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MAGNETIC PROPERTIES OF THIN FILM AMR SENSOR STRUCTURES IMPLEMENTED BY MAGNETIZATION AFTER ANNEALING

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Magnetoresistive sensors based on the anisotropic magnetoresistance effect (AMR) are widely used for measuring magnetic fields, and in compasses, angle/position sensors and current sensors. In spite of the later appearance of GMR structures, AMR sensors are still preferred in many fields because of their higher sensitivity and flexible technology. In this work the capacity for the production of high-quality devices is investigated for a technology flow based on magnetization of the AMR layer after annealing. The produced devices are single-stripe resistors on oxidized silicon wafers and on ceramic substrates. They demonstrate an AMR effect near to the theoretical value for the material. Two versions of AMR bridges are fabricated and investigated – with and without a barber pole structure. They exhibit comparable characteristics to those of devices manufactured by world recognised producers. The technology used is compatible with conventional CMOS processes, thus allowing the integration of AMR sensors with control ASICs on one chip, in order to obtain multifunctional smart systems.

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1. Introduction

Thin film magnetoresistive sensors based on the Anisotropic Magnetoresistance (AMR) effect are widely used in various applications: transducers for angular position and linear displacement, measurements of rotational speed, magnetic reading heads, magnetometers and compasses, current transducers etc. In spite of the later emergence on the market of devices based on the Giant Magnetoresistance (GMR) effect, AMR sensors are still preferred in cases where high sensitivity, flexibility of the design and compatibility with standard microelectronics technology are needed [1 - 5]. The AMR effect is based on the dependence of the resistivity of some ferromagnetic materials on the angle between the direction of the current flow and the direction of their magnetization. When such a material is deposited as a well ordered thin film, it exhibits one “easy axis” of magnetization in the plane of the film and is spontaneously magnetized along this axis. In a long stripe cut of such film along its “easy axis” the current flows in parallel with the magnetization, and at zero applied field the stripe exhibits its maximum resistance. Applying an external magnetic field of a certain magnitude H, directed perpendicular to the “easy axis”, results in a rotation of the vector of magnetization around its initial position at some angle $\pm\theta$ and a decreasing in the resistance. The AMR effect is symmetrical at declinations to either side, and the change in resistance depends only on the absolute value of θ. The effect is a saturation state when the vector of the magnetization is rotated by $\pm 90^{O}$. The maximum relative change of the resistivity $\Delta\rho/\rho$ is a characteristic that is constant for the magnetoresistive material used. For the widely used material permalloy, with composition Ni:Fe = 81:19, $\Delta\rho/\rho$ = 2.2 to 2.5 %. Permalloy can be processed by standard microelectronics technology, and AMR sensors could be integrated on one chip with

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CMOS ICs. AMR sensors are implemented in a single-path version or shaped as meanders when greater resistance over a small area is needed. For compensation of the relatively strong temperature dependence of the resistivity, usually four AMR resistors are integrated in a Wheatstone-bridge circuit. When a sensitivity to the polarity of the measured field is needed, "barber pole" structures are widely used. This approach utilises of an initial declination of the current flow from the axis of the stripe (the initial direction of the magnetization). This is achieved by deposition of "shorting bars" over the stripe, inclined at 45^{O} with respect to the axis [6,7].

2. Experimental details

Four types of structure were manufactured and investigated through a technology flow based on magnetization of permalloy layers after annealing at 450^{O}C. They comprised a single-path magnetoresistor, a four-arm bridge, a four-arm bridge with a "barber pole" structure, all on oxidized silicon wafers, and a single-path magnetoresistor on a sital substrate. The NiFe layer was sputtered from a NiFe target of composition Ni – 82.8%, Fe –17.2% in an Ar plasma, with process parameters: U_{RF} = 1.7 kV, $P_{A\,r}$= 0.5×10^{-2} mbar. Over the NiFe layer, a passivating SiO_2 layer was sputtered from a SiO_2 target at U_{RF} = 2.0 kV, P_{Ar} = 1.0×10^{-2} mbar, in the same deposition cycle without breaking the vacuum. The magnetic properties of the NiFe layer covered by the passivating SiO_2 layer were formed by annealing (1h at T = 425^{O}C [8] in an ambient of N_2 and H_2 with a ratio of 1:1, and a flow rate of 50L/h + 50 L/h) and subsequent cooling (over a 20 min. period) to room temperature in a magnetic field of approximately 800 Oe. A standard annealing oven without any upgrading was used for this purpose. After the magnetization, both layers were patterned by photolithography. For the "barber pole" samples, a second photolithography step for opening contact windows to the permalloy film and a second deposition cycle were carried out. The latter consisted of three successive processes: plasma etching of the remnants of the SiO_2 in the contact windows, deposition of a thin adhesive Ti layer, and deposition of a thick Al contact layer. The three processes were implemented by RF magnetron sputtering in an Ar plasma, and in one cycle without breaking the vacuum in the deposition chamber. Plasma etching of the SiO_2 was carried out by low-rate RF sputtering of the NiFe surface (U_{RF} = 0.5 kV, P_{Ar} = 1.0×10^{-2} mbar, duration – 1.5 min).The adhesive Ti layer was sputtered at U_{RF} = 2.0 kV and P_{Ar} = 0.5×10^{2} mbar (duration – 1.5 min, thickness – 40 nm) and the shunting Al layer was sputtered at U_{RF} = 1.5 kV and P_{Ar} = 0.5×10^{2} mbar. The Ti and Al layers were simultaneously patterned by a third photolithography stage. Samples were tested in a homogenous magnetic field created by a pair of Helmholtz coils in the range of -25.12 to +25.12 Oe (-2 to +2 kA/m).

3. Results and discussion

The AMR effect in thin films is very sensitive to the smoothness of the substrate. Usually, AMR magnetoresistors are implemented on oxidized silicon wafers that have a perfect smoothness [9]. The dependence of such a single-path magnetoresistor produced by the technology described above is shown in Fig. 1a. This particular sample exhibits a typical value of the maximum change in the resistance of 17.1 ohms (from R(0) at H=0 to R_S at saturation). This means that the maximum change of the resistivity of the layer is:

$$\frac{\Delta\rho}{\rho} = \frac{[R(0) - R_s]}{R(0)} \tag{1}$$

where $\Delta\rho/\rho$ = 2.1%. Another important parameter is the anisotropy field H_K that determines the sensitivity of the magnetoresistor to the applied fields and the range of measurement (before saturation). According to the basic theory of the AMR effect [10], R(H) can be expressed as:

$$R(H) = R(0) - R(0)\frac{\Delta\rho}{\rho}\left(\frac{H^2}{H_k^2}\right). \tag{2}$$

At larger magnetic fields, there are significant discrepancies between the above formula and real experimental curves, but at a relatively small fields it is followed exactly. Based on that in Fig 1b, part of the experimental curve from Fig. 1a is fitted with a parabolic function of H. By using such a fit to obtain the factor *b* multiplying H^2, one can calculate H_K from Eq. 2, as:

$$H_k = \sqrt{\frac{R(0)\frac{\Delta\rho}{\rho}}{b}} \tag{3}$$

For this sample, the calculated value of H_K, according to Eq. (3), is 13.27 Oe.

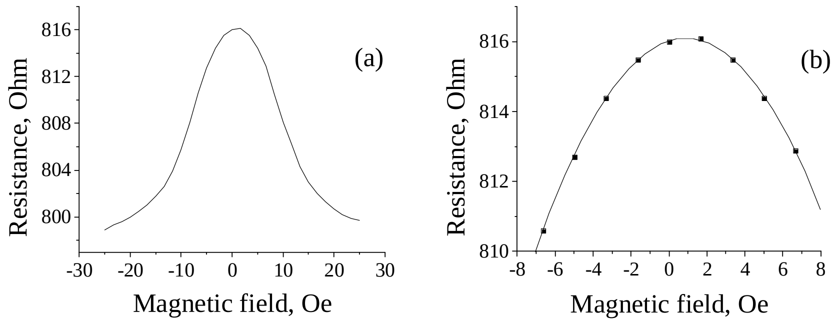

Fig. 1. AMR effect of a single stripe magnetoresistor deposited on a SiO_2 layer: (a) dependence of the resistance R on the applied magnetic field H; (b) fit of the dependence R(H) to a parabolic function (dots - experimental data).

In Figs. 2a and 2b, the same dependence is represented for a magnetoresistor with dimensions L = 14.3 mm, W = 70 μm and t = 200 nm, implemented on a sital substrate. Several kinds of ceramic are available as substrates, but sital (a kind of glazed ceramic) proved to be the only very good candidate here. Magnetoresistors deposited on other ceramics exhibited a reduced AMR effect because of insufficient smoothness of the substrate. However, those implemented on sital are competitive with those on oxidized silicon wafers ($\Delta\rho/\rho$ = 2.66 %, H_K = 9.34 Oe).

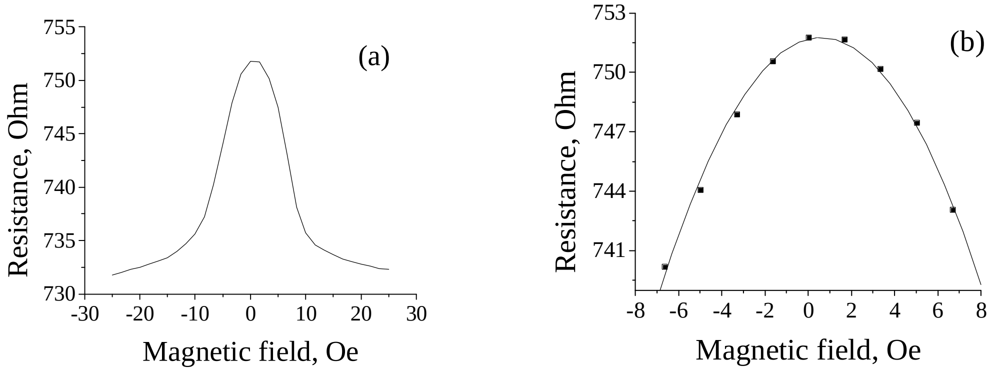

Fig. 2. AMR effect of a single stripe magnetoresistor deposited on a sital layer: (a) dependence of the resistance R on the applied magnetic field H; (b) fit of the dependence R(H) to a parabolic function (dots - experimental data).

The response of an AMR bridge fabricated on a oxidized silicon wafer is shown in Fig. 3a. The total resistance of the bridge is 704 Ω and the obtained sensitivity is 0.536 mV/V/Oe. The bridge consisted of two resistors magnetized in the direction of their length, and two magnetized in the perpendicular direction. As expected, the response was symmetric with respect to the point H = 0. In Fig. 3b, the response of a four-arm bridge with a barber pole structure is demonstrated, featuring a sensitivity S = 1.01 mV/V Oe. The response is anti-symmetric and nearly linear in the applied field range ± 5 Oe.

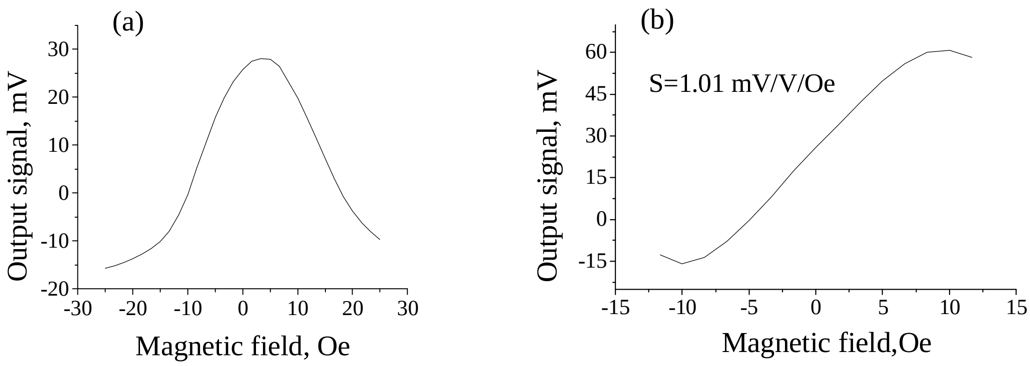

Fig. 3. Dependence of the output signal U on the magnetic field applied to two kinds of bridges: (a) without a barber pole effect; (b) with a barber pole effect.

3. Conclusions

A technology flow for the production of AMR devices has been developed, based on annealing of the deposited AMR layer and successive magnetization during the process of cooling to room temperature and outside the annealing oven. This allows the use of high magnetic fields (~ 800 Oe) and results in well-ordered and stable thin films. The effectiveness of this technology flow is proved by producing long single-stripe magnetoresistors and AMR bridges with and without barber pole structures. These devices exhibit parameters that are equal to those of the best world recognised producers [2 - 5]. Sital ceramic plates are found to be a very good competitor to oxidized silicon wafers as substrates for AMR devices. Equal (and sometimes higher) parameters of the AMR devices implemented on sital are obtained. This leads to a broadening of the possibilities for integration, in order to create multifunctional smart systems integrating CMOS chips and other devices.

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