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MAGNETIC NANOWIRE BASED SENSORS

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The paper describes a challenge of innovation in the field magnetic sensing devices. The main idea is the use of magnetic nanowires as sensors for electric or nonelectric quantities. Two main problems have to be solved: contacting the nanowires and their reduced sensitivity. Thus, custom templates are obtained using an ion microprobe or a single ion irradiation facility to irradiate polycarbonate foils. After etching the ion tracks and after filling the resulting nanopores with desired metals, contacts are added using sputtering through masks or etching the previously Cu deposited layer like in PCB. Using nanowires as sensitive elements the achievement of two sensors will be demonstrated: a current sensor using single nanowire and an angular sensor using two technical solutions. The current sensor will be based on a single nanowire embedded in a polycarbonate (PC) foil. The angular sensor uses 8 magnetic nanowires or groups of nanowires connected in parallel, equidistant placed on a circle and connected in two Wheatstone bridges.

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1. Introduction

Nanowires raise continuously the interest of researchers during the last two decades because of specific properties induced by their reduced dimensions [1-5]. Multiple applications can be found in sensor's construction as highly sensitive elements or in electronic circuits (memories) [6-8]. Various materials are used for their growth: metals, semiconductors, polymers. There are two basic approaches used for synthesizing nanowires: top-down and bottom-up. The first approach starts from bulk material which is cut down using ion beams, lithographical processes or similar techniques. In the second approach the nanowires are grown using electrodeposition from liquid solutions or chemical vapor deposition (CVD). The synthesis from solution is more advantageous because it can produce large quantities of nanowires with relatively low cost and inexpensive infrastructure. While vapor growth is used mainly for semiconducting materials, the deposition from solution is employed for both metallic and semiconducting structures.

Due to their small dimension (1000 times smaller than the human hair) providing nanowires with electric contacts is a difficult task. Nowadays many nanotechnological research centers employ nanomanipulators associated with scanning electron microscopes (SEM) and with focused ion beam devices (FIB). They are very expensive and the nanomanipulation of nanowires is time consuming because of the 2D imaging. Moreover the techniques are suited for serial fabrication and not for high throughput production.

For metallic materials electrodeposition from a salt solution using a template represents an attractive alternative. The template allows a precise control of geometry, nanoporous membranes with cylindrical pores being employed for the task. The most common template is the anodic alumina. Such alumina nanoporous membranes are prepared by a simple anodization process, the geometrical characteristics of the pores being easily controlled [9]. Although it allows mass production of nanowires, the template is difficult to dissolve afterwards in order to get access to individual nanowires. A second type of template often used for fabricating nanowires is the so called ion track polymer membrane. This is prepared by swift heavy ion irradiation of polymer

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foils and subsequent etching of the ion track [10-12]. Further electrochemical deposition is employed for easily filling the pores of the membrane with the desired material either metals such as copper, nickel or cobalt or with semiconductors such as CdTe or ZnO [13-18].

The present paper describes our results for the complete processes, from polymer irradiation to electronic circuitry for obtaining two types of magnetic field sensors using ion track membranes as templates.

2. Experimental

2.1. Polymer irradiation

The films of polymer are irradiated at a heavy ion accelerator facility (figure 1). The ion passing through a polymer breaks the polymer's chains along the path. Heavier are the ions, greater are the damages, better the ion track there are.

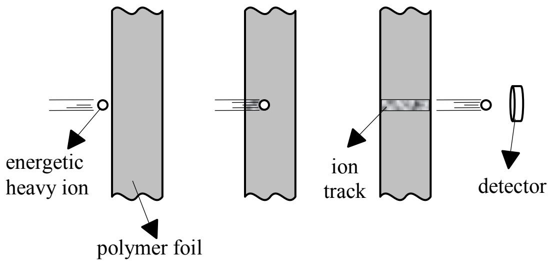


Fig. 1. Heavy ion piercing a polymer foil and producing latent ion track.

Unlike anodic alumina template which offers only a high number of hexagonal prisms templates to be filled, ion tracks can be etched under different conditions in order to obtain various shapes: cylindrical, conical or double conical and cigar like [Man et al. 2007)]. Ion tracks can be obtained in various densities, from $10^4/cm^2$ to $10^7/cm^2$ using just a Faraday cup as ion detector. Knowing the ion charge, the irradiation can be stopped when the desired density is reached. Using electronic systems a finite number of ion tracks can be obtained [Fischer (1988)], starting from one to several hundreds. If the tape can be precisely moved a regulated pattern will be obtained (figure 2).

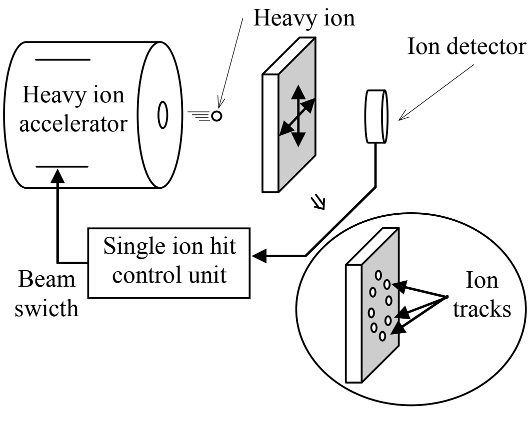


Fig. 2. Regular pattern with ion tracks obtained by moving the polymer in front of the ion beam.

Another solution is to deflect the beam using an ion microprobe [Fischer (1988)] (figure 3). It has a resolution of less than 1μm, but it can not cover a large area (less than 1mm). For larger movements an XY stage must be used.

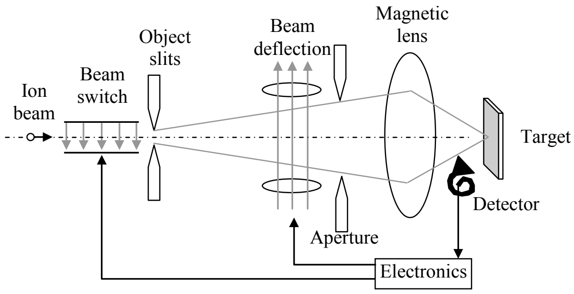


Fig. 3. Microprobe schematic diagram.

2.2. Nanowire preparation and contacting

Contacting the nanowires is very tricky. Their reduced dimensions and fragility constrain to careful manipulation and processing.

When the template is anodic alumina, for contacting the nanowires, the template must be etched away to open the access at the nanowire's ends. This process leaves the film unprotected and fragile and it is unsuitable for device fabrication. There are two options: to dissolve the template and to place them on the circuit using nanomanipulators or to grow the alumina substrate on a silicon wafer [Rabin (2003)]. First option needs expensive equipment and is time consuming resulting in a solution not usable for mass production. The second option gives the necessary rigidity for manipulation but only a group of nanowires can be contacted.

The ion tracks technique enables to obtain single or regular patterns in which the nanowires can be grown. Afterwards they can be contacted while they are still embedded in the polymer.

The process of preparing the template and electrodepositing the nanowires is presented in figure 4. The process starts with a layer of Cu sputtered on one side of the polycarbonate foil. This is used as a base for the backside copper layer (10μm) which is electrodeposited from solution. Latter-on the copper layer will be used as backside electrode for etching and for the electrodeposition process and will ensure the rigidity of the sensor. In the next step the foil is inserted in a double compartment electrochemical cell for the etching process and one of the cell's chambers is filled with NaOH solution at 50 ◦C (5M NaOH 80% vol. and methanol 20% vol.) [Enculescu et al. (2007)]. During the etching the voltage applied over the cell is a square wave with 0.1V amplitude and frequency 0.1Hz. The etching process is stopped when the desired diameter of the nanopore is reached. This is linear dependent with the current through the cell. The pore structure is conical, but cylindrical structure can be also obtained when etching from both sides. Next, the etchant is removed and the camber is filled with the electrolytical bath containing the salt of the metal to be deposited. The magnetic nanowires used as sensible elements have a multilayered structure with alternative Cu and Co layers which will enable a GMR effect in the nanowire. Thus, the solution consists of 360 g/l $CoSO_4 \cdot 7H_2O$, 10 g/l $CuSO_4 \cdot 5H_2O$, 35.4 g/l H_2SO_4 and 40 g/l H_3BO_3 (i.e. $[Co^{2+}]:[Cu^{2+}]=32:1$) [Enculescu et al. (2007)]. In order to get a multilayered structure a pulsed voltage will be applied between the back electrode (copper layer) and the working electrode immersed in solution. The nanowire structure starts with Cu, followed by a sandwich of 1000 Co/Cu layers and another Cu piece at the other end. The process is stopped after a mushroom is grown on top of the polymer. In the next step, the foil is removed from the cell, and a copper layer is sputtered through a mask in order to ensure the top side contacts. The bottom side is covered with photoresist and after UV exposure through another mask, the exposed photoresist is removed and the copper layer is etched away. In the end only the desired tracks that contact the nanowires remain on the bottom side.

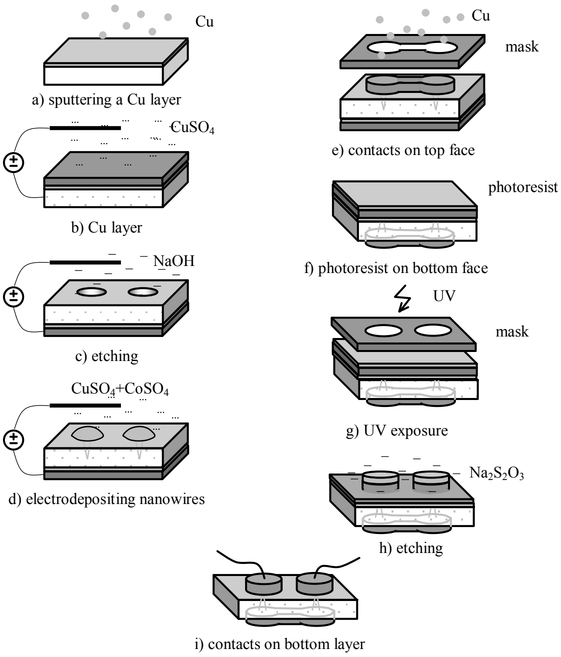


Fig. 4. The technological process for sensor development.

When a sample with a single or a regular pattern is processed, the masks must match the nanowire positions (figure 5.a). This can be done using alignment markers on the sample. These markers are used for the alignment of the masks between them. When the sample has random spread ion tracks (figure 5.b) only the alignment between masks must be fulfilled.

3. Results and discussion

In the following two innovative applications of the magnetic nanowires and contacting process above is described: a current sensor based on a single homogeneous nanowire and an angular sensor based on a matrix of GMR nanowires.

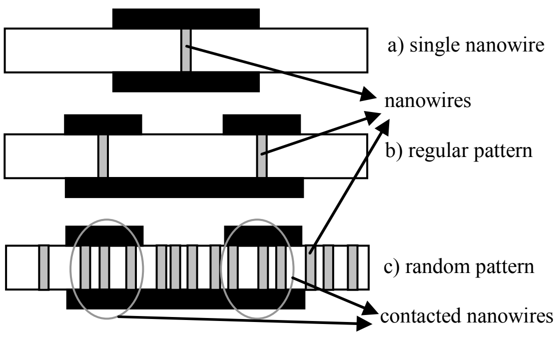


Fig. 5. Possible nanowire configurations.

A sample having a single ion track is very simple to process. Only the steps “a” to “e” from figure 4 must be accomplished. Adding the contacts leads to a parasitic capacitance in parallel with the wire. At 5MHz its impedance is negligible beside the wire impedance.

The sensitive element is fixed into an airgap of a magnetic core. The current to be measured will pass thrugh the hole in the core. Because the response curve is nonlinear and non-monotonic with the magnetic field [ ], the sensor must be linearized and the working point must be shifted. Thus, it is connected in the loop of a single transistor oscillator. The output signal is fed into a phase locked loop (PLL), at its output resulting a voltage proportional with the input frequency. After amplification and after adding an offset voltage it drives a coil, mounted on the magnetic core. The feedback field will translate the working point of the nanowire in the middle of the cuasilinear region and will extend the input domain (figure 6) [Zet et al. (2006):

$$B_r = K_B[U_{REF} - K_U(f - f_0)]$$

The total magnetic field in the core is the sum of the two fileds: feedback and generated by the measured current:

$$B = (\mu_0 \mu_r / L)(I - NI_r)$$

where N is the number of turns, L is the length of the magnetic circuit and μ_r is the relative permeability of the core.

Forcing the transformation from figure 6.a, the output frequency is:

$$f = K_I I + f_0$$

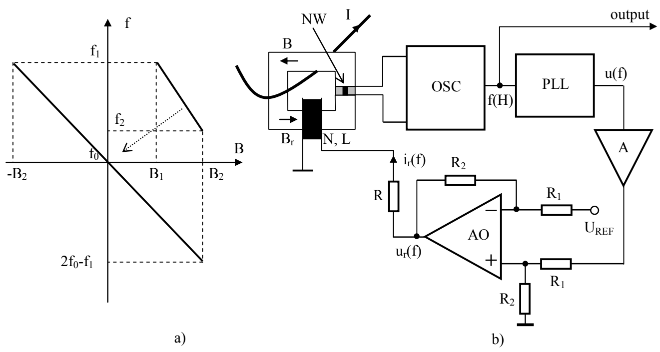


Fig. 6. Nanowire based current sensor.

where K_I is a constant depending on the circuit parameters: N, L, U_{REF}, A, etc. and f_0 is a well chosen frequency.

The dependence of the output is linear depending on the measured current. The PLL output voltage can be also used as output signal. Its dependence is also linear in the chosen interval of the input current.

An angular sensor measures the angular position of a mobile element which is a magnet usually. There are various solutions for angle measurement. The sensor we propose is for applications where dimensions are critical.

For sensing a rotating magnet, 8 magnetoresistive sensors are needed, connected in two Wheatstone bridges (figure 7) [Costineanu et al. (2009)].

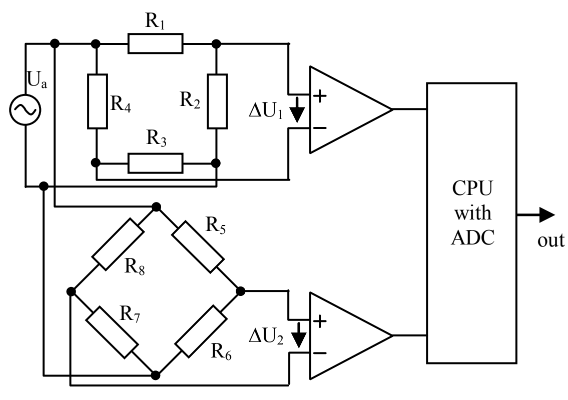


Fig. 7. Angular sensor schematic

The two bridges are 90 degrees physical shifted one to the other. While the magnet is rotating in front of them, the voltages ΔU_1 and $\Delta U2$ are also 90 degrees phase shifted. By processing the two signals the magnet angular position can be computed:

$$\Delta U_1 = U_0 \frac{\Delta R^2}{4R_0^2}\cos(2\alpha)$$

$$\Rightarrow \alpha = 1/2 \arctan(\Delta U_1 / \Delta U_2)$$

$$\Delta V_2 = U_0 \frac{\Delta R^2}{4R_0^2}\sin(2\alpha)$$

The main problem is how to arrange the nanowires to form the bridges and mainly how to contact them. Two solutions for nanowire arrangement were imagined.
For the first one a special template arangement was created (Fig. 8).

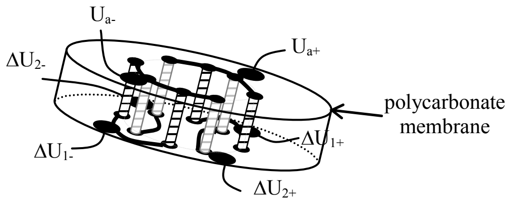
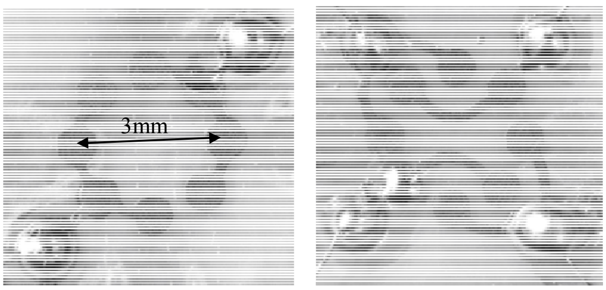


Fig. 8. The nanowire arrangement for the angular sensor

The polycarbonate foil was irradiated with single ions eight times in equidistant positions on a circle. The foil was shifted with a XY table. Following GMR nanowires were electrodeposited in the etched nanopores. The nanowires were contacted using the process described in the second paragraph (figure 4) and the result is presented in the Fig. 9.



Top face Bottom face

Fig.9. Nanowire contacts.

The nanowires are arranged over a circle having 3mm in diameter. Smaller dimensions are still possible. The processing electronics can be placed under the sensor in order to minimize the occupied space.

The second solution uses a random irradiated polycarbonate foil with 10^4 ions/cm^2. If the pad has a diameter of 0.5mm it means that under each pad around 20 nanowires are contacted. The tracks on the two faces do not overlap than on the round pads. This solution is more robust than the first one, but the bridges are not exactly balanced like in the first case. This causes errors on the measured angle.

4. Conclusions

The effective use of nanowires in the sensor's construction is almost absent in the scientific literature. This is due to their fragility and difficulty of contacting. The present paper proposes a cost effective technology for contacting them individually or in bundles while they are arranged in either a regular or an irregular pattern.

The innovative idea is to use and combine well known techniques from different fields in order to create something new and functional without the need of expensive machinery.

The techniques for obtaining single nanowires and contacting them is known from more than a decade. Using just sputtering and electrodeposition firm and long lasting contacts can be obtained. But their reduced sensitivity made them almost useless. Even so, they still have an atu: the large saturation field and a quasilinear region. These are exploited for the current sensor construction. Large currents create a large magnetic field, which are supported by the tiny nanowire and also creates large variations of the magnetic field which are sensed by its poor sensitivity. Using an adequate electronic circuit the output scale can be linearized while the errors are kept under 1%.

Regular patterns with ion tracks are available from many research groups. Irregular patterns are even more available and cheaper to produce. For preparing a sample with nanowires one needs a picoamperemeter and DAQ card. Till their use as sensors just the contacting problem is left to be solved. By combining the PCB technology with sputtering technique through a mask, almost any pattern can be realized. Above an angular sensor construction was demonstrated, based on two Wheatstone bridges, conveniently arranged.

The ion track technology together with PCB technology promises a new generation of microtransducers using nanosensors. By bringing together different techniques, innovation at nanoscale level becomes facile for industry.

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