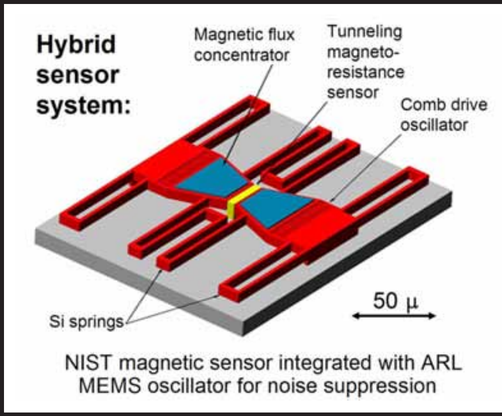
Future Directions for Magnetic Sensors:

Achieving Better Sensitivity, Smaller Size, Lower Cost, & Lower Power Use

Objective

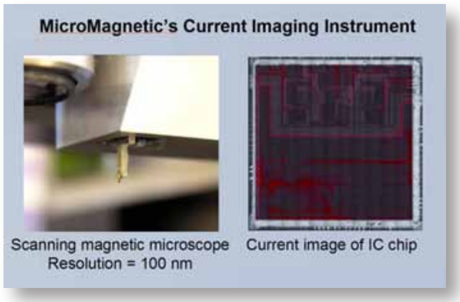
Our goal is to develop the scientific expertise needed to allow modeling and simulation to become the driving force in improving magnetic sensors and to implement the resulting advantages. Our approach permits industry to target its resources with greater effectiveness in developing new and improved magnetic sensors. By quantifying the improvement in sensor performance that will result from design changes or from improved materials properties, our approach reduces guesswork.

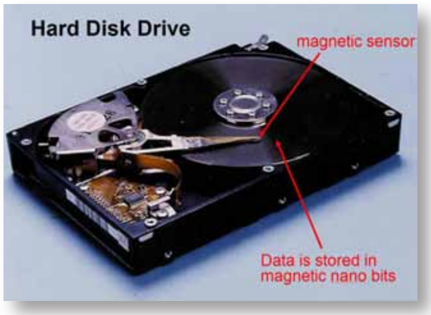


NIST magnetic sensor integrated with ARL MEMS oscillator for noise suppression

Impact and Customers

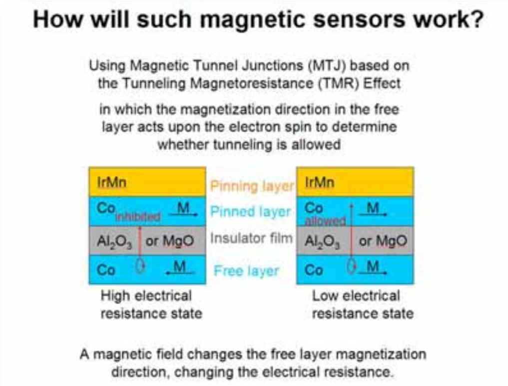
- Magnetic sensors are a $1.2 billion per year market, worldwide, according to Frost & Sullivan.
- The economic impact of magnetic sensors is far greater than their sales volume because they increase economic productivity by playing key roles in data storage in computers, in manufacturing technology, and in health care.
- NIST is providing the scientific research needed to develop and implement a design-software package based on the physics of magnetic sensor operation, to predict real-world performance.
- NIST is leading a team of collaborators that include small companies, universities and national labs to leverage the best facilities, technologies, and personnel for this task.
- NIST interactions with industry leaders such as Seagate, Western Digital, Nonvolatile Electronics, MicroMagnetics, et al ensure that the approach is closely coupled with industrial needs.





Approach

Bringing new or improved magnetic sensors to market requires modeling for rapid assessment of the effect of new designs or improved materials properties. To this end, we are investigating the fundamental properties of a new class of magnetic sensors that is rapidly displacing those based on older technology. The new sensors are based on Magnetic Tunnel Junctions (MTJs), which use the Tunneling Magnetoresistance Effect (TMR). To optimize MTJs, NIST has purchased an instrument that diagnoses the TMR properties early in the fabrication process to maximize efficient use of time. These instruments are not widely available, and NIST is beginning to serve as a clearing house for MTJ testing by offering diagnosis of MTJs from outside groups. The resulting collaborations with small companies, universities, and national labs allow NIST to lead the world in non-proprietary MTJ research. The leverage made possible by these collaborations creates an impact beyond what would be possible if NIST were to operate independently in magnetic sensor research.



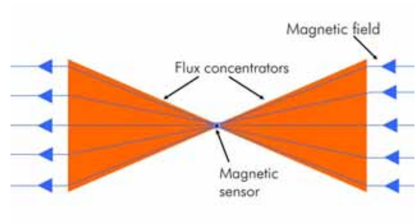
HYBRID MATERIALS

855-11-126

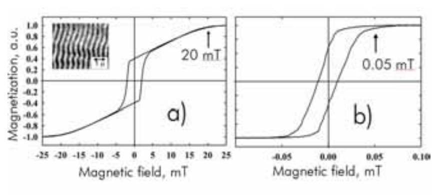
Typical customers:

Accomplishments

Magnetic tunnel junction (MTJ) sensors are rapidly becoming the technology of choice for many magnetic sensor applications. They have the advantages of high sensitivity, small size, low cost, and low power consumption. Often these sensors are used in conjunction with magnetic flux concentrators. These are magnetic thin films designed to concentrate a magnetic field on a magnetic sensor to improve its sensitivity to small fields, as illustrated below.



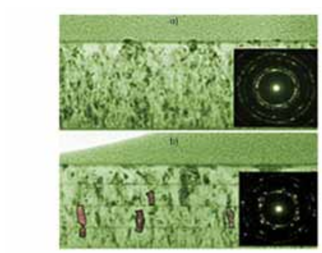
However, two critical requirements of flux concentrators are that they be both magnetically soft and thick enough to absorb a significant fraction of the ambient magnetic field. We have found that when the softest materials are made as thick as they need to be, they are no longer soft. The two figures below illustrate the point.



In a), a continuous film of the softest material (the alloy Ni$_{77}$Fe$_{14}$Cu$_5$Mo$_4$), 400 nm thick, is not fully magnetized until a field of 20 mT is applied. The inset shows the perpendicular stripe domains responsible. In b) the magnetic film is split up into four segments of 100 nm each and separated by a 5 nm Ag film. The result is a 400-fold reduction in the field needed to fully magnetize the film. It is rare to find any magnetic film as soft as the one in b), much less one that is ≈400 nm thick. This result represents an important step forward for flux concentrator technology.

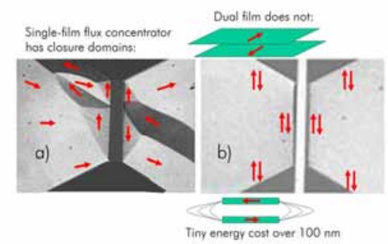
We investigated the films to find the source of the 400-fold improvement. In stress measurements we found the film in a) had a biaxial stress 200 times larger than the film in b). In fact, the stress was about equal to the tensile strength of the material, meaning the stress was as large as it was physically possible for the material to sustain. Plastic flow was setting an upper limit on the stress. It is common in magnetic films that stress induces strongly preferred magnetization directions, and prevents them from being magnetically soft (responding magnetically to small fields). The layering of the film with Ag was relieving the stress.

It was of interest to understand from a materials point of view to see what was happening inside the films to cause such a large effect. The grain structure in the two transmission electron micrographs below tells the story.



In a) the continuous 400 nm film shows many small grains. Small grains are commonly associated with high stress because grain boundary tension acts like a dense network of springs. In b) the Ag interlayers are nucleating significantly larger grains (several are highlighted in color). We now understand that a markedly different type of grain growth is responsible for the effect. This work has just been published in the Journal of Applied Physics, and has been highlighted in a number of publications and newsletters.

Another shortcoming of flux concentrators is that they tend to break up into magnetic domains. The closure domains make flux concentrators hysteretic, which impairs their ability to measure small magnetic fields. They also tend to introduce noise in the magnetic measurements, limiting sensitivity. It does not appear that anyone has previously found a way to deal with these problems. The illustration below shows our solution.



Typical closure domains are illustrated in a single-film flux concentrator in a). Energy considerations drive the formation of these domains. By having the magnetization (red arrows) curve around the edges of the flux concentrator, the magnetic flux that is forced to exit the film into free space is reduced, lowering the magnetostatic energy cost. What is needed is an innovative design to avoid this cost. Our solution is illustrated in b). We have a two layer flux concentrator, with the two layers magnetized in opposite directions. The two closure domains are needed to reduce the magnetostatic energy, which is drastically reduced because flux closure occurs on a length scale of 100 nm. As in the illustration, no closure domains are observed in b), and the flux concentrator operates by magnetization scissoring. Initial tests indicate superior performance for our novel flux concentrator.

Our short-term goals are to transfer these technological advances to the magnetic sensor industry.

Learn More

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Publications

Edelstein AS, Burnette J, Fischer GA, Cheng SF, Egelhoff, Jr. WF, McMichael RD and Nowak ER *Advances in Magnetometry Through Minaturization* J. Vac. Sci. Technol., (in press, 2008)

O SY, Lee CG, Shapiro AJ, Egelhoff, Jr. WF, Vaudin MD, Ruglovsky JL, Mallett J and Pong PWT *X-Ray Diffraction Study of the Optimization of MgO Growth Conditions for Magnetic Tunnel Junctions* J. Appl. Phys., (in press, 2008)

Pong PWT, Dennis CL, Castillo A, Chen A and Egelhoff, Jr. WF *Detection of Pinholes in Magnetic Tunnel Junctions by Magnetic Coupling* J. Appl. Phys., 103: 07A902 (2008)

Sudbrack CK, Chiaramonti AN, Hiller JM, Egelhoff WF and Petford-Long AK *Comparison of the Chemical Heterogeneities and Microstructure Between CoFeB/MgO/CoFeB and CoFeB/Al-O/CoFeB Magnetic Tunnel Junctions* Microsc. and Microanal., 13 Suppl. 2: 620 (2007)