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SENPIMAG

A novel technology for ultra-sensitive reliable integrated magnetic sensors: a new era in magnetic detection

STREP

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Project coordinator organisation name: University of Cambridge

Revision 1

Introduction

The aim of this project is to develop a new technology of magnetic sensors. Specifically we aim to develop a new technology that can improve all the important characteristics of a magnetic sensor at the same time and in absolute value: ultra high sensitivity, micron or even nano-size scale, low cost, high reliability, broad frequency range, very low power consumption and easy fabrication process.

This new technology will be based on interfacing a magnetostrictive magnetic material and a piezoelectric that will act as a sensor element. The sensor head is made by the ferromagnetic material grown on top of the piezoelectric sensor and the electric contacts that read the voltage induced in the piezoelectric. The head contains current lines that create the driving a.c. magnetic field which periodically magnetises the magnetostrictive material in the direction perpendicular to the measuring axis. The voltage induced in the piezoelectric will be at double the frequency of the frequency of the driving field which enables noise rejection schemes to be applied. An external field will change the amplitude of this output signal. Importantly, no coils are required for detection.

The scientific and technical objectives of the project are as follows.

(1) To develop a new technology for magnetic sensors able to improve all aspects of the actual magnetic detection. In particular, we aim to provide an extremely versatile sensor, with potential use in almost all the applications where a magnetic sensor is required.

(2) To reduce the size of the magnetic sensor to the micrometre range, consistent with high sensitivity, reliability, low cost and easy construction. Reducing the size to nanometre is a subject of further analysis.

(3) To open new lines of research in the field of magnetic research by combining piezoelectric and ferromagnetic materials. This will allow the control of some of the magnetic properties with an electric field which is expected to have applications beyond the sensor developed under this programme.

(4) With the help of specialized companies we will implement a final product. We intend to develop a sensor that could require minor modifications for most of the applications.

Contractors involved

Cambridge University, U.K.(Device Materials Group): Coordinator: Prof. Mark Blamire. It is in charge of optimising piezoelectric film growth by pulsed laser deposition. Also in charge of the micro and nano-lithographic processing of the prototypes.

Polytechnic University of Madrid in Spain (Magnetic Devices Group): In charge of optimising the ferromagnetic material by sputtering deposition. This group has a wide experience in magnetic sensors and their applications in transport security and vehicle detection. Therefore, they will be directly involved in the design of the electronics and the prototype of these kind of applications.

Czech Technical University in Czech Republic: They have been for years the world leading group in flux-gate detection. Their experience is transcendental for the characterization and consequent optimisation of the sensor. They will be also actively involved in designing the prototype for aerospace applications.

INTA (National Institute of Aerospace Technology) in Spain: INTA is a public company dedicated intensively to aerospace research. Their experience with projects on satellites, vehicle control and detection and security in airports is a key in achieving practical goals. Their main task will be the design of a final prototype for aerospace and security applications.

SINTEF (Electronics & Cybernetics) in Norway: SINTEF is a company with wide experience in microtechnology in different industrial and social fields. They will apply modelling tools to optimise the electromechanical operation of the device and develop processing routes for the commercial production of the devices.

Work performed and results achieved.

Overview

This new technology is based on interfacing a magnetostrictive magnetic material and a piezoelectric that will act as a sensor element. The figure below shows a schematic representation of the possible sensor from the original project proposal. The sensor head is made by the ferromagnetic material grown on top of the piezoelectric sensor and the electric contacts that read the voltage induced in the piezoelectric. The head is placed in the middle of two current lines that create the driving a.c. magnetic field. This field is magnetizing periodically the magnetostrictive material in the direction perpendicular to the measuring axis. The voltage induced in the piezoelectric will be double frequency (2f) of the frequency of the driving field (low noise configuration). An external field will change the amplitude of this 2f output. No coils are required for detection.

Fig. 1(a) Lateral view of the head

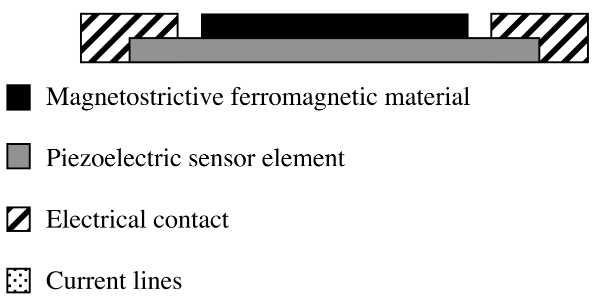
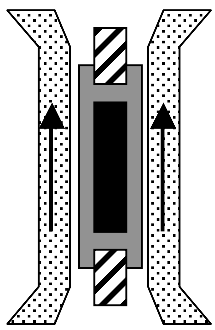


Fig. 1(b) Top view



As will become clear in the report, many aspects of this original concept were modified during the development of the project. However, the basic aim of coupling magnetostrictive drive to a strain-based sensor using an on-chip drive field remains and we demonstrate the success with which we have realised these goals.

This report is divided into a discussion of the development of the individual components of the device followed by a description of the fabrication and performance of the final integrated device.

Magnetostrictive materials

For the ferromagnetic material, we have to optimise the composition to maximize the magnetostriction and the permeability of the thin film and at the same time minimize the coercivity of the ferromagnetic film, so the hysteresis of the final sensor is easier to remove by ac techniques. We initially adopted the approach of combining of Permalloy ($Ni_{80}Fe_{20}$ (Py)) with the amorphous magnetostrictive FeCoB. Although, the results showed that it was possible to control the anisotropy and the coercivity within these multilayers, while retaining the magnetostriction, we discovered that we can also control the coercivity of the magnetic material with multilayers only of the magnetostrictive material, by altering the induced anisotropy in every other layer of the multilayer. This is fixed as the primary material for the sensor device.

Multilayers of amorphous $(Fe_{80}Co_{20})_{80}B_{20}$ were sputter deposited changing alternatively the anisotropy direction of the successive layers. This composition shows a magnetostriction coefficient of 30 ppm. The hysteresis loops show how the anisotropy field can be controlled by playing with the thickness ratio of the layers. Additionally, a clear decrease of the coercive field when the anisotropy direction rotates 90º from layer to layer is observed. This effect seems to have its origin in the mechanical energy accumulated in each layer.

Using a sample-target distance of 70 mm and a deposition power of 70W and 6 mTorr of Ar pressure the deposition rate is 17 nm/min. The sputtering target is not directly above the sample, but forming an angle of approximately 30º with the direction perpendicular to the sample plane. We have observed that this oblique incidence of the plasma induces a strong anisotropy axis in the direction of incidence.

To minimise the coercivity of the films for our device it was necessary to reduce the anisotropy in the deposited films. One way of doing that (without changing the

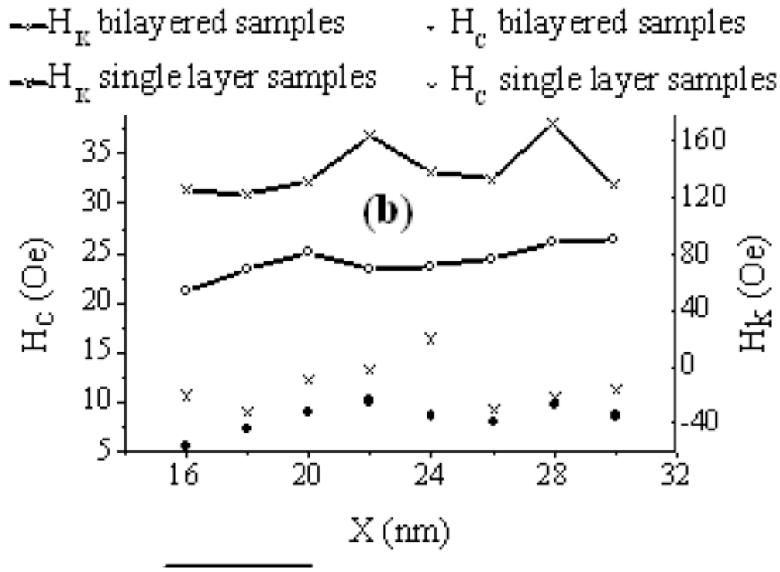


Fig. 2.

Anisotropy and coercive field of the multilayer samples(X nm - 9 nm) series of samples and their correspondent single layer with the same total thickness.

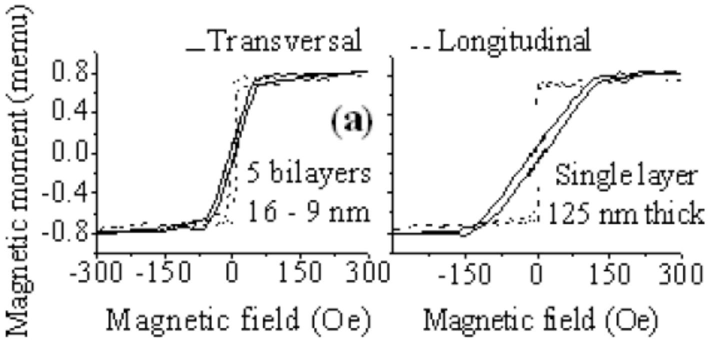


Fig. 3. Longitudinal and transversal hysteresis loops of a bilayered sample with X = 16 nm and its counterpart single layer sample with the same total thickness.

deposition conditions) is to rotate the sample constantly the sample during deposition, so the sample grows isotropic in plane (note that this does not mean zero anisotropy, the sample will show randomly oriented domains that increase the coercive field). Alternatively, one can deposit the sample rotating the anisotropy 90º every few seconds (always in the plane of the sample), obtaining a sample made of multilayers with the anisotropy in-plane but perpendicular from one layer to the next. The overall effect is isotropic behaviour if the layer thickness is lower than exchange length (for instance rotating the anisotropy 90º every 9 nm would result in an isotropic sample). If we make this multilayer asymmetric, one layer thicker than the next one, we can control the anisotropy field and reduced the coercive field.

Figure 2 shows the decrease of H_c in all the multilayers with respect to the value H_c of a single layer of the same total thickness. Figure 3 shows Significant differences on the linearity, anisotropy field and coercive field, can be observed between the two hard axis hysteresis loop for the single layer and multilayer films. This important result has been submitted for publication in Applied Physics Letters.

Piezoelectric materials

For the piezoelectric film, we chose to work with fatigue-free bismuth-layer-structured ferroelectric materials, in particular strontium bismuth tantalate $SrBi_2Ta_2O_9$ (SBT). We optimised the growth of SBT ferroelectric thin films on commercial Pt (100-150 nm)/TiO_2 (150 nm)/SiO_2 (400 nm)/Si (100) substrates using laser ablation. We determined that although in-situ growth gives high quality films with high polarisation values, the roughness is incompatible with subsequent magnetic layer film growth which is an essential aspect of the proposed device. Consequently ex-situ growth, in which SBT films were deposited at lower temperature and post-annealed has been developed and optimised.

Ex-situ depositions were carried out at room temperature in order to minimize thermal effects during the target-substrate transfer and the target-substrate distance was kept at 65 mm. The as-deposited films were post-annealed in a furnace in flowing oxygen for different periods of time (60–180 min) at annealing temperatures varying in the range of 680–780 ºC in a furnace in flowing oxygen.

Polycrystalline SBT thin films with preferential (115) orientation were successfully grown with half-range d_{33} piezoelectric coefficients of order 12–15 pm V^{-1}. A Bi-gradient architecture produced smooth ferroelectric films without evidence of pyrochlore and fluorite phases. The optimized processing window for gradient architecture in this experiment was found at processing temperatures of 720–730 8C and 120 min annealing time. An electric bias of 30Vapplied during the post-annealing procedure was successfully utilized for imprint minimization. The Bi-gradient triple layer architecture, although showing slightly lower d_{33} values, is better suited for integration in semiconductor technology due to the better surface quality, lower coercive voltage, and lower processing temperatures. This approach was adopted for the integrated devices.

Piezoresistive output

During the programme we identified an alternative sensor concept which incorporates a piezoresistive rather than piezoelectric output. In all other respects, the device design and operation is identical, but the new structure is much more readily fabricated using conventional semiconductor processing routes and should therefore be considerably cheaper to produce. During the project this structure was developed in parallel with the original device. The doped-Si piezoresistors used in the final device are conventional structures widely applied in other microelectromechanical devices.

Current lines for integrated magnetic fields.

The integrated current lines are required to generate the excitation fields for the sensor. This requires optimised coupling between the fields and magnetostrictive elements and minimising the overall resistance of the drive lines. Work was performed to simulate the performance of current lines and to study the best materials and the configuration for the current lines.

During the project several configurations of current lines were modelled with respect to the ability to magnetize the magnetostrictive material. The magnetic flux density achievable under specified conditions – current density and relative permeability of the magnetostrictive material was investigated.

A device structure with a closed flux configuration for the MS material and current lines was found to give optimal sensitivity. Two device configurations were selected for realisation:

(1) A conventional cantilever with two parallel but separate MS regions

(2) A "crocodile" structure consisting of a beam suspended at four nodes.

Several configurations of return conductor were modelled – including the return conductor next to the magnetostrictive layer, multilayer structures including the return conductor material and return conductor enclosing the magnetostrictive material. Trial models were implemented in the simple cantilever design to determine the separation required between the two adjacent MS closed flux regions. The results indicate that the separation gap does not have to be very wide. Even with a gap of only 1 micrometer wide, the flux density in neighbouring sandwiches do not influence each other significantly (See Fig. 4). This is because the flux densities generated by the currents in both sandwiches do have the same direction in between the sandwiches and support each other instead of subtracting.

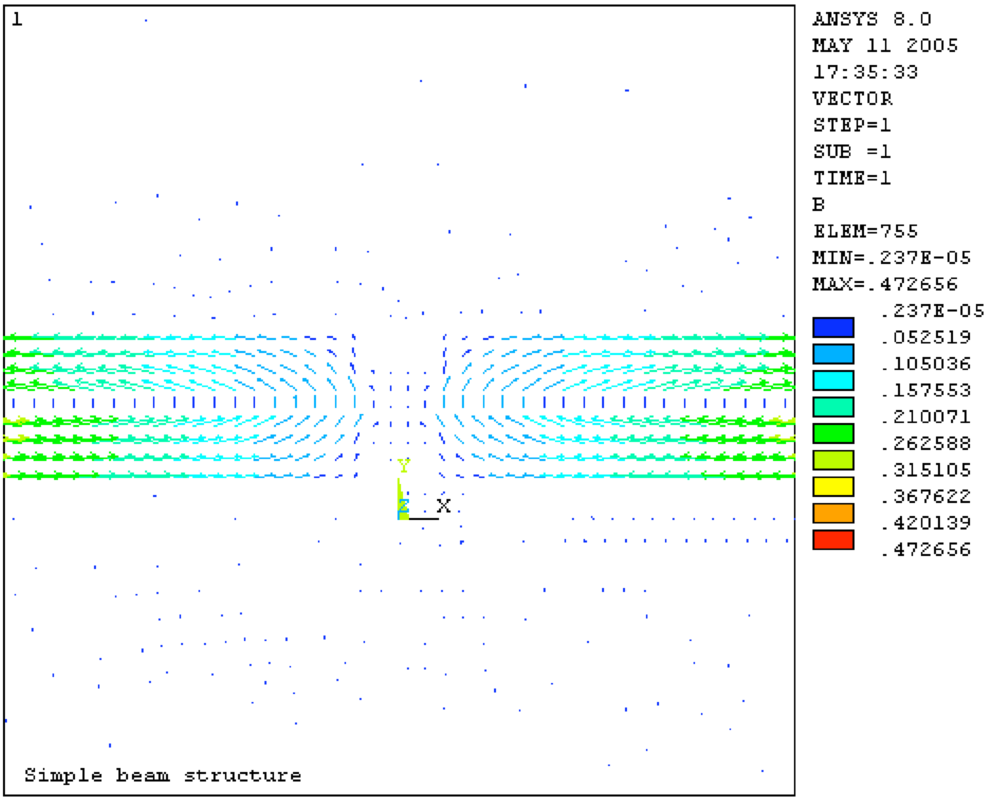


Fig. 4 Modelling of the magnetic coupling between opposed flux closure structures carrying opposite currents

The micromagnetic modelling of the expected performance was unequivocal and a total energy model (see Fig. 5) developed during the programme supported our original performance figures.

During the project, a significant uncontrolled impact of the current lines in heating during operation was revealed. Since the associated thermal expansion couples to the output at twice the current drive frequency it has the potential to interfere directly with the output. For this reason it was decided to model operation of the device at the fourth harmonic of the drive frequency.

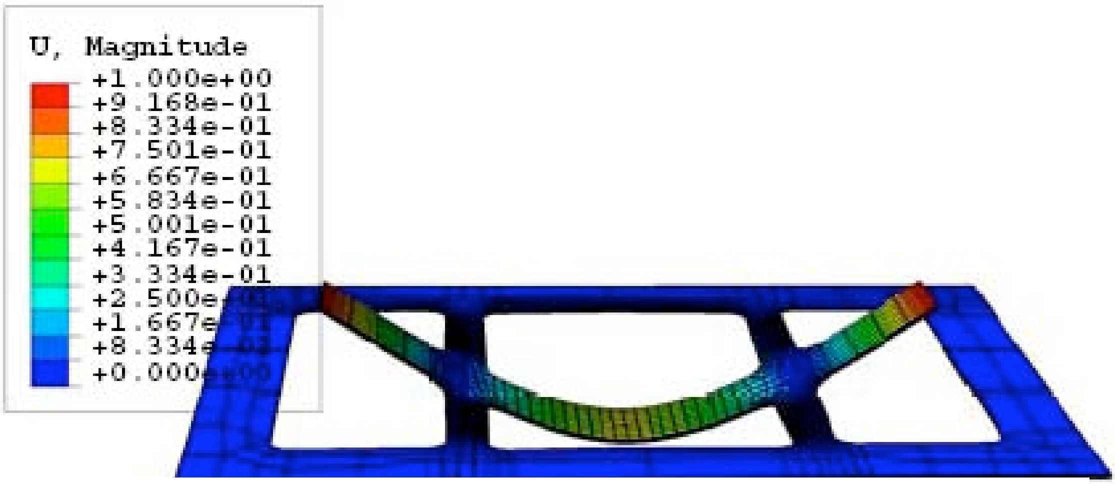


Fig. 5 Electromechanical model of stress distributions in the “crocodile” structure.

Knowledge Management Support

INTA gave knowledge management support to the consortium from three different points of views:

Technology Watch Reports - TWR: previous work

State of the Art in “Magnetic Sensors”

Study of potential users of the SENPIMAG final product

Technology Watch Reports

A. Patents of Magnetic Sensors made of piezoelectric and magnetostrictive materials

To establish the State of the Art in the field of “*hybrid magnetic sensors based on piezoelectric and magnetostrictive elements*”, INTA made a TWR entitled: “Patents of Magnetic Sensors made of piezoelectric and magnetostrictive materials” in which a systematic search of related patents was performed following the strategy and methodology of the CIMN – *Círculo de Innovación en Microtecnología y Nanosistemas* (Initiative of the Madrid Region – EU Innovation Network). This is an iterative process which is performed until the results are satisfactory (see Fig. 1).

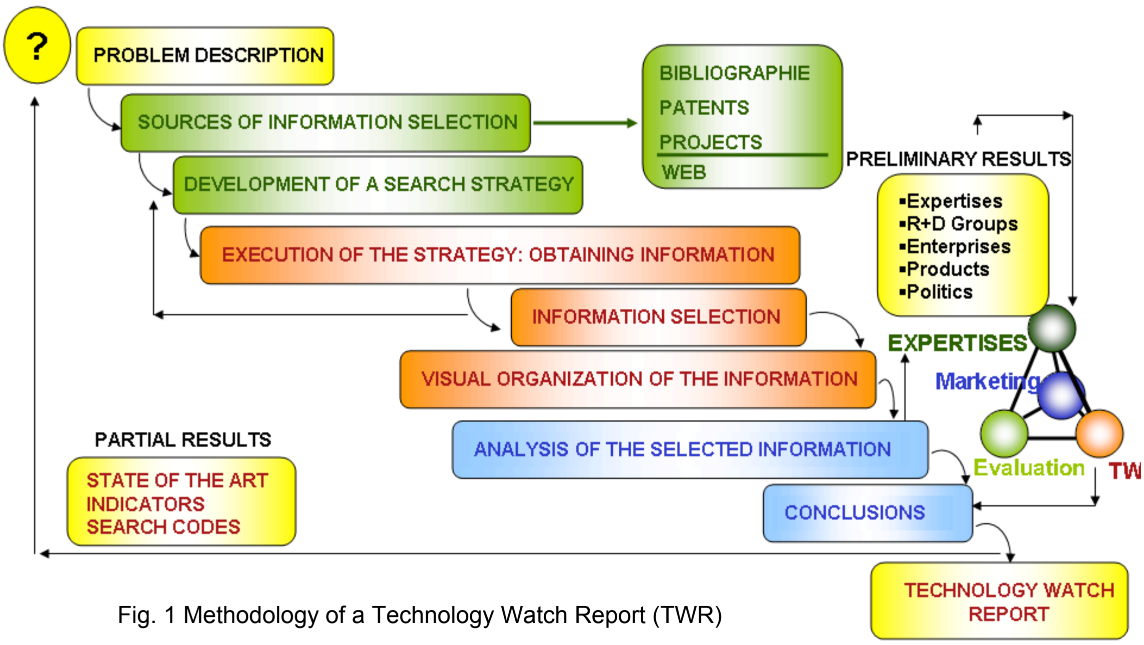


Fig. 1 Methodology of a Technology Watch Report (TWR)

The sources analyzed to carry on this study were:

Europe’s Network of Patent Databases (ESPACENET)

United States Patents and Trademark Office (USPTO)

Japan Patent Office (JPO)

World Intellectual Property Office (WIPO)

Canadian Intellectual Property Office (CIPO)

Derwent World Patents Index (DWPI)

After the analysis and detailed study of the most applicable results, 62 documents were extracted. To make easy their analysis by members of SENPIMAG consortium, these patents were listed in a Table highlighting the following aspects:

Name of the patent with a link to the "full text"

Image of the invention

Brief description of the patent

Use / Application of the patent

B. Magnetic Hybrid Sensors: "Current Line" and "1/4 Resonance Frequency Excitation

A second TWR was developed to evaluate the degree of innovation and the potential patentability of the results obtained.

In this TWR two concepts were searched in previous patents and other works:

The excitation by means of "current lines"

The subharmonic detection so as to minimize the thermal heating

There were 1000 patents analysed and from this analysis it was concluded that both techniques were a novelty for the hybrid sensors under development.

State of the Art in "magnetic sensors"

To make easier the comparative study of the SENPIMAG resulting sensor, INTA developed a list of the magnetic sensors with the most remarkable magnetic properties and the frequent applications.

SENPIMAG sensor would potentially have room in the order of µT range competing in range and resolution with sensors as Hall probes, GMR, AMR, magneto-optical sensors, among other technologies (Fig. 2)

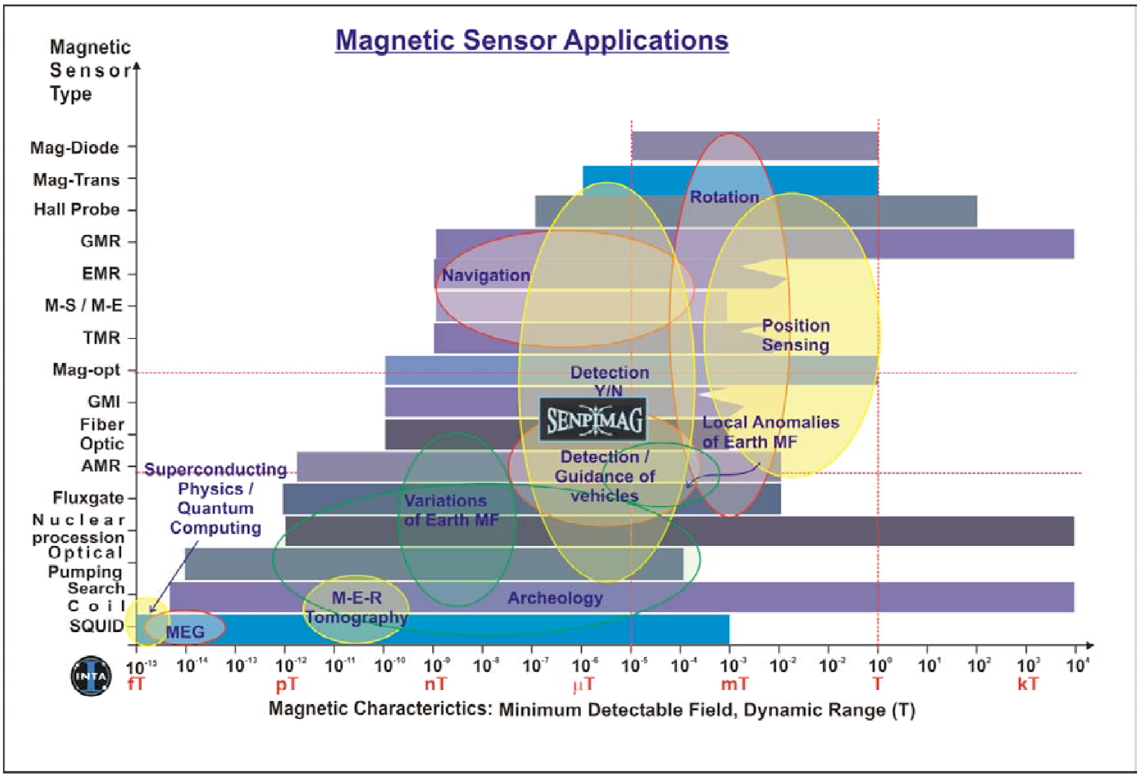


Fig. 2 Magnetic Sensors vs. magnetic properties. Applications

Total energy modelling

The project team has spent considerable time in developing the understanding of magnetic field sensor based on magnetostrictive principles. In particular, attention was devoted to developing models that allow for the calculation of the mechanical stress that is generated when magnetic fields are applied to magnetostrictive materials. We derived a total energy model for the semi-static deformation of this structure and a total energy derivation for a composite magnetostrictive cantilever including a magnetostrictive thin film based on the Stoner–Wohlfarth model.

Integrated device fabrication

Two approaches were adopted based on the same generic device structures.

The piezoelectric approach involves UCAM in the deposition, patterning and annealing of the SBT film, followed by deposition and patterning of insulator structures in SiO_2. The lift-off mask lithography is then performed and sample then shipped to UPM for MS film deposition. The complete structure is then released by etching away the support Si. After careful consideration and discussion the use of wet etching from the back of the Si substrate was agreed as an optimal approach for the release etch of the device bridge structure. However, it was found that with the equipment available it was impossible to align with sufficient accuracy the completed bridge and the etch mask on the wafer back surface. We therefore switched to front-side etching using both chemical and plasma etching techniques.

The experiments based on (Tetramethyl Ammonium Hydroxide) (TMAH) were performed using an oxide mask to protect the device during etching. The high etch rate of the process is beneficial and we measured an average etching rate of ~60 μm/hour on a test sample. However, the process is highly anisotropy and the rate strongly depends on crystal orientation – (111):(100) ~ 1:10 to 1:35 so that to release the suspended structure requires substantial etching times. An alternative approach involved plasma dry etching using a $CF_4 + O_2$ gas mixture. This results in isotropic etching, but requires a metal (Cr, Ni, Al, Au) etch mask to prevent damage to the complete bridge structure. Using this approach a limited number of devices were made available, but these were non-functional due to process-induced damage.

SINTEF have developed a design for the incorporation of a piezoresistive element. The process flow for this devices is shown in Fig. 6. This process is based on the transfer of a Si membrane to a glass carrier wafer by release etching. This membrane has conductor and resistor channels implanted within it for the piezoresistive read-out. The reverse side of membrane forms the substrate for the deposition of the magnetostrictive materials and the current drive lines. Finally, the patterning of the membrane was performed to create free-standing cantilevers overlying the wells in the glass handle wafer.

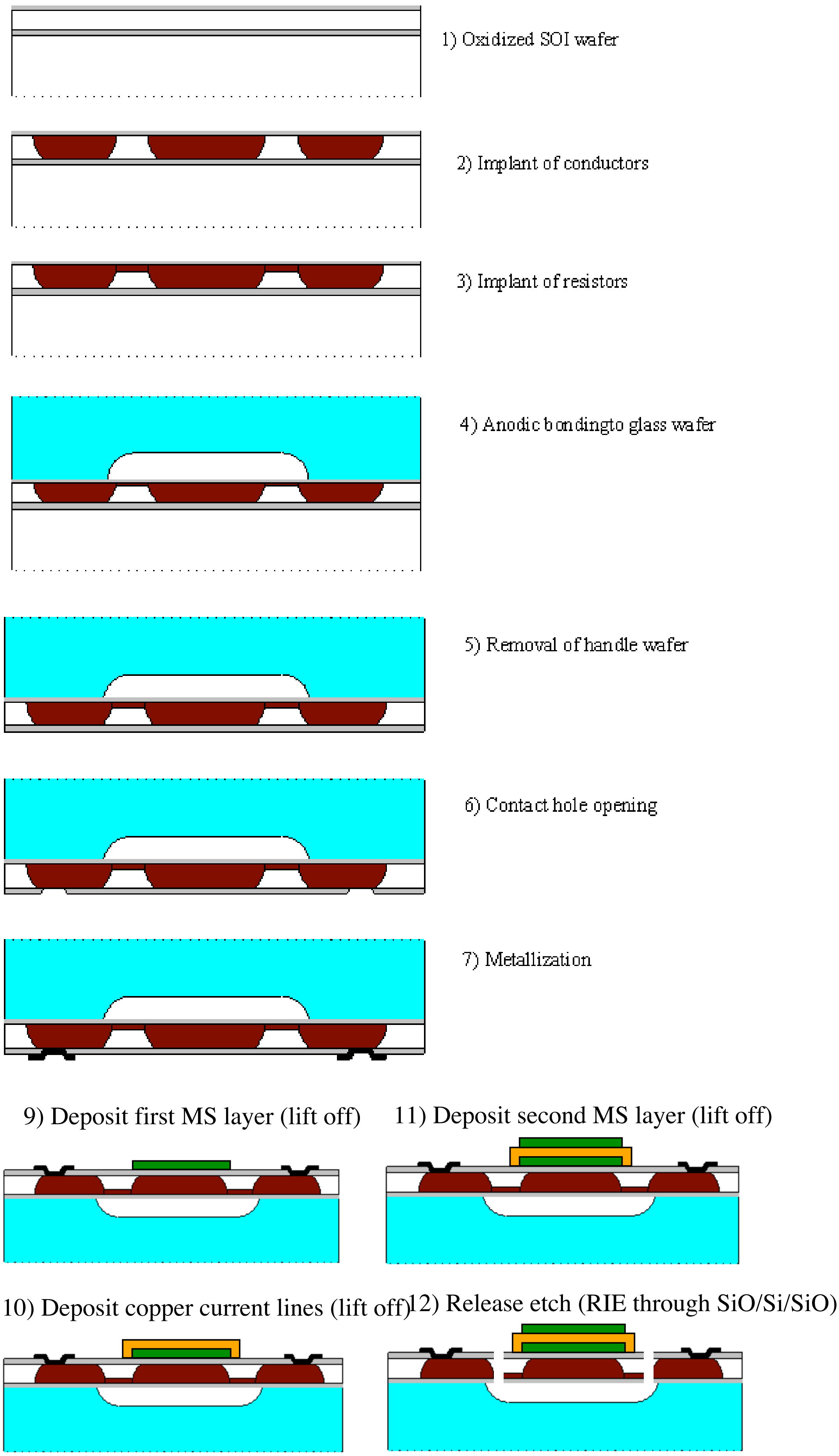


Figure 6. The process flow for the fabrication of the piezoresistive device.

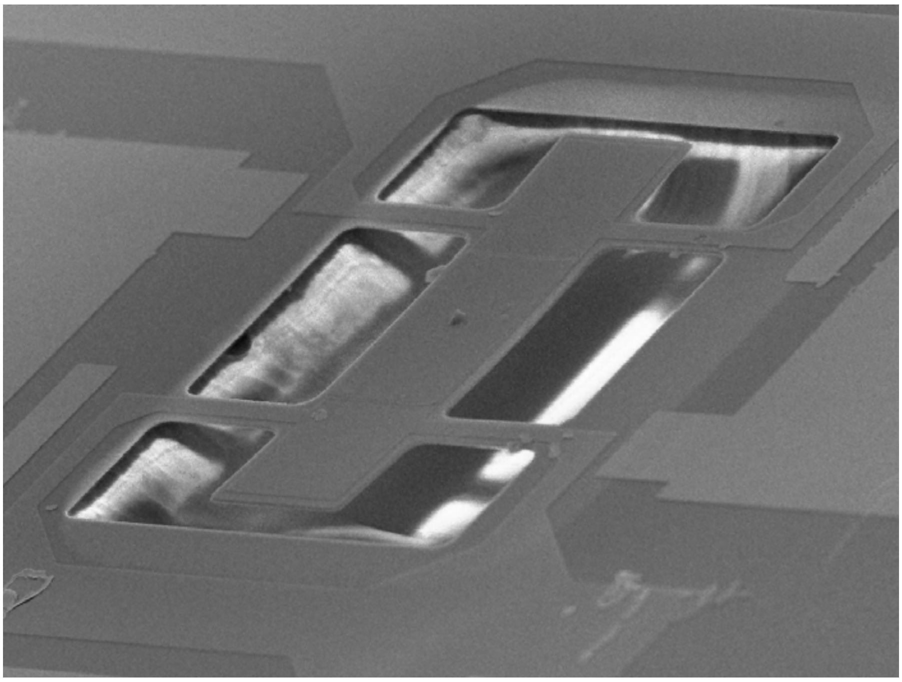
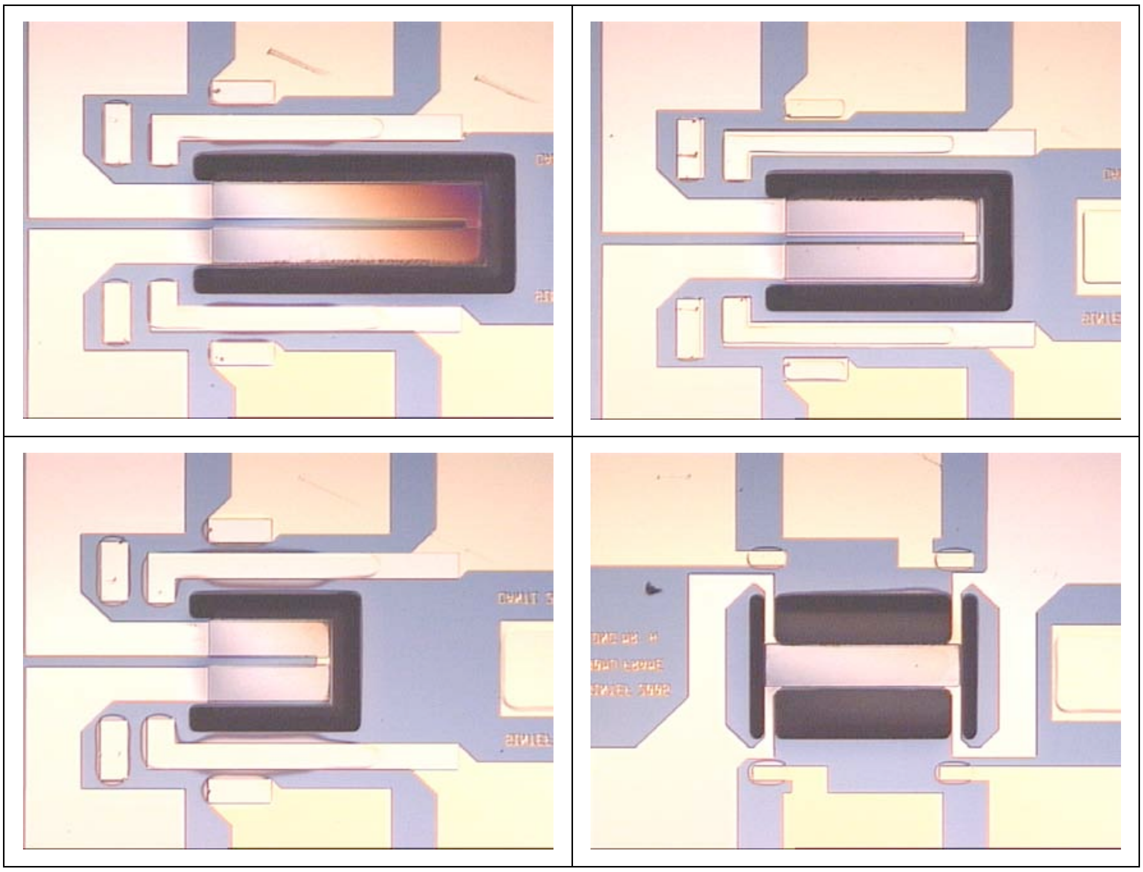


Figure 7 show a scanning electron micrograph of a completed device.



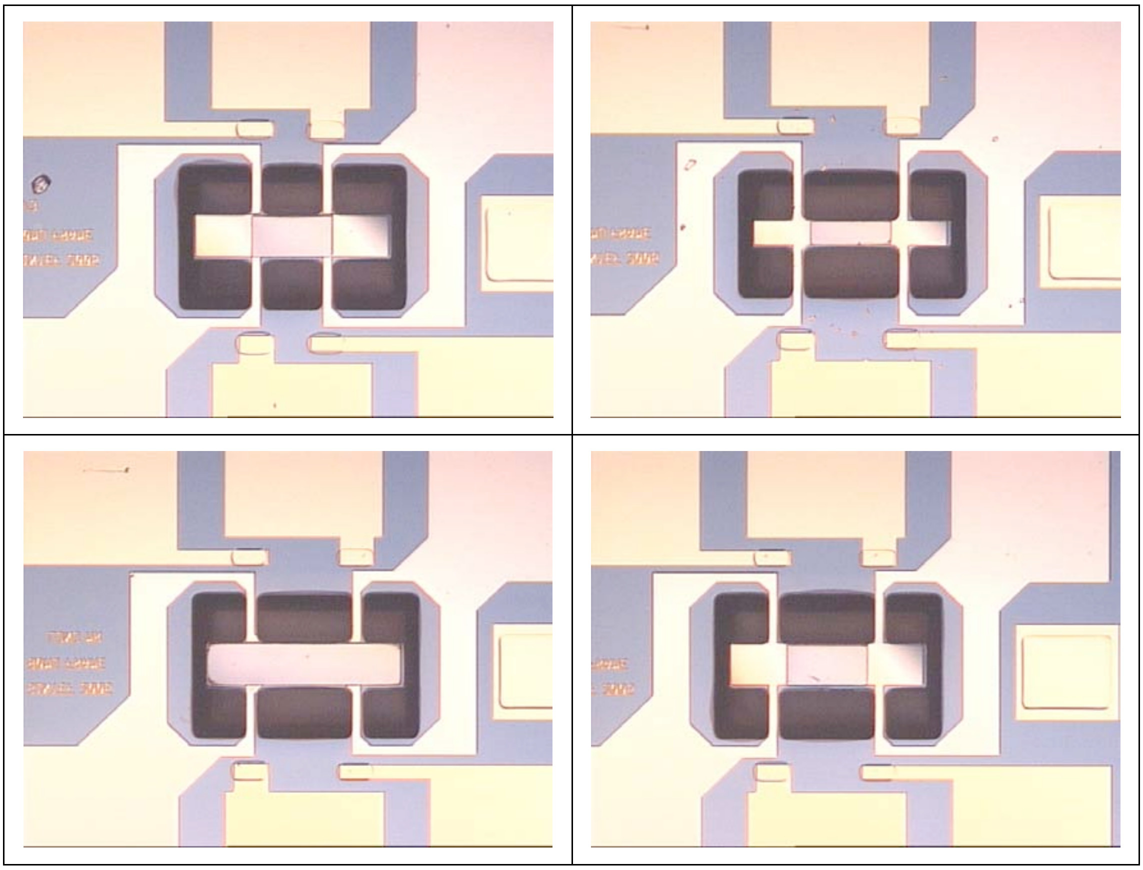


Figure 8 View of the different type of devices.

Device performance and Results

Response at 4f

As it was mentioned before, the thermal expansion caused by the current flowing through the current lines would create a 2f signal (as the dissipated power goes with the square of the current). The best solution would be to excite the sensor at fr/4 and read at fr (resonance frequency). Figure 9 shows the performance of a long cantilever device for both 2f and 4f. As it can be seen the Q-factor at 4f is even better than at 2f, although there is a slight drop in the signal.

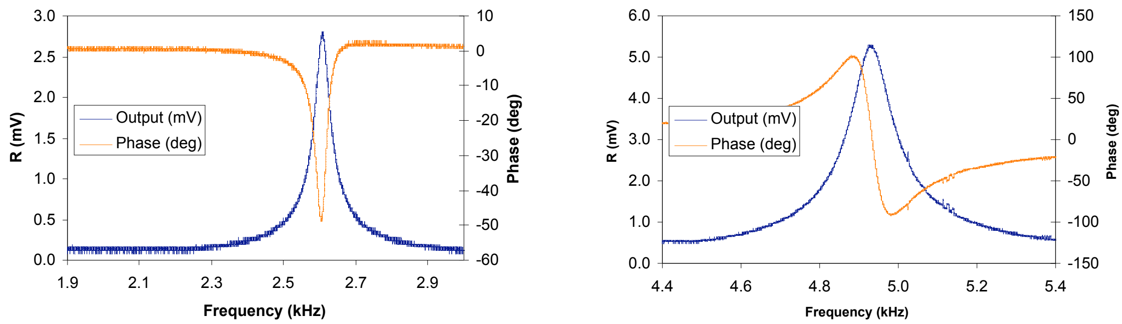


Figure 9. R-Theta response curves for fr/4 (left) and fr/2 (read) excitation.

Operation in Vacuum

The simulations performed by SINTEF showed a predicted improvement in the Q-factor of the sensors on a factor of 100 when operating in vacuum instead. Figure 10 shows the resonance curve for atmospheric pressure and for two different instants after starting the pumping sequence. There is a clear improvement in the response of the device:

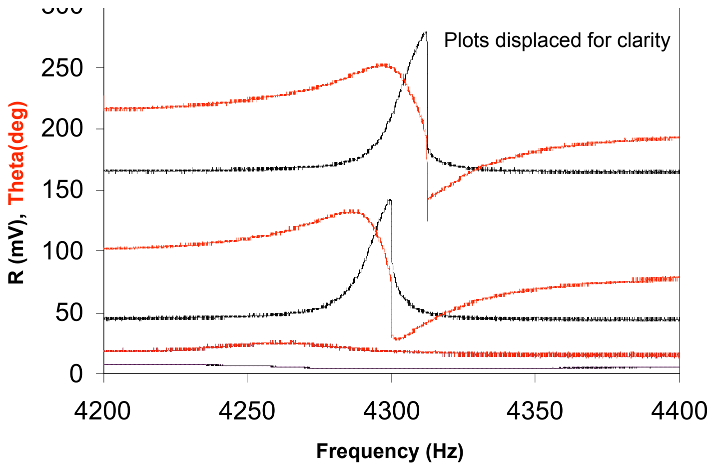


Figure 10. Resonance plots for a standard cantilever (sample SG-13), measured at fr/4. Bottom plots are at atmospheric pressure. Going up the plots for better vacuum.

Certainly, what is important is not the improvement in the Q-factor, but the improvement on the sensitivity of the sensor. Figure 11 shows the comparative performance on a long cantilever on sample SG-11 for vacuum and atmospheric pressure. Note that the signal initially increases for small fields. In this sample the anisotropy axis is perpendicular to the length of the cantilever as an attempt to get the working point at zero field (refer to next sections for comparison with anisotropy along the length of the cantilever).

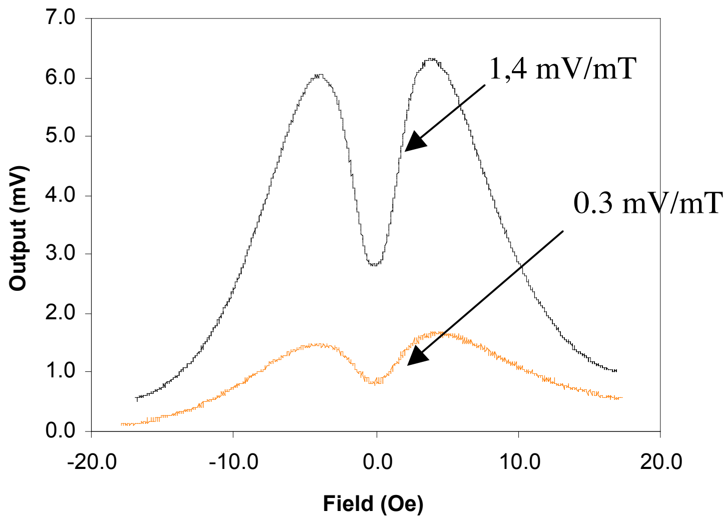


Figure 11. Difference on the response for atmospheric pressure (red) and vacuum (black).

The sensitivity of the sensor only improves by a factor of 4. These plots have been measured exciting with an AC field the cantilever (instead of a current). The can used for the vacuum measurements when exciting with AC field, seals only with vacuum grease, and we believe this might be the reason of the poor improvement of the sensitivity. For current excitation the improvement of the sensitivity is much better (see next section), although other problems with lack of uniform magnetization are present.

Current excitation (current lines)

The current has to be pulsed to avoid heating problems. UPM has developed a pulsed current generator were the pulses are 1μs and up to 1 A. Figure 12 shows the performance of a long cantilever in the sample SG-11 (the plots should be comparable to the black curve in Figure 11).

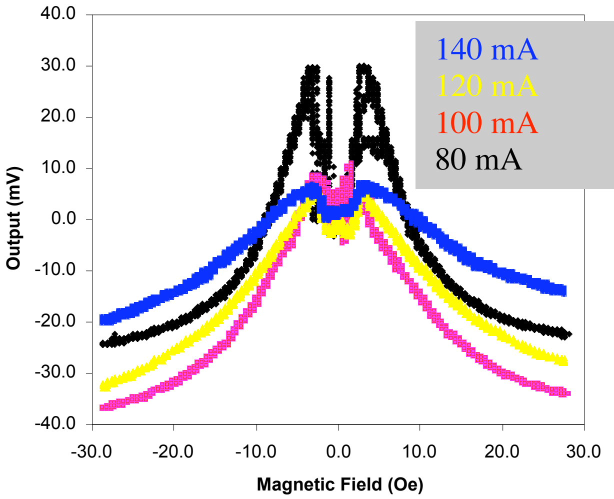


Figure 12. Response of a long cantilever for different current excitation

The first noticeable feature is that 80 mA is enough current to excite the sensor. For larger currents the sensor starts to saturate. Another important point is that the signal is larger for current excitation (figure 12) than for AC field excitation (figure 11). We believe this is due to the better vacuum that can be obtained in the can for the current measurements. It is important to note that the signal around zero field has very noticeable Barkhausen noise. We believe this is due to the lack of uniformity when magnetizing with current lines (effects at the corners etc). Some of the configurations address this problem and we expect better results when these devices are calibrated. No significant heating is measured in the devices.

Anisotropy along the cantilever axis

The typical curve for a sensor when the anisotropy axis is along the cantilever axis is displayed in figure 13. This is the even curve that one could expect from the original design. Obviously, in terms of sensitivity it is better to have the anisotropy perpendicular to the length of the cantilever.

Most of the curves presented in this report are measured for a current flowing through the piezoresistive bridge of about 1 mA. Values larger than 2 mA start to overheat the cantilever. For values smaller than 0.5 mA there is a significant drop in performance.

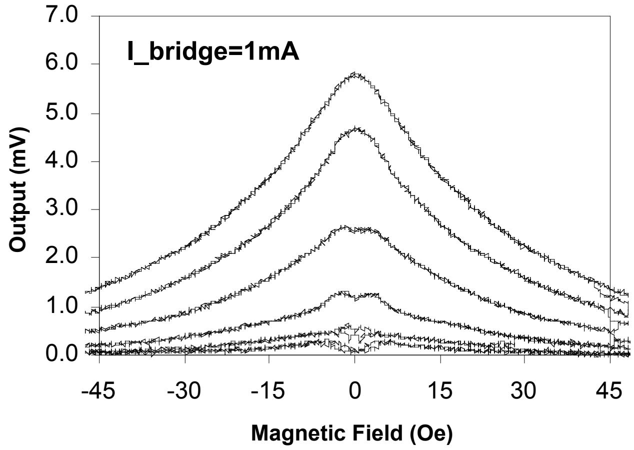


Figure 13. Plots for a long cantilever with the anisotropy along the length of the cantilever. The different plots are for different excitation fields: from bottom to top 24 Oe, 28 Oe, 34 Oe, 41 Oe, 47 Oe

Expected final performance

The values shown in the plots above are the result of the calibration of the first set of devices. They demonstrate the good performance of the current lines, working with pulsed current. This will certainly be of great technological interest. The sensitivity obtained so far is not as good as expected. There are three main reasons for that.

Firstly, the piezoelectric approach could not be realized during the project. A piezoelectric reading should be much more sensitive than the piezoresistive reading. SINTEF is now able to deposit PZT films over Si wafer and they can produce cantilevers from those structures. Some partners within the consortium will collaborate in the future to achieve this approach.

Secondly, the magnetic material drops slightly in performance when deposited over the device (instead over an ultra flat Si wafer). Some more optimization will be required.

Thirdly, the magnetic material has a magnetostriction of 30 ppm. At the moment UPM is working on developing soft magnetic films with larger magnetostriction, based on their results on WP1.

The sensor is even, so it cannot detect the direction of the field unless is biased. Many applications do not require the detection of the direction of field, but rather the amplitude or even just the presence of magnetic field. For applications requiring the detection of the direction of the field, the sensor would have to be biased with a permanent magnet.

The consortium expect to address most of these issues during the next 6 months, before the publication of the results.

Test for Aerospace Applications

INTA developed a planning for sensor testing devoted to up – qualify the sensor for aerospace applications.

The set of tests planned are of two types: an up-screening process to increase the reliability of the sensor and to measure the failure rate, and a vibration test not only for aerospace applications but also applicable for terrestrial vehicle integration.

Fig. 3 shows the up-screening process.

SENPIMAG sensor is a potential sensor for magnetic sensing in small satellites where there is an increasing trend of using qualified COTS – Components Of The Shelf microsensors of low cost and high reliability.

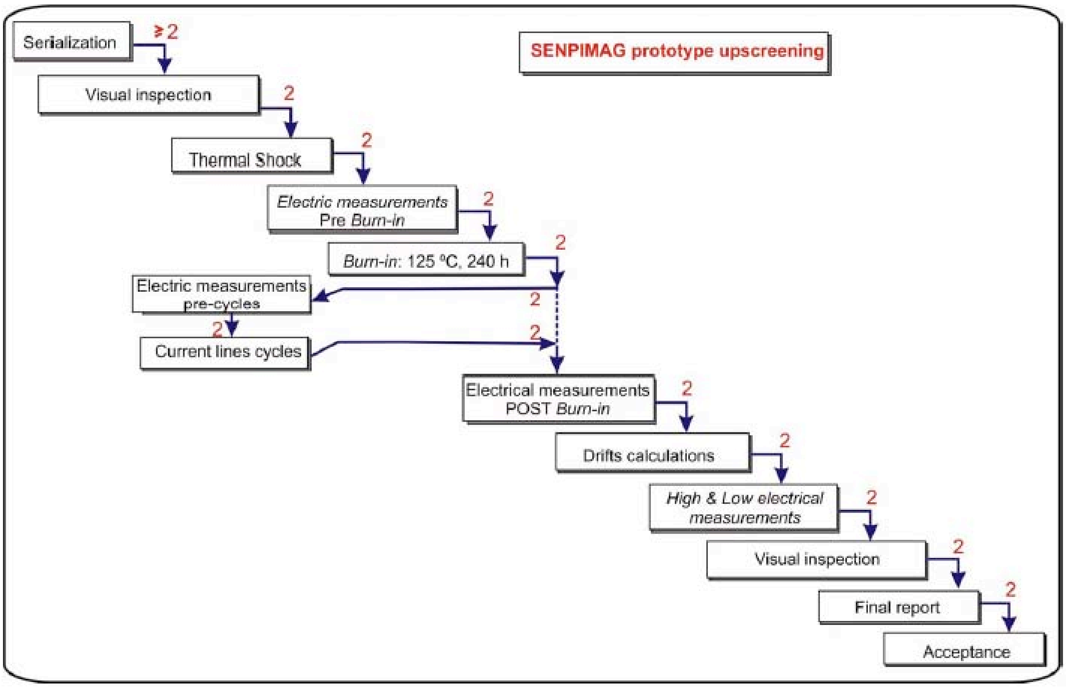


Fig. 3. Up-screening plan

A vibration test was run on a final SENPIMAG sensor. Result was satisfactory.

Fig. 4 shows the setup for the vibration test: the SENPIMAG sensor integrated on a PCB in the vibration equipment for the lateral vibration.

Fig 5 shows the detail of the PCB and the accelerometers on the sample holder.

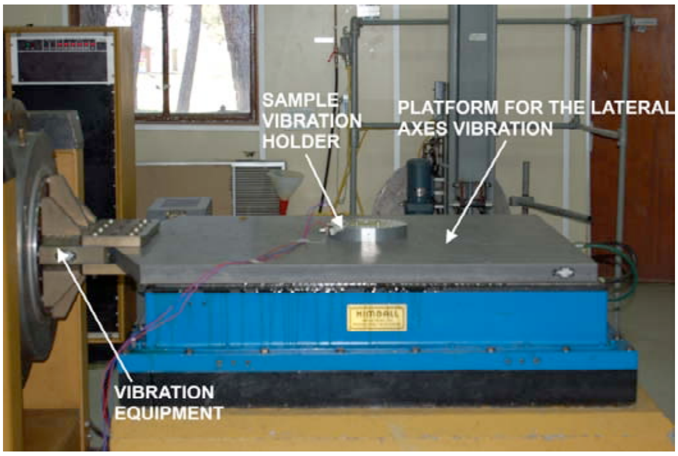


Fig. 4. Setup for the lateral vibration test

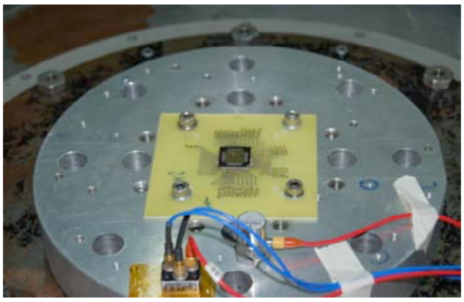
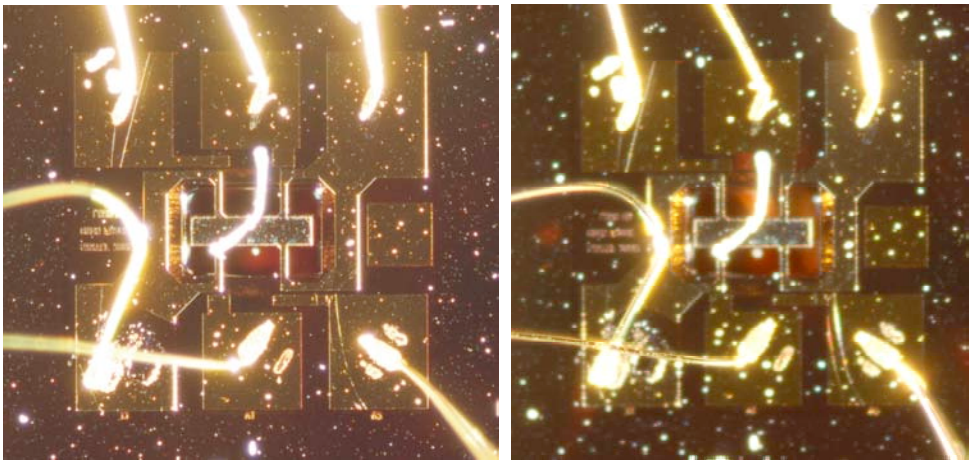


Fig. 5. PCB with the SENPIMAG sensor fixed on the sample holder for the vibration test

Apart from the electrical and magnetic properties of the sensor before and after the vibration test, a visual inspection is performed following the norm ECSS Basic Specification No. 2049000 Issue 2 Nov 2003 to see if the sensor suffered any damage. Fig 6 shows the SENPIMAG sensor before and after the test.



Intentions for use and impact.

An ultra sensitive integrated magnetic sensor is something of major socio-economical interest. Magnetic detection is involved in plenty of the aspects of our modern lives, from detection of metals for security purposes to control and navigation. Improving the performance of a magnetic sensor is always welcome. But most important of all in terms of social impact are the potential applications in which the actual magnetic sensors cannot fulfil the requirements. One of the focuses is medical application where the magnetic fields are in the range of pT. Here, an integrated and extremely sensitive magnetic sensor would be largely interesting. Other point of interest is the identification of vehicles or labels. This could increase the security in big shopping areas or airports for instance.

Providing the expected impact in industry and society, the good perspectives for economic development are quite significant, especially for companies working in magnetic field detection. Our intention to protect the IPR emerging from this project and work with partner organisations to the commercialisation of the technology.

The most clear potential applications are vehicles guidance and “Yes / No magnetic detection”, which are fields of extremely importance with the increase of technologic devices in final products.

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Project website

http://www.msm.cam.ac.uk/dmg/ResearchNew/SENPIMAG/