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MICROFLUIDIC MICROSYSTEM FOR MAGNETIC SENSING OF NANOPARTICLES WITH GIANT MAGNETO-IMPEDANCE TECHNOLOGY

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ABSTRACT

We have fabricated a microfluidic microsystem integrating a Giant Magneto-Impedance wire sensor that successfully detected the passage of magnetic nanoparticles in liquid medium. Giant Magneto-Impedance microwire sensors consisted in CoFeSiBNb alloy, 40 μm diameter and 1 cm long wires. By magnetizing the magnetic nanoparticles in the liquid perpendicularly to the sensitive axis of the Giant Magneto-Impedance microwire sensor, we have observed magneto-impedance signal variations induced by the magnetic dipole field from the magnetic nanoparticles. A peak detector was used to measure the voltage signal due to the magneto-impedance variations. The voltage signal was subsequently demodulated by a lock-in amplifier.

KEYWORDS

Giant Magneto-Impedance (GMI), magnetic sensor, magnetic nanoparticles, microfluidic, microsystem

INTRODUCTION

Magnetic labeling with nanoparticles is intensively studied since it can be operated in opaque media and do not suffer from bleaching like fluorescent labeling [1]. Magnetic labeling offers additional functionalities like manipulation (concentration) or treatment (hyperthermia) of the bound biospecies [2]. For all applications, their detection is a key technological bottleneck.

SQUID or fluxgate magnetic sensors are not well adapted for room temperature microsystems format. Spin-valve or Giant Magneto-Resistance (GMR) sensors have been recently integrated in microsystems [3]. Giant Magneto-Impedance (GMI) materials are promising since their sensitivity and noise properties are better than those of GMR sensors [4]. GMI microribbons or microwire have been used for static detection of magnetic nanoparticles [5]. The novelty of this work is to explore the use of GMI microwires for the detection of magnetic nanoparticles flowing in a microfluidic channel.

In this work, the magnetic moment of the magnetic liquid exposed to the magnetization field is sensed by the Giant Magneto-Impedance microwire sensor. The presence of the magnetic liquid modulates the amplitude of the recorded signal. A video camera allows the dating of the passage of the black colored magnetic liquid.

PRINCIPLE OF OPERATION

The basic idea of detecting magnetic nanoparticles in liquid medium is to magnetize the superparamagnetic nanoparticles with a magnetic field and then to detect their magnetic moments by a magnetic sensor as a

Magneto-Impedance microwire sensor. Under the magnetization field H_{magn} , the magnetization of the magnetic nanoparticles in the liquid is given by $M = \chi H_{\text{magn}} [A.m^2]$, where χ is the susceptibility of the magnetic nanoparticles in the liquid. The magnetization of the liquid sample induces a magnetic induction at a point P of the space which maximum can be expressed by

$$B_{r_{\text{max}}}(P) = \frac{\mu_0 \chi H_{\text{magn}} V}{4\pi d^3} [T]$$

where V is the volume of the magnetic liquid and d is the distance between the point P and the magnetic liquid.

In order to sense the field induced by the magnetic liquid the magnetic sensors are placed perpendicularly to the magnetization field. This enables a higher measurement dynamic and prevents the saturation of the magnetic sensor. However, it requires a precise mechanical positioning of the sensor so as to zero the response in the absence of nanoparticles. This perpendicular configuration is illustrated in Figure 1.

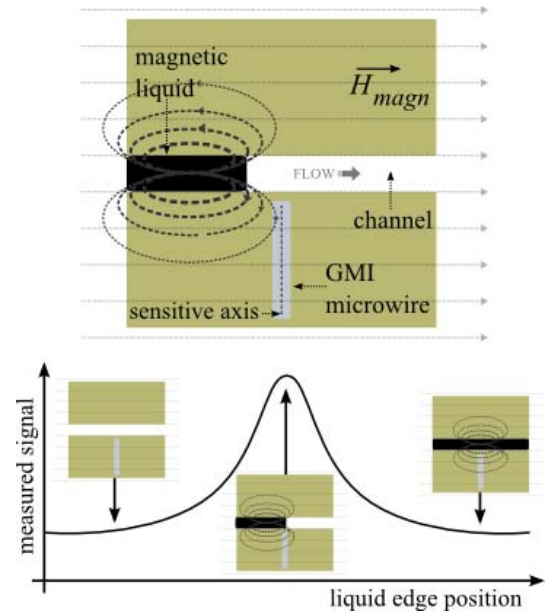


Figure 1: Principle of the detection of the magnetic nanoparticles. The external field, H_{magn} , magnetizes the magnetic liquid, which is sensed by the GMI microwire sensors. The amplitude of the measured signal varies according to the position of the magnetic liquid in the channel.

The amplitude of the sensed field varies according to the position of the magnetic liquid into the channel as illustrated in Figure 1. When the liquid flows into the channel, the sensed signal increases up to a maximum corresponding to the position of the edge of the liquid in front of the magnetic sensor (in our case the GMI

microwire). Then, the signal decreases due to opposite contribution of the parts of the liquid across the axis of the magnetic sensor. In this work, we have used an external AC magnetization field.

EXPERIMENTAL SET-UP

Figure 2 shows the schematic diagram of the set-up. It consists in four main parts

- the microdevice part,
- the magnetic excitation and measurement part,
- the data acquisition part,
- the microfluidic part.

Those parts are successively described in this section.

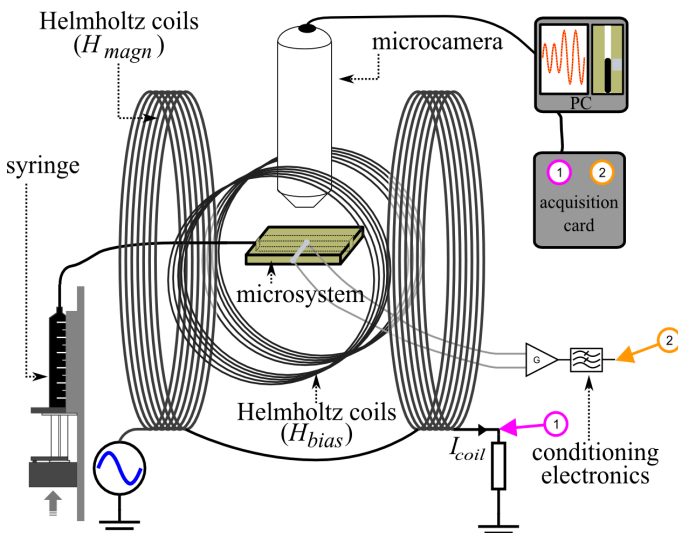


Figure 2: Schematic view of the general experimental set-up. The GMI microwire senses the magnetic field produced by the magnetic liquid. A video camera records the displacement of the liquid in the channel induced by a syringe pump.

Microdevice

Description

The microsystem is fabricated using standard microtechnologies and is composed of three elements (Figure 3).

- Microchannel (2 inlets/2 outlets) used to deliver magnetic particles to the GMI sensor area. The microchannel is connected to glass capillaries.
- GMI microwires inserted in trenches, perpendicularly to the microchannel. The distance between the sensor end point and the channel is close to 40 μm .
- Gold electrodes electrically connected at each end of the GMI microwires. They are used for acquiring electrical response of GMI microwire sensor versus magnetic field when the magnetic nanoparticles are flowing in the microchannel.

Microfabrication process

A 3 inch double polished wafer of intrinsic silicon is cleaned by a piranha solution (mixture of sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2), v:v 1:1). Silicon Nitride (300 nm) film is deposited by low pressure chemical vapor deposition (LPCVD) technique. Ti/Au (30/100 nm) film is deposited by sputtering on this SiN

film. The Ti/Au electrodes are patterned by lithography followed by lift off. AZNLOF2020 negative photoresist is used for the lithographic step. Therefore, silicon nitride film is used as insulator and avoids leakage currents between each electrode (Figure 4.a).

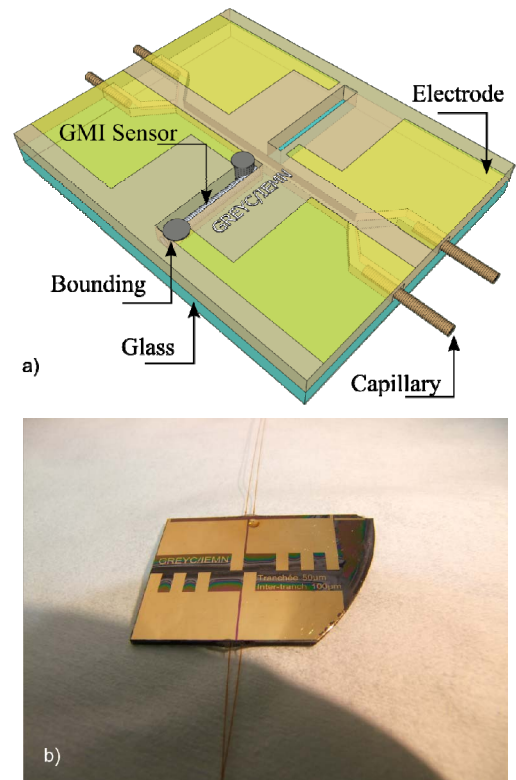


Figure 3: Schematic and picture of the microfluidic microsystem.

On the back surface of silicon, aluminum film (100 nm) is patterned by lift off process using AZNLOF2020 photoresist in order to define the channel part of the microsystem (Figure 4.b).

The third lithography step (Figure 4.c) consists in coating and developing 8 μm thick AZNLOF2070 photoresist. Then, wet etching (H_3PO_4 at 60°C) of unprotected aluminum is carried out in order to have access to the silicon substrate before deep reactive ion etching (DRIE) etching.

Thereafter, first DRIE step using Bosch process (STS equipment) is used to etch the two trenches in the microsystem as shown in Figure 4.d). The thickness of silicon etched during this first DRIE step is equal to the thickness of the silicon wafer minus the thickness of the microchannel. Then, the remaining photoresist mask (AZNLOF2070) is removed thanks to remover 1165 (Microposit).

A second DRIE step finishes the etching of the two trenches and creates the microchannel (Figure 4.e). After that, wet etching of aluminum is performed to remove the physical mask and to prepare the micro-machined silicon substrate for the bonding step.

Pyrex (700 μm thick from Neyco) is cleaned by a piranha solution. The two substrates are bonded using a thin buffer layer (2 μm thick) of Benzocyclobutene (BCB) at 150°C for 5 min. A pressure of 2 bars for 1 hour at 130°C is applied and the bonding process is completed

by curing the BCB at 200°C (Figure 4.f).

The final microsystem dimensions are 2×2.5 cm² after cutting with a saw equipment (Kulicke and Soffa). Finally, GMI sensor is bonded with a conductive epoxy and flexible fused silica capillary tubing (internal diameter: 75 μm, external diameter: 150 μm) are fixed by epoxy.

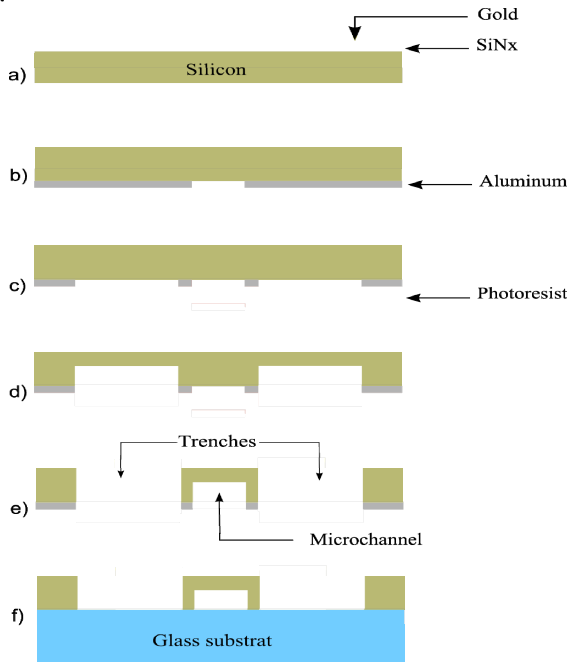


Figure 4: Microfabrication process. a) Deposition of thin films [Si_xN_y (300 nm) / Ti (30 nm) / Au (100 nm)] and patterning of electrodes; b) Deposition and patterning of Al (100 nm) to define the microchannel geometry (H_3PO_4); c) Definition of the geometry of the trenches (for accurate GMI microwires positioning) with photoresist; d) DRIE etching of silicon for trench formation; e) DRIE etching of the microchannel and the remains of the two trenches; f) Bonding of Pyrex and Si micromachined structure by BCB.

Magnetic excitation and measurement part

The microfluidic microdevice is placed between two sets of Helmholtz coils (Figure 2). The first set of Helmholtz coils is parallel to the sensitive axis of the GMI microwire sensors while the second set is perpendicular to the sensitive axis.

The first parallel set of coils defines a proper working point for the GMI microwire sensors by applying a DC bias field, H_{bias} . The bias field was around 40 A/m depending on the GMI microwires.

The second set of Helmholtz coils perpendicular to the sensitive axis of the GMI microwire generates the AC field H_{magn} that magnetizes the magnetic liquid in the channel. The frequency of the AC field, H_{magn} was 6 Hz and its amplitude 1034 A/m. The frequency of the magnetization field H_{magn} is restrained by the bandwidth of the set-up used (180 Hz).

Resistor placed in series in the Helmholtz coils circuit enable the monitoring of the bias and the magnetization fields through the measurement of the current flowing in the coils. The GMI microwire sensors are inserted into a diode rectifier demodulation circuit presented in detail in [6]. The amplitude variations involved by the magnetic

liquid displacement are demodulated with a lock-in amplifier (SR850 Stanford Research Systems) whose post-detection bandwidth is set at 260 mHz.

Data acquisition

A National Instrument© acquisition card (NI-USB-6251) coupled to a Labview© interface on a computer is used for the recording of the output of the lock-in amplifier and of the current flowing into the magnetization Helmholtz coils. The computer also hosts an USB microscope to record the displacement of the magnetic liquid into the channel.

Microfluidic circuit

The flexible fused silica capillary tubing of the device are connected to a syringe containing the magnetic liquid at one end and set free at the other end. The syringe was either pumped back-and-forth manually or with a syringe-pump.

Two types of magnetic liquids were used (1) ferrofluid from Ferrotec© and (2) dispersed suspension of magnetic nanoparticles BioMag® from PolySciences©. The nanoparticles in both liquid media are considered as a magnetic dipole, and their susceptibility were experimentally found to be around 0.5 and 0.025 for ferrofluid and BioMag® beads, respectively.

Experiments were performed in the GREYC magnetically shielded room and at room temperature.

According to the geometry of the device developed in this work, the amplitude of the external applied field and the susceptibility of the magnetic liquid samples used, the expected magnetic induction scales between few nano-Teslas to several tens of nano-Teslas for the volume of the channel around 100 nl (170 μm×70 μm×1 cm). The GMI wire were approximately 1 cm long; therefore in first approximation, the distance between the equivalent punctual sensor and the channel was 0.5 cm. Previously performed macroscale experiments, using 250 μl ferrofluid samples, lead to the assumption that the equivalent punctual sensor for the GMI microwire sensor correspond to its center.

RESULTS

At first, experiments with non-magnetic liquid were performed to discriminate any pressure or magnetic noise contribution to the recorded signal. Non-magnetic liquid passing in the channel did not produce any significant signal. Afterwards, experiments with magnetic liquid showed correlation between the sensed magnetic signal and the position of the magnetic liquid in the channel while the liquid was drawn and withdrawn. Figure 5 shows a recorded measured signal during a 150 s long experiment with five complete draw and withdraw of the magnetic liquid in the microdevice. The measured signal is rising when the edge of the magnetic liquid in the channel is approaching the GMI microwires. This particular position corresponds to the maximum signal configuration (*cf.* Figure 1). Hence magnetic liquid flow

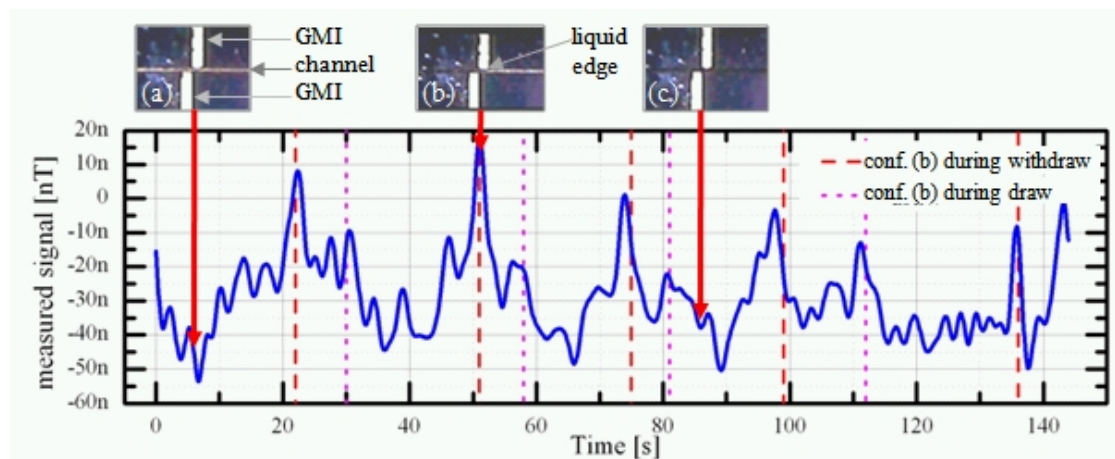


Figure 5: Measured magnetic signal during successive draw and withdraw of the ferrofluid in the microfluidic channel (in a 260 mHz post detection bandwidth). The pictures extracted from video recording illustrate 3 typical configurations: empty channel (a), half-filled channel (b), full channel (c). The instants of passage of the edge of the liquid in front of the two GMI sensors, corresponding to the configuration of the inset fig (b), are represented by dashed lines. The measured magnetic signal is maximum when the edge of the liquid is in front of the GMI sensors.

into the microchannel is detected. The amplitude of the maximum is different depending on whether the magnetic liquid is drawn or withdrawn. The amplitude maximum during the draw is lower than the amplitude maximum during the withdraw phase. This can be explained by the speed difference of the magnetic liquid in the channel depending on draw and withdraw action. Draw speed imposed by the pumping system is quicker than the withdraw speed that depends on the microchannel geometry. Consequently, this speed difference (300 nl/s and 90 nl/s during draw and withdraw respectively) induces an amplitude difference because of the experimental set-up overall bandwidth (260 mHz). The sensed signal during draw is more filtered than the one during withdraw. Those first results confirm the basic detection capabilities of the system.

DISCUSSION

Three main limitations were observed during this first experiments dealing with the detection of magnetic liquid into a microchannel using GMI technology: (1) The limited bandwidth of the magnetization coils leads to working points in $1/f$ noise regime of the GMI sensor; the limited bandwidth also filters part of the signal. (2) Experiments revealed that the distance between the end of the GMI wire and the channel was not the key parameter, instead of that, the distance that should be taken into account is the distance between the middle of the GMI wire and the channel. (3) The GMI wire did not work at their optimum detection potentialities, possibly because of bonding conditions. The maximum GMI sensitivity was only 500 V/T while it can be 10 to 20 times higher [6], similarly the noise level recorded were two orders of magnitude worse than expected.

Hence potential improvements exist. Future will involve new and smaller magnetizations coils so as to reach higher frequency and hopefully the white noise regime of the GMI sensor. The magnetization field might also be increased up to 10 mT which is still below the

saturation of the magnetic fluids. The signal-to-noise ratio will be enhanced and consequently the detection limit.

Finally new bonding techniques will be tested. In those conditions, a one thousand improvement gain is expected at least for the signal-to-noise ratio. This would scale down the detection volume below 100 pl, i.e. a $(50 \mu\text{m})^3$ volume.

CONCLUSION

We fabricated a microfluidic microsystem integrating a GMI wire sensor and demonstrated that this device has successfully detected the passage of magnetic nanoparticles in liquid medium. The identification of the actual limitations opens the door to major improvement in the signal-to-noise ratio of the experimental set-up and therefore to a more sensitive detection of magnetic nanoparticles in microchannels.

REFERENCES

- [1] L.L. Vatta, et al., "Magnetic nanoparticles: Properties and potential applications", *Pure Appl. Chem.* Vol. 78(9), pp. 1793-1801, 2006.
- [2] M. Kettering, et al., "Magnetic nanoparticles as bimodal tools in magnetically induced labeling and magnetic heating of tumour cells: an in vitro study", *Nanotechnology* Vol. 18, 175101, 2007.
- [3] G. Li, et al., "Detection of single micro-sized magnetic bead and magnetic nanoparticles using spin valve sensors for biological applications", *J. Appl. Phys.* 93(10), pp. 7557-7559, 2003.
- [4] G.V. Kurlyandskaya, "Giant magnetoimpedance for biosensing: advantages and shortcomings", *J. Magn. Magn. Mat.* Vol. 320, pp. 659-662, 2009.
- [5] H. Yang, et al., "Giant magnetoimpedance-based microchannel system for quick and parallel genotyping of human papilloma virus type 16/18", *Appl. Phys. Lett.* Vol. 97, 043702, 2010.
- [6] A. Boukhenoufa, et al., "High-sensitivity giant magnetoinductive magnetometer characterization implemented with a low-frequency magnetic noise-reduction technique", *IEEE sens. j.*, Vol. 5(5), pp. 916-923, 2005.