Proceedings of the 16th Czech and Slovak Conference on Magnetism, Košice, Slovakia, June 13–17, 2016

The Investigation of Spin Seebeck Effect in $Co_{79}Si_{10}X$ Alloys

Ł. Bernacki[a,*], R. Gozdur[a] and W. Pawlak[b]

[a]Department of Semiconductor and Optoelectronics Devices, Łódź University of Technology, B. Stefanowskiego 18/22, 90-924 Łódź, Poland

[b]Institute of Materials Science and Engineering, Łódź University of Technology, B. Stefanowskiego 1/15, 90-924 Łódź, Poland

The paper presents experimental study of the spin Seebeck effect based on the widely used ferromagnetic $Co_{79}Si_{10}X$ layer, partially covered with Pt layer. The total thickness of tested sample is about 20 μm, which makes it the first confirmed presence of the spin Seebeck effect in bulk material. Experiment was carried out under magnetic flux density 300 mT, room temperature and for constant temperature difference across the sample ranging from 1 K to 21 K. The measured value of induced voltage drop achieved 0.5 µV per 1 K.

DOI: 10.12693/APhysPolA.131.872

PACS/topics: 85.80.Fi, 72.15.Jf, 75.76.+j

1. Introduction

In 1987 Johnson and Silsbee [1] introduced a concept of spin-caloritronics when they came to the conclusion that the transport of heat in a ferromagnetic system is correlated with the transport of spin. First results confirming above statement were shown in 2008 by Ken-Chi Uchida [1]. The spin Seebeck effect was observed in ferromagnetic NiFe (permalloy) nanolayer with Pt contact [2]. The effect was also observed in NIG ($Nd_{3-x}Bi_xFe_5O_{12}$) [3], ferromagnetic semiconductors (GaMnAs) [4], electrically insulating YIG ($Y_3Fe_5O_{12}$) [5], and Heusler alloys [6]. This observation opens entirely new strategies to enhance efficiency of heat to electric power conversion.

2. Motivation

The spin Seebeck effect (SSE) is the process, in which a spin voltage is induced by a temperature gradient in a ferromagnetic material. The temperature difference is applied to the ferromagnetic layer in the direction perpendicular to the nonmagnetic metal contact. The spin voltage enables injection of spin current from ferromagnetic material into the attached nonmagnetic metal (NM) [8]. Injected spin current generates an electric field E_{ISHE} via the inverse spin Hall effect (ISHE) due to strong spin–orbit interactions in the nonmagnetic metal [9]. The transverse SSE converts thermal energy into electric power that is proportional to the sample area and therefore does not require complicated thermopile structuring. It is attractive to be used in large-area thermoelectric power generators that can be made by manufacturing of suitable layers [9, 10].

*corresponding author; e-mail: lukasz.bernacki@dokt.p.lodz.pl

The ferromagnetic materials at the nanoscale are considered as the ones that can easily control a magnetic texture under low magnetic field density, hence the SSE, hitherto, has been observed in nanolayers only. Small thickness (20–200 nm) results in poor mechanical properties and limited utilization in industrial applications. The thicker layers of several micrometers would be characterized by higher mechanical strength and they could be manufactured with easy coating technique. For those reasons, authors have decided to conduct an experimental study of the spin Seebeck effect in bulk layers. The commercially available amorphous film $Co_{79}Si_{10}X$ has been chosen in order to enhance mechanical properties.

3. Construction and measurement

The prepared sample consists of 20 µm thick ferromagnetic layer made of amorphous ribbon of Vitrovac 6025 l50X. Vitrovac 6025 150X is a soft magnetic metallic foil with an amorphous atomic structure. The preparation of material provides a high mechanical hardness, flexibility, excellent magnetic properties and higher permeability values compared with MUMETALL. The magnetic properties of Vitrovac 6025 150X are presented in Table I.

TABLE I

Physical and magnetic properties of Vitrovac 6025 l50X.

Curie temperature	T_C	220 °C
coercitivity	H_c	≈ 1 A/m
max. permeability	μ_{max}	> 100 000
remanence	B_r/B_s	≈ 0.7

In the paper, Vitrovac 6025 150X is described as $Co_{79}Si_{10}X$ because the elements Co and Si have the greatest weight fraction. The measurement using electron imaging of $Co_{79}Si_{10}X$ shows a detailed composition of the chosen material. Manufacturer (Vacuumschmelze

GmbH) describes it as $Co_{69}Fe_4Mo_3(Nb\ Si\ B)_{REST}$ and it has been confirmed by our analysis. Details of SEM analysis are gathered in Table II.

TABLE II

Composition of Vitrovac 6025 150X.

Element	[wt%]	[at.%]
Si	10.23	19.65
Fe	4.29	4.14
Co	79.75	72.99
Mo	5.73	3.22
Pt	0.00	0.00
total	100.00	100.00

Schematic construction of the examined devices is shown in Fig. 1. The amorphous layer forms an interface with the heat source. 50 nm thick Pt layers have been deposited with the aid of thermal evaporation on two ends of the ferromagnetic layer. Sample dimensions ($L_x \times L_y \times L_z$) of the ferromagnet and nonmagnetic layers are 4 mm × 3.5 mm × 20 μm and 1 mm × 3.5 mm × 50 nm, respectively.

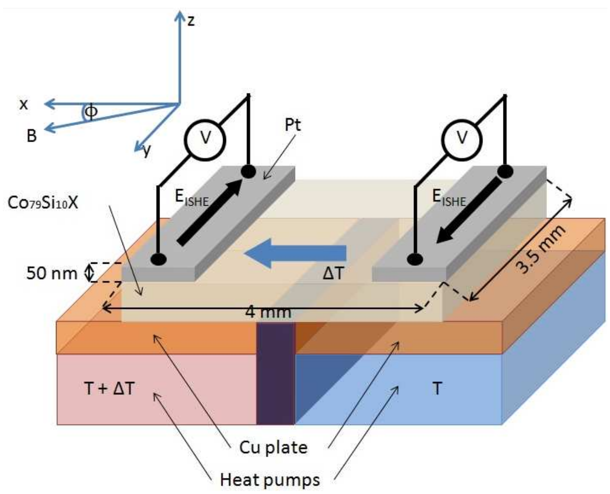

Fig. 1. Schematic construction of the examined device consisting of the $Co_{79}Si_{10}X$ layer with Pt contact. Two 9 W Peltier cells were used as heat pumps. Temperature difference ΔT (maximum 21 K) and external magnetic flux density (with magnitude 300 mT) are applied along the x-direction.

To identify SSE in the setup two copper leads have been attached to the edges of Pt layer separated by the distance L_y. The thin probes have been used to minimize heat losses through the leads. The electric voltage difference V_{ISHE} has been measured by digital nanovolt/micro ohm meter Agilent 34420A. Two Cu plates with Peltier cells have been mounted at the bottom of ferromagnet. They provide a uniform temperature gradient ΔT between the two Cu plates in x-direction, parallel to the investigated structure. The distance between Cu plates is around 0.5 mm and the gap is filled with ceramic insulator. Temperature difference ΔT has been measured and controlled continuously with the aid of two Pt100 probes and digital nanovolt/micro ohm meter Agilent 34420A. External magnetic flux with density 300 mT has been applied in the x–y plane at an angle Φ to the x-direction. The magnetic field density has been measured using LakeShore 475 DSP Gaussmeter with HMMT-6J04-VF probe. During the experiments, investigated structure has been placed in thermal chamber to mechanically secure, isolate from the environment, and provide a solid thermal and electric contact. Here we note that every connector, between the devices and the investigated structure, has been made from the same material and has been placed inside the chamber at a constant temperature. In addition, the device has been calibrated to the prevailing conditions. Therefore thermoelectric voltage generated in the leads attached to the structure or between any contacts is negligible.

4. Experiment

Presented paper focuses on identifying the presence of the SSE in investigated material. The effect has been measured by using ISHE that converts the spin current driving through the ferromagnet, due to temperature difference, into an electric current. SSE measurements have been conducted for different values of temperature difference. Stabilization time around 60 min has been kept after changing the temperature to ensure thermal equilibrium between the sample and the measurement system. Results of measured voltage drop V as a function of time taken across the Pt layer on the hot side and on the cold side are presented in Fig. 2a and in Fig. 2b, respectively.

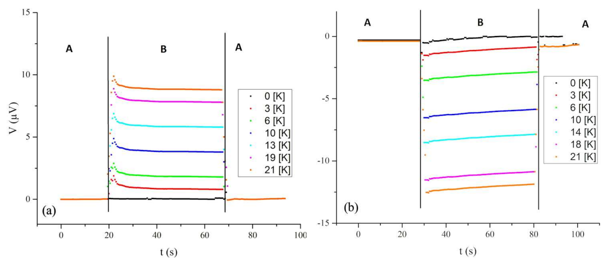

Fig. 2. (a) Electric voltage difference V (Pt contact on hot site) as a function of the time under constant value ΔT. (b) Electric voltage difference V (contact on cold site) as a function of the time under constant value ΔT.

When a magnetic flux is applied along the x-direction ($\phi = 0$), the value of V is observed (part B). The V signal is not observed when the magnetic flux is not applied (part A). The change of V magnitude is associated with the appearance of V_{ISHE}. This effect is explained by the fact that, if the spin voltage is generated in the ferromagnetic layer, it drives the spin current flow into Pt layer. This movement generates an electromotive force E_{ISHE}, or electric voltage along the y-direction due to the ISHE in the Pt layer.

An influence of the magnetization angle ϕ on the magnitude of the voltage drop V taken on the hot side and

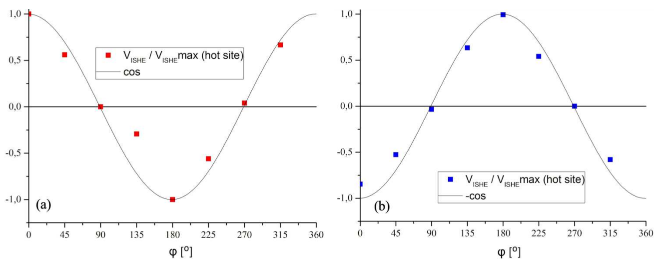

Fig. 3. (a) Magnitude V as a function of magnetization angle ϕ (Pt contact on hot site). (b) Magnitude V as a function of magnetization angle ϕ (Pt contact on cold site).

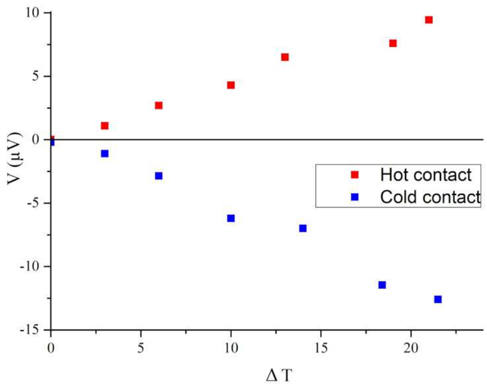

Fig. 4. V_{ISHE} versus temperature difference ΔT.

the cold side are presented in Fig. 3a and in Fig. 3b, respectively. The measurements have been conducted for constant temperature difference $\Delta T = 21$ K. The magnitude V reaches 0 when $\phi = 90°$ and $270°$.

Moreover, the V_{ISHE} versus temperature difference ΔT under constant magnetization condition is depicted in Fig. 4. The magnitude of V is proportional to ΔT. It is also confirmed that the sign of the measured V can be changed by reversing the ΔT or by attaching Pt contact on the cold side or on the hot side, as it is shown in figures above.

5. Conclusions

In summary, the presence of the spin Seebeck effect in bulk ferromagnetic layer made of $Co_{79}Si_{10}X$ compound has been confirmed with the aid of the ISHE in Pt layer. Under magnetization $B = 300$ mT voltage V_{ISHE} achieves 0.5 µV per 1 K. This value is comparable to the currently reported values for NiFe nanolayers. The third dimension cannot be neglected in such a thick layers, hence one may expect a better arrangement of spins and a higher V_{ISHE} magnitude if higher magnetic flux density is applied. The utilization of the transverse SSE can be beneficial due to the fact that it occurs in simple, versatile systems.

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