/2 days	1 day
Plug-Back Cost	$80,000		
Cost to Build Curve	$225,000	$180,000	$145,000
Window Cutting Savings (from Table 1)			-$35,000
Cost to Cut Window & Kickoff the Curve	$365,000	$320,000	$250,000
Total Savings/Well		$45,000	$115,000

* Assuming a wireline gyro steering tool is available

Gyro replacement cost savings tables[1]

[1] Estes, R. A. and Epplin, D. M. *Development of a Robust Gyroscopic Orientation Tool for MWD Operations.* SPE 63274, 2000.

Non-Confidential Section

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The project began by designing a high temperature gyroscope. FEA was used to optimize and verify the design before fabrication. Figure 2 shows the simulation results that indicate that the gyro sensor design will not buckle under the harsh thermal conditions and should operate successfully.

The design has very tight dimension tolerances, which push the limits of fabrication capabilities. Therefore, an initial MEMS fabrication run was performed to produce MEMS test structures targeting the design specifications for linewidth and sidewall. Figure 3 shows an example of a fabricated test structure. Electrical properties were gathered and a mounting and packaging process for the device was developed. A second design was developed from the gathered data to optimize the design for the fabrication process.

A control circuit also was developed for driving the gyroscopes and sensing changes in capacitance in the range of picofarads. The control circuit design was completed and is currently being fabricated. A vacuum test chamber for the gyroscope has been built which will be used to create a test setting typical of a drilling environment.

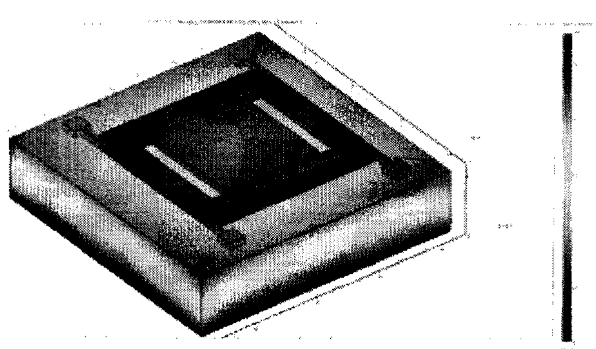

Figure 2. COMSOL simulation graph confirm gyroscope stability at 200 C.

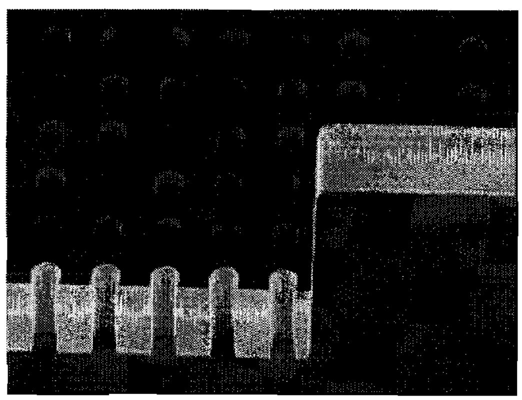

Figure 3. Fabricated test structures confirm MEMS process accuracy for the design specifications.

Non-Confidential Project Results

The work started out with a basic MEMS gyroscope design to perform temperature sensitivity analysis and study the effects of temperature. FEA modelers were used to study thermal-structural interactions for fixed-fixed flexure structures and simplified gyroscope frames.

In the first simulation, the fixed-fixed flexure, one of the basic and critical parts of the gyro was studied. This was performed for temperatures ranging from 0 to 200°C. The maximum displacement observed is a 0.6% deflection of the total thickness of the structure.

As each study confirmed thermal compatibility, the next level of complexity was added to create a more realistic representation of the actual gyro. The same input parameters for the simulation were used. The results showed that the beams had much less out-of-plane deformation (maximum of 0.1%) along its length. Structural deformation of the device layer is reduced since the substrate will expand along with the flexure as opposed to the last study where the anchors were fixed.

The next step toward demonstrating the thermal robustness of the MEMS gyroscope design was to include a full structure simulation at a temperature of 200°C (Figure 2). The total deformation at this temperature was considered negligible. All of these results confirm that the thermal effects the gyro would encounter in a drilling environment will not affect its performance.

The resulting final design provides a multi-fold sensitivity increase, as compared to the initial gyroscope design.

A closed-loop control circuit was developed and is responsible for oscillating the gyroscope's drive mass while simultaneously detecting any movement from the sense mass. The circuit outputs a signal proportional to the rotation rate sensed by the gyro. It must be able to detect small capacitance changes in the sense combs, correct for errors such as quadrature and the Coriolis offset, and keep any electrical noise to an absolute minimum.

A custom test chamber was built that can be heated up to 200°C simulating the drilling environment. The test vacuum chamber has feedthroughs to connect a power supply and receive signals from the sensor. The chamber is connected to a vacuum pump and mounted to a rotary table with two axis of rotation capable of rotating at a rate of 0.25°/min.

The operation of the control circuit and the gyroscope has been verified. The signal from the mechanical sensing element has demonstrated features typical of an operating gyro. Approximately 75% of the test effort is completed. The next step will be to test the gyro into the vacuum test chamber and then measure performance in a high temperature environment.

Non-Confidential Upcoming Tasks

Additional testing and optimization will continue. Development work will continue to improve the gyroscope and integrate them into the test system to test performance in a simulated down-hole environment. Revisions to gyroscope design are being made to incorporate additional enhancements to improve the fabrication yield and performance.