Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

The role of the semiconductor layer in the exchange-bias film structure of CoNi / Si / FeNi / Si with a spin spring effect

To cite this article: A V Kobyakov *et al* 2019 *J. Phys.: Conf. Ser.* **1389** 012028

The role of the semiconductor layer in the exchange-bias film structure of CoNi / Si / FeNi / Si with a spin spring effect

A V Kobyakov[1,2], I A Turpanov[2], G S Patrin[1,2], V I Yushkov[1,2], S A Yarikov[1,2], M N Volochaev[2] and Ya A Zhivaya[1].
[1] Siberian Federal University, prospect Svobodny, 79, Krasnoyarsk, 660041, Russia
[2] L.V. Kirensky Institute of Physics of Siberian Branch of Russian Academy of Sciences, Krasnoyarsk, 660036, Russia

E-mail: nanonauka@mail.ru

Abstract. CoNi / Si / FeNi / Si structures were synthesized by ion-plasma sputtering. A negative hysteresis loop bias was detected at the thickness of the silicon layer was less than 2 nm and the temperature was less than 100 K. A positive hysteresis loop bias was detected at the thickness of the silicon layer was more than 2 nm and the temperature greater than 100K.

1. Introduction

To present day the problem of forming of magnetic state in multilayer system ferromagnetic metal / semiconductor is remaining undecided totally. The interlayer interaction in such systems is responsible for the formation of a magnetic state.

In some cases, the exchange interaction of magnetic layers leads to the appearance of exchange bias or unidirectional anisotropy [1]. The elucidation of the fundamental role of the exchange bias effect in the spin valve and tunnel devices led to the study of binary ferromagnet – antiferromagnet systems and caused a rapid growth in this direction [2-4].

It is believed that the exchange bias occurs in layered and nanostructured magnetic materials containing a magnetically soft ferromagnetic and highly anisotropic antiferromagnetic phase [1–4]. However, positive and negative exchange bias effects were also found in structures with ferromagnetic layers: FeGdferri/FeSnferro or FeGdferri/FeTbferri [5] and when replacing an antiferromagnetic layer with a magnetically hard ferromagnetic layer, many properties of such a system will be similar to the properties of a ferromagnet — an antiferromagnet of the system. In addition, a positive exchange bias arose in an ultrathin bilayer Si/Co/Si film at room temperature. This is associated with the presence of antiferromagnetic layers of the CoxSi1-x alloy at the Co/Si interfaces. These layers act as "fixing" antiferromagnetic layers on a magnetically "fixed" ferromagnetic Co layer [6].

In the case of conjugated magnetically soft and magnetically hard ferromagnetic layers, a new state similar to the magnetic spring can occur. Then, the magnetization process involves certain stages and the hysteresis loop has a specific [7].

Such nanostructures occur in many variations and geometries, including but not limited to multilayers and granular composites. In layered structure, the soft phase and the hard phase is exchange coupled only at the interface. The coercivity, predicted from the micromagnetic energy equations, varies as $1/L^2$ as a function of the soft layer thickness L. For large values of L, the soft phase switches easily and this coercivity reduces. This initiates the magnetization reversal of magnet and gives rise to unfavorable "wasp-like" hysteresis-loop shape. The corresponding switching of the soft regions is also known as exchange-spring magnetism [8-9].

For example, in multilayer magnetic systems $(FeNi\text{-}Co)_N$ in the region of overlapping permalloy island islands with cobalt, the magnetic moment of “soft” FeNi island is pinned and oriented along the magnetization vector of “hard” cobalt islands. [10].

One of the promising directions for the use of exchange springs is the perpendicular magnetic recording [11]. One of the main problems is that the thermal oscillations of the grains lead to a spontaneous switching of the magnetization. But a decrease in grain size can be balanced by large anisotropy [12].

It is likely that the effects of «exchange bias» and the formation of an “exchange spring” in magnetoresistive materials and structures with semiconductor layers will provide additional degrees of freedom to control the conduction process in spintronics devices.

Previously, a three-layer structure CoNi/Si /FeNi, was obtained. They found the effect of positive exchange bias. The interlayer interaction of ferromagnets depends on the thickness of the semiconductor layer [13]. The study was continued to determine the effect of the semiconductor layer on the effect of positive exchange bias and the determination of the partial contributions from the hard magnetic and. soft magnetic layers.

2. Experimental

The films of the CoNi / Si / FeNi /Si composition on a glass substrate at a base pressure of ~ 10–8 Torr have been synthesized by the method of ion-plasma sputtering.

The nickel content in the CoNi layer was 19.5 at. %, and in the FeNi layer was 84 at.%. The thickness of magnetic hard layer (CoNi) was t_h ~ 25 nm and magnetic soft layer (FeNi) was t_s~ 25 nm. The thickness of intermediate nonmagnetic semiconducting layer (Si) was variable and it was changed in range t_{Si} ~ 3 – 9 nm. The last layer of silicon 3 nm thick is used to prevent oxidation of iron.

The substrate temperature before the deposition of CoNi layers was 450 K, then the substrate was cooled to 373 K. This was carried out to improve adhesion with the substrate and to induce uniaxial anisotropy. The following silicon and permalloy layers were sprayed at the same substrate temperature in order to eliminate (minimize) the formation of silicides. The deposition rate of the layers was v ≈ 0.15 nm/s. It was also found that the CoNi film was polycrystalline and was in the hexagonal phase.

The thickness of the layers was monitored with a JEOL JEM-2100 electron microscope (when preparing the sample on a Gatan PIPS instrument). The crosssection of the film shows a clear interface between the silicon layer and the two magnetic layers (figure 1).

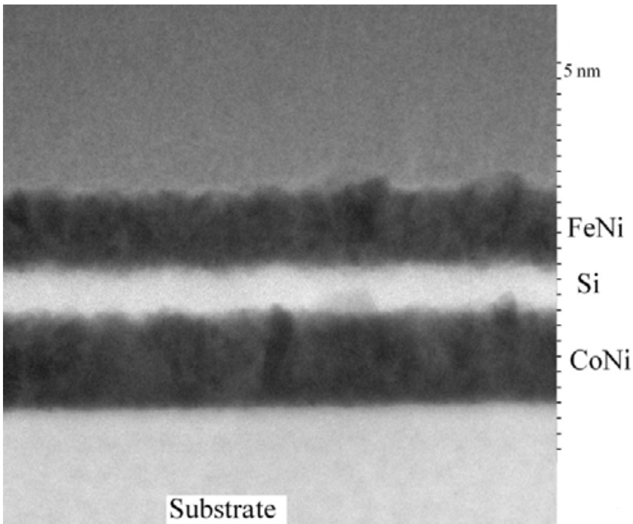

Figure 1. TEM images for CoNi / Si / FeNi film.

Magnetization measurements were carried out on an MPMS-XL installation in the temperature range from helium to room.

3. Results and discussions

The hard magnetic and soft magnetic layers are mated through a non-magnetic layer of semiconductor silicon (t_{Si}). In this case, the shape of the magnetization loop depends on the thickness of the Si layer (figure 2). In all films studied, a two-step hysteresis loop is observed. This behavior of magnetization can correspond to the behavior characteristic of a magnetic spring with a moderate interlayer coupling.

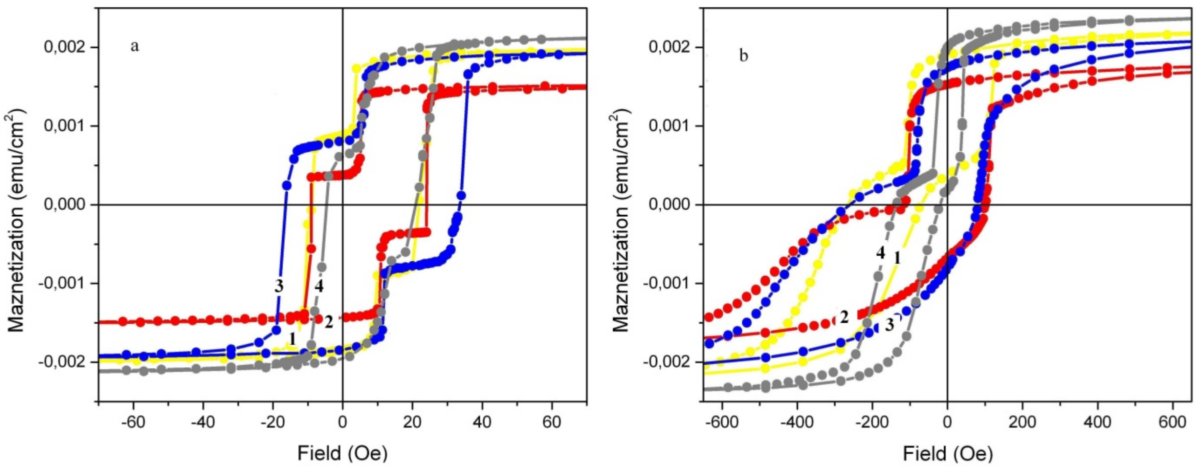

Figure 2. Magnetization loops for CoNi/Si/FeNi/Si films: 1, 2 , 3, 4 – t_{Si}= 3, 5, 7, 9 nm, a, b – T = 300, 5 K.

In figure 2 it can be seen that the increase of the coercive force of the hard magnetic and soft magnetic layers occurs with decreasing temperature. It is noticeable that the increase in the coercive force of the magnetic-hard and magnetic-soft layers occurs with a decrease in the measurement temperature of the hysteresis loop. The shape of the loop becomes more elongated. An increase in the area under the curve in the negative region is also visible.

A hysteresis loop bias in the negative direction was observed, for a structure with a silicon layer thickness of less than 5 nm, at a temperature of less than 100 K.

For films with the same thickness of silicon CoNi (53 nm) / Si (2 nm) / FeNi (72 nm) with large thicknesses of the hard magnetic and soft magnetic layers, a feature was traced [13]. The effect of "positive bias" is observed at temperature less than 100 K (inset in figure 3).

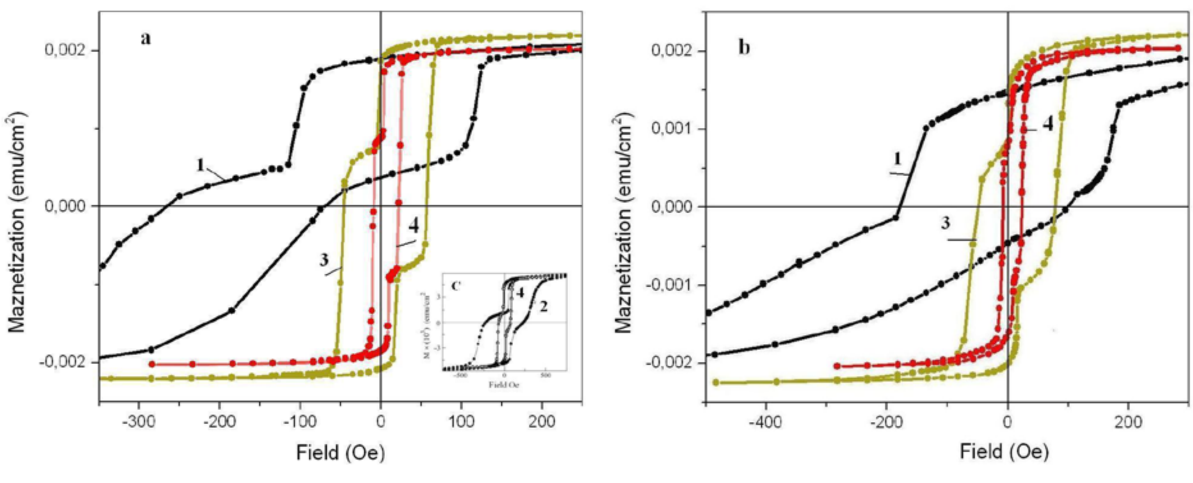

Figure 3. Magnetization loops for CoNi (25 nm) / Si / FeNi (25 nm) /Si films. a, b – tsi = 2; 7 nm, inset c – CoNi (53 nm) / Si (2 nm) / FeNi (72 nm) films, 1, 2, 3, 4 – T = 5, 40, 100, 300 K.

Now, the effect of "positive bias" with smaller thicknesses of the hard magnetic and soft magnetic layers is manifested on the contrary at temperatures above 75 K (figure 3).

Here, the interlayer exchange interaction through the silicon layer plays an important role.

The oscillations of the exchange bias (figure 4) are associated with the competitive nature of the mechanisms determining the effect of the exchange bias, or with the activation mechanism responsible for the formation of a magnetic state.

The situation is similar to the superparamagnetism of an ensemble of uniaxial particles. The magnetic energy of this type (here) is the sum of the anisotropy energy of the granules and the energy of interaction of the matrix with the external field. In our case, the interlayer exchange interaction through a silicon layer is added to the total energy. Both magnetizations are functions of an external magnetic field.

The sign of the exchange interaction constant will determine the direction of bias of the magnetization curve. Where it is negative, a positive displacement is observed in the magnetization circuit. Where it is positive, a negative bias is observed in the magnetization circuit.

This behaviour seems to be related to the ratio of the share of the magnetically soft and magnetically hard layers and surface anisotropy in the border areas.

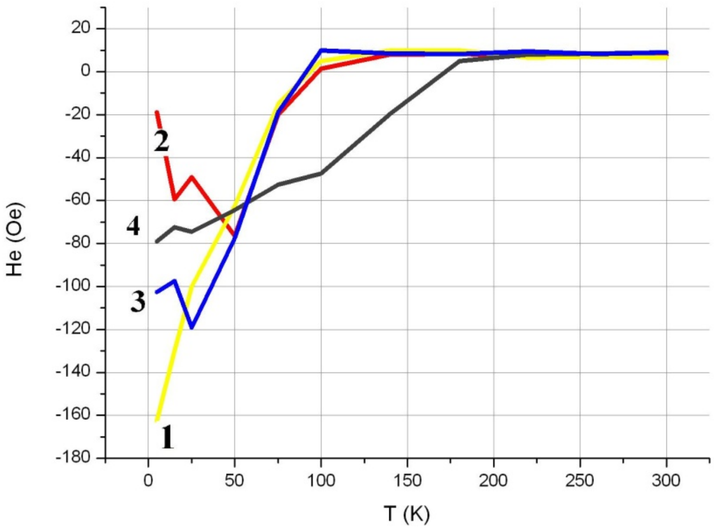

Figure 4. Temperature dependences of the exchange bias field of CoNi / Si / FeNi / Si films. 1, 2 , 3, 4 – t_{Si} = 3, 5, 7, 9 nm.

4. Summary and conclusion

In conclusion, we note the main results of this study.

◦ In the system of magnetic hard-magnetic-soft material with a semiconductor layer, a structure with controlled interlayer interaction was created.

◦ Interlayer interaction depends of the thickness of the semiconductor layer and the ratio of the share of soft magnetic and hard magnetic layers.

◦ A positive exchange bias and negative bias effect has been detected.

Acknowledgments

These studies are conducted with financial support from the Russian Foundation for Basic Research (grant No. 18-02-00161-a).

References

[1] Meiklejohn W H and Bean C P 1956 *Phys. Rev.* **102** 1413
[2] Nogu´es J, Sort J, Langlais V et al 2005 *Phys. Rep.* **422** 65
[3] Radu F and Zabel H 2008 *Springer Tracts Mod. Phys.* **227** 97
[4] Giri S K and Nath T K 2014 *J. Nanosci. Nanotechnol.* **14** 1209

[5] Canet F, Mangin S, Bellourd C, Piecuch M, and Schul A 2001 *J. Appl. Phys*. **89** 6916
[6] Roy S, Menyhárd M, Majumdar S, Novikov D and Nath Dev B 2011 *Journal of Materials Science and Engineering* **5** 200-211
[7] Bader S D, 2006 *Rev. Mod. Phys.* **78** 1
[8] Kneller E F and Hawig R, 1991 *IEEE Transactions* **27** 3588–3560
[9] Tayade R, 2014 Theoretical and experimental contribution to the study of exchange-spring magnets *Materials Science [cond-mat.mtrl-sci] ENS Cachan* p 1
[10] Boltaev A P, Pudonin F A, Sherstnev I A, 2011 *Physics of the Solid State* **53** 5
[11] Victora R H and Shen X, 2005 *IEEE Transactions on Magnetics* **41** 537
[12] Charap S H, Lu P L, and He Y J, 1997 *IEEE Trans. Magn.* **33** 978
[13] Patrin G S, Turpanov I A, Yushkov V I, Kobyakov A V, Patrin K G, Yurkin G Yu, Zhivaya Ya A 2019 *JETP Letters* **109** 324-329