

Development of a Resonant Magnetometer

Zaki Izham¹, Michael CL Ward², Kevin M Brunson³, Paul C Stevens⁴

¹Microsystems Group, School Mechanical Engineering,
University of Birmingham, Edgbaston, Birmingham B15 2TT, UK. Izham@gmx.net

²Senior Lecturer, MEMS Group Leader, Microsystems Group,
School Mechanical Engineering,

University of Birmingham, Edgbaston, Birmingham B15 2TT, UK.

^{3,4} Microsystems Microengineering Business Group Qinetiq,
St. Andrews Road Malvern WR14 3PS, UK.

ABSTRACT

A new design and analysis of a novel MEMS resonant magnetic sensor is presented. The design method is based on a single mask and the Advanced Surface Etch (ASE™) process on BSOI (bonded silicon on insulator) wafers. The design philosophy considers ease of manufacturability i.e. minimum number of steps and processes with the intention to mass produce. The predicted device performance is a detectability of 0.1 μT per root Hz with a noise floor of 0.4 μV in a 100 Hz bandwidth.

Keywords: Magnetic sensor, resonant mechanical sensor, modeling.

1 INTRODUCTION

Solid-state magnetic sensors have been available and used for decades. A large number of these magnetic sensors are based on the Hall effect [1]. Resonant sensors have been developed for over 30 years and over the past 10 years many more resonator based sensors have been developed [2] mainly due to the potential for high sensitivity, accuracy and low fabrication costs. The Q multiplication factor inherent to resonant sensors is exploited here in the design of a resonant magnetometer to achieve displacements that are easily detectable with current technology. Silicon is a high strength elastic material and thanks to the integrated circuit manufacturing industry high quality single crystal silicon wafers with low levels of defects and dislocations are readily available [3,4].

This paper describes the design of a resonance based MEMS magnetometer that will be manufactured using the Advanced Surface Etch (ASE™) process developed by Surface Technology Systems (STS) from BSOI wafers. The design philosophy considers the ease of process, manufacturability, minimum number of steps and mask plates required for the development of the sensor. This paper describes the modelling and analysis of a conservative design that should be relatively easy to manufacture with a high yield.

2 PRINCIPLE OF OPERATION

The principle of operation of this magnetic sensor is based on the Lorenz effect. The metal tracks on the resonant beams act as a current carrier which experiences a force when placed in a magnetic field. The force generated and hence the deflection of the beams will be directly proportional to the strength of the field. The deflection of the beams will be detected by the asymmetrically spaced comb fingers. Since the current will be alternating at the resonant frequency of the device the deflection will be sinusoidal and also Q multiplied thus making the detection of weak fields possible.

3 MODELLING

Simple analytical models for the mechanical, electromagnetic and electronic aspects of the design were built to obtain a first order estimate of the performance of the resonant magnetometer schematically shown in figure 1.

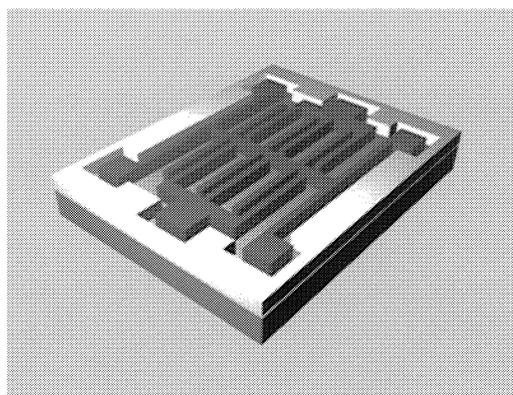


Figure 1: Resonant magnetometer device schematic.

3.1 Electromagnetics

The device works by utilizing the Lorenz force that is generated when a current carrying conductor is placed in a magnetic field. The current passing through each resonating beam is calculated using equation 1.

$$I_T = \frac{V_{excite} w_T t_T}{\rho_{Al}} \quad (1)$$

Where I_T is the current passing through the resonating beams, w_T is the width of the metal tracks sputtered to a thickness t_T , V_{excite} the potential difference applied across the beams and ρ_{Al} is the resistivity of the aluminium track. The amount of current passing through the beams is directly proportional to the amount of Lorenz force generated, this is shown in equation 2.

$$F_L = BI_T L_T \sin \theta \quad (2)$$

Where F_L is the generated Lorenz force along the whole beam of length L_T when placed in a magnetic field B perpendicular to the sensor (θ is 90 degrees).

3.2 Mechanics

After establishing the Lorenz force generated the static deflection δx of the device is estimated using equation 3.

$$\delta x = \frac{F_L L^3}{384 E I_{bx}} \quad (3)$$

Where E is the Young's modulus of silicon, L the length of the resonating beam and I_{bx} the moment of inertia of the beam in the x-axis.

The resonator's resonant frequency has to be estimated in order to excite it at that particular frequency. Most structures can be modelled by assuming a lumped sum and a particular spring constant assuming the masses of the springs are negligible compared to the shuttle which is not the case for this resonator. Since the mass of the resonant beam which provides the spring restorative force is more than 12 percent the weight of the shuttle assuming it to be massless would greatly over estimate the resonant frequency of the device. Equation 4 has to be modified to take the mass of the beams into account.

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \quad (4)$$

Where f is the resonant frequency k the effective spring constant of the beams and m the mass of the shuttle. By using the energy method to analyse the kinetic and potential energy of the support beams equation four can be modified to take the mass of the beams into account as shown in equation 5.

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m_s + m_{eff}}} \quad (5)$$

Where m_s and m_{eff} are the shuttle mass and the effective mass of the beams. Solving the equation for the maximum kinetic energy shows that the effective mass of a fixed-fixed beam is equal to two-thirds the mass of the beam.

The deflection magnitude of the beams is dependent of the magnetic field strength; the deflection of the beams is sensed by the change of capacitance between the asymmetrically spaced comb fingers. The change in capacitance is directly proportional to the effective overlapping area, the number of fingers and inversely proportional to the distance between the finger pairs. Equation 6 shows how the change in capacitance relates to a change in displacement.

$$\Delta C = \frac{An\epsilon_0}{d \pm \delta x} \quad (6)$$

Where ΔC is the change in capacitance, A the overlapping area of each finger pair, ϵ_0 the permittivity of free space and d the gap between the pickoff fingers. Since the displacement of the resonating beam brings the comb fingers closer together and farther apart the displacement has to be both added and subtracted to the spacing between the fingers. The overall change in capacitance will be the sum of the difference of capacitance of the closely spaced fingers and the distantly spaced fingers.

4 Q FACTOR MULTIPLICATION

The Q multiplication factor inherent to micro resonators is not typically exploited. Most commonly the change in resonant frequency due to a change in measurand is employed to monitor a change in measurand. This magnetic sensor exploits the Q multiplication factor which has no related noise in the amplification of the device displacement which leads directly to an amplification in device signal.

Since the device will be packaged in a vacuum it is assumed that the damping factor of the resonator will be minimal and hence a Q factor of around 10,000 is expected. This relates directly to an increase of dynamic deflection at resonance of $4.35 \times 10^{-7} m$ when an alternating current at the device's resonant frequency is passing through the conductors on the resonating beams as opposed to a static deflection of just $4.35 \times 10^{-11} m$.

5 RESULTS AND DISCUSSION

5.1 Results

This section shows the simulated results for a 100 μm thick device carrying an alternating current of 29mA through each resonating beam in a magnetic field of 50 μT assuming a worst possible case scenario for a Q factor of only 2000 i.e. the device being packaged in a weak vacuum. The device resonant frequency is 8.7 kHz. The static deflection in the magnetic field will be $2.175 \times 10^{-11}\text{m}$ and the dynamic deflection (Q multiplied) of $4.35 \times 10^{-8}\text{m}$. This relates to a dynamic change in capacitance of $2.91 \times 10^{-14}\text{F}$. Figure 2 shows the predicted change in capacitance, C in Farads with respect to the magnetic field strength, B in Teslas.

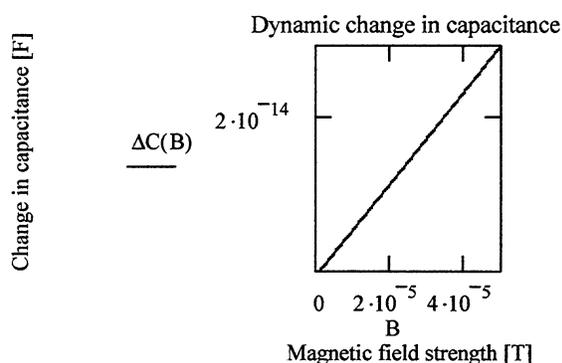


Figure 2: Predicted change in capacitance.

Figure 3 shows the comparison between the analytical models and the finite element models analysed using Coventor Ware™ for different device geometry to compare the effectiveness of the two-thirds beam mass theory. It can be seen that taking the mass of the beams into account matches the resonant frequency of the devices very well.

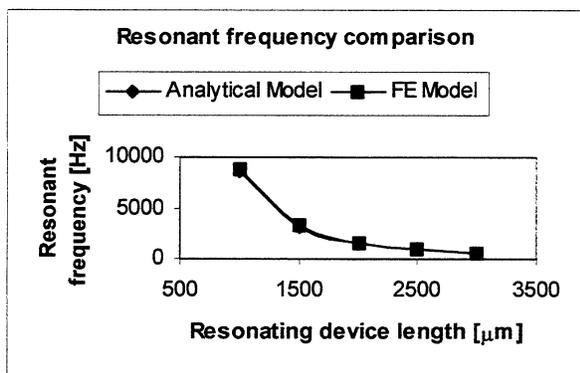


Figure 3: Analytical and finite element modeling.

Figure 4 shows a manufactured resonator on a 90 μm thick device layer on a BESOI wafer.

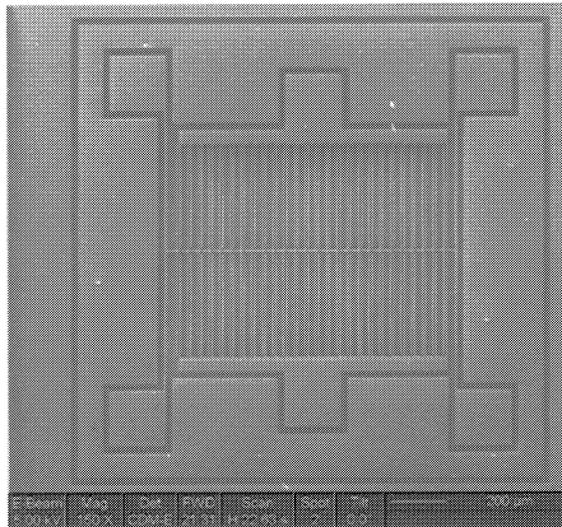


Figure 4: First generation device etched.

5.2 Discussion

This paper has discussed the design and predicted performance of a practical resonant magnetic sensor. The pickoff electronics analysis is beyond the scope of this paper though a noise analysis has been carried out. Based on a simple charge amplifier circuit employing the OP27 low-noise, precision operational amplifier the noise floor of the device will be 0.4 μV in a 100 Hz bandwidth. This would then relate to a detectability of 0.1 μT per root Hz for the first generation device. With some design specifications changed this device demonstrates the potential to be more sensitive and promises better performance than previously reported resonant magnetic sensors [5,6].

6 CONCLUSION

A new magnetic sensor based on the ASE by STS Technology has been designed analysed and manufactured. The device is expected to respond linearly within the interested range intended for navigational purposes. With further design improvements detection in the nano Tesla range would be possible.

7 ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support given by the UK Ministry of Defense within their materials domain corporate research programme.

REFERENCES

- [1] S. Kordic, 'Integrated silicon magnetic field sensor', *Sensors and Actuators*, 10 (1968) 347-378.
- [2] R.M. Langdom, 'Resonant sensors-a review', *J. Phys. E: Sci. Instr.* 18 (1985) 103-113.
- [3] G. Stemme, 'Resonant silicon sensors', *J. Micromech. Microeng.* 1 (1991) 113-125.
- [4] K.E. Petersen, 'Silicon as a mechanical material', *Proc IEEE* 70 (1982) 420-457.
- [5] Eyre B. et. Al., 'Resonant mechanical magnetic sensor in standard CMOS'. *IEEE Elec. Devices*. Vol.19, no.12 Dec 98.
- [6] Z. Kadar, A. Bossche, and J. Mookinger, 'Integrated magnetic field sensor', *Sensors and Actuators*, Vol. A41, nos. 1-3, 66-69, Apr 1994.