Unconventional GMR structures for magnetoelectronics

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Conventional electronic devices work on the basis of electrical currents, i.e., they use the charge of the electron. Recently, researchers began investigating devices which functionality depends not only on electron charge but also on electron spin. Since spins are responsible for magnetic phenomena, it gives a potentially new dimension to future magnetic devices. In the foregoing decade a number of artificial layered structures have been designed to study the spin polarized transport or to exploit the specific response of the system for sensing a magnetic field in devices.

In this contribution we present the results of our investigations concerning the improvement of the magnetoresistive properties of layered magnetic thin films consisting of two or more ferromagnetic layers (F) separated by nonferromagnetic spacer layers (S). These systems, for metallic spacer layer, with thicknesses in the nm-range may exhibit the ***G***iant ***M***agneto ***R***esistance (***GMR***) i.e., a property, which is important both for the basic understanding of spin-dependent magnetotransport as well as for their application in sensors and data storage technology. The main requirement to observe the ***GMR*** effect is the mutual rotation of the magnetizations in adjacent ferromagnetic layers from their noncolinear (usually antiparallel) to parallel configurations induced by magnetic field. There are several strategies to realize the GMR effect [1]. The first and the oldest one is the utilization of the antiferromagnetic coupling between ferromagnetic layers which provides, for the certain spacer layer thickness, the antiparallel configuration of magnetization direction in adjacent ferromagnetic layers. In the second strategy one can use the ferromagnetic materials with different coercive fields ($H_{C1} \neq H_{C2}$). Then the antiparallel magnetization configuration occurs for external magnetic fields $H_{C1}<H<H_{C2}$. The third approach, particularly designed for low-field sensing devices, uses the phenomenon of exchange bias which occurs between antiferomagnetic and ferromagnetic layer being in direct contact. In such structures the magnetization direction of one ferromagnetic layer is pinned in a certain direction by direct exchange coupling to the antiferromagnetic layer. The other ferromagnetic layer is decoupled from the biased layer by thick enough spacer layer and therefore switches its magnetization at zero field. We have utilized all mentioned above approaches to produce the layered structures with parameters being very promising from the application point of view of GMR elements. Below we will describe more precisely our very recent achievements in this field.

One of the main aim of our research was to obtain the layered structures exhibiting large GMR values accompanied with low magnetic saturation or the switching field. Moreover, it is desirable from the application point of view that these structures show a low field GMR at room temperature. We have focused our attention on **$Ni_{80}Fe_{20}/Co_1/CuAgAu/Co_2$** sandwiches (Fig.1a) [2-4] and **$[Ni_{80}Fe_{20}/CuAgAu/Co/CuAgAu]*10$** (Fig. 1b) [5-7] multilayer structures composed of ferromagnetic metals with different coercivities, The fairly large GMR amplitude accompanied by high GMR field sensitivity of about 5%/Oe and 6.8%/Oe observed in our trilayers and multilayers, respectively locate them among the most promising structures from the application point of view as magnetic field sensors. The high values of parameters

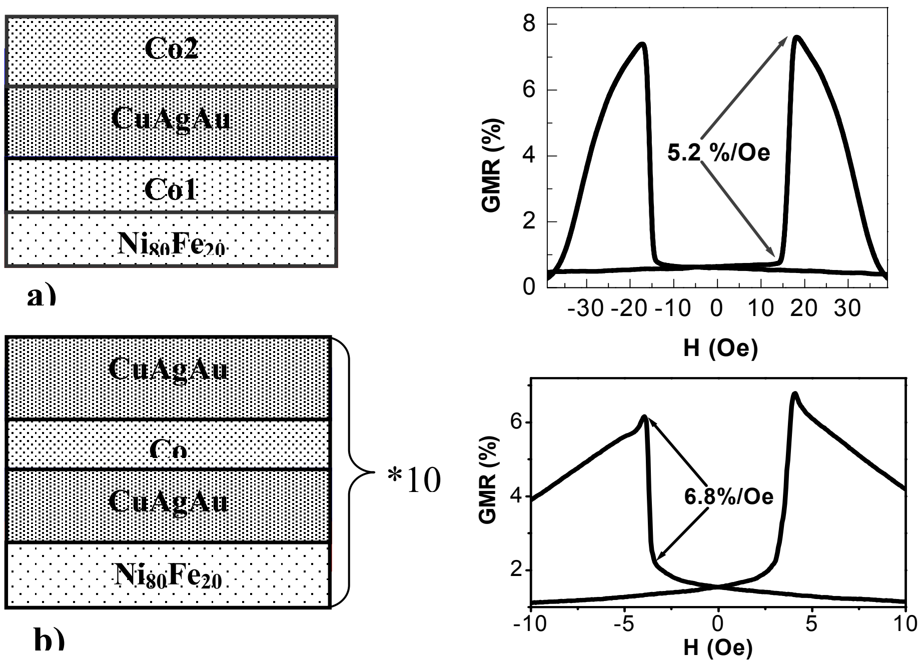

Fig. 1. The examples of GMR(H) characteristic of NiFe(3.5 nm)/Co1(2.5 nm)/CuAgAu(2.04 nm)/Co2(2.5 nm) sandwich (a) and [NiFe(2 nm)/CuAgAu(2.5 nm)/Co(0.75 nm)]*10 multilayer (b) with highest GMR field sensitivities.

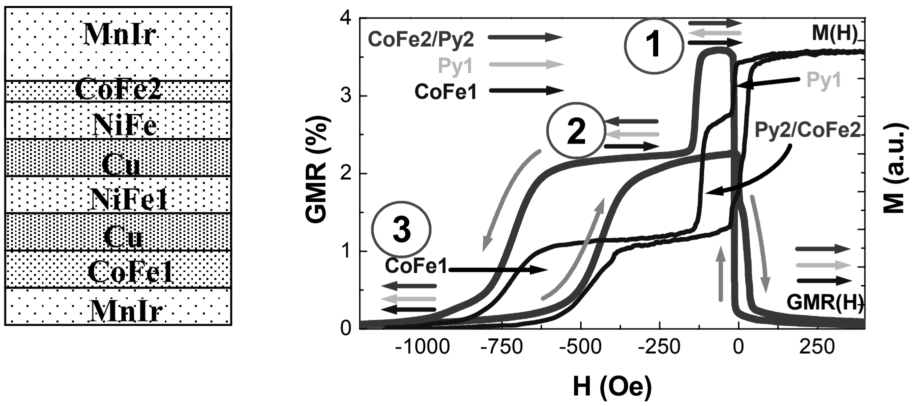

Fig. 2. GMR(H) and magnetization M(H) characteristics of MnIr/CoFe1 (1.6 nm)/Cu (3.3nnm)/Py1 (1.4 nm)/Cu (3.3 nm)/Py2 (0.5 nm)/CoFe2 (1.4 nm)/MnIr asymmetric dual spin-valve. Three different magnetization configurations are numbered and sweeping directions are indicated by gray arrows.

characterizing the GMR effect was only possible to achieve due to the balancing effect between RKKY-like exchange coupling and the magnetostatic orange-peel coupling. We have shown that the values of the ferromagnetic coupling between $Ni_{80}Fe_{20}/Co_1$ and Co_2 for a constant CuAgAu spacer layer thickness can be either enhanced or reduced depending on the ratio between Co_1, Co_2 and $Ni_{80}Fe_{20}$ thicknesses. Therefore, the examined layered structures could be of interest for second generation of the GMR sensors since, their characteristics can be tailored by tuning the magnetic layer thickness.

In some applications of the GMR effect, the multilayer structures with special resistance characteristics on magnetic field R(H) are required. The most promising systems, which have already found a practical application, are spin-valve structures. We proposed a new layered system with two different ferromagnetic materials used as pinned layers in dual exchange biased structure (asymmetric dual spin-valve) **MnIr/CoFe1/Cu/NiFe1/Cu/-NiFe2/CoFe2/-MnIr** deposited onto thermally oxidized Si(100) [8]. Since in this structure the different ferromagnetic layers are exchange coupled to antiferromagnetic MnIr layer therefore we expected that there will be a different exchange coupling fields H_{ex} between MnIr and CoFe1 and Py2/CoFe2 layers. We have shown that for properly chosen structure, with certain pinned layer thicknesses, of the dual spin-valves a novel three stages GMR(H) characteristic can be realized - three state logic system (Fig. 3).

For some applications, such as quantitative measurements of magnetic field, both a linear dependence of the resistance on a magnetic field *R*(*H*) and a negligible hysteresis are desirable. We have shown that these properties can be achieved in $\mathbf{(Ni_{83}Fe_{17}/Au/Co/Au)_{15}}$ multilayers (Fig. 3) [9-11]. In this structure Permalloy possesses pronounced in-plane anisotropy, whereas Co layers (for certain thickness) sandwiched between Au have a strong perpendicular anisotropy. For Au sublayers thicker than 1.5 nm magnetization reversal of Ni-Fe and Co layers takes place independently and therefore, in such structures, the GMR effect can be used to study the individual magnetic properties of cobalt and Permalloy layers.

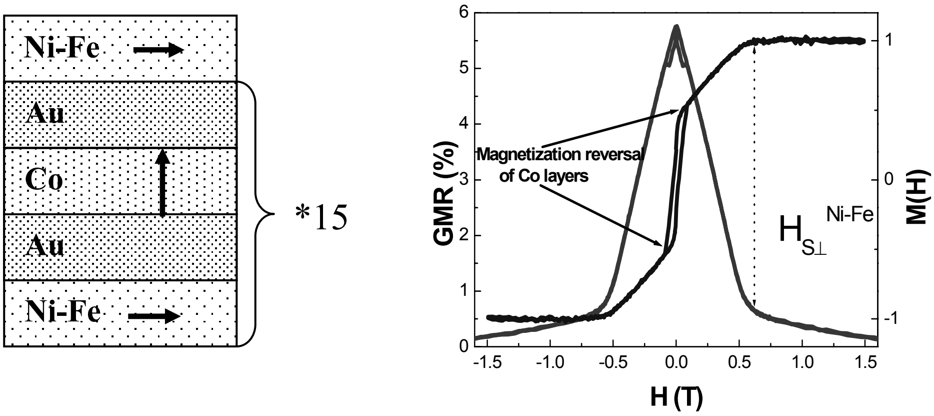

Fig. 3. Exemplary magnetic hysteresis loop M(H) and GMR(H) dependence for [NiFe(2 nm) / Au(3 nm) / Co(0.6 nm) / Au (3 nm)]$_{15}$ multilayer with alternating in-plane and perpendicular anisotropy for magnetic field applied perpendicularly to the sample plane.

The GMR effect can also be realized in layered structures with a use of an artificial antiferromagnet instead of antiferromagnetic layer. Since we have found that very strong antiferromagnetic coupling $J = -1.93/m^2$ accompanied by saturation field of 1.5T can be realized in Fe/Si multilayers therefore we applied this system as an artificial antiferromagnet in magnetoresistive $\mathbf{(Fe/Si)_{15}/Fe/Co1/Cu/Co2}$ pseudo-spin-valve (Fig. 4). We have used Co1/Cu/Co2 trilayer as the magnetoresistive structure with Co1(2) and Cu thicknesses of about 1.5 nm and 2.5 nm, respectively. The last Fe and the Co1 layers are in the intimate contact and therefore Fe/Co1 bilayer behaves as a first magnetoresistive layer in the examined structure. The field dependence of the sample resistance, shown in Fig. 4, reflects a typical GMR behavior. As can be seen, there are two switching fields: H_1 related to the magnetization reversal o f the top Co2 layer and H_2 due to switching of the pinned Fe/Co1 bilayer.

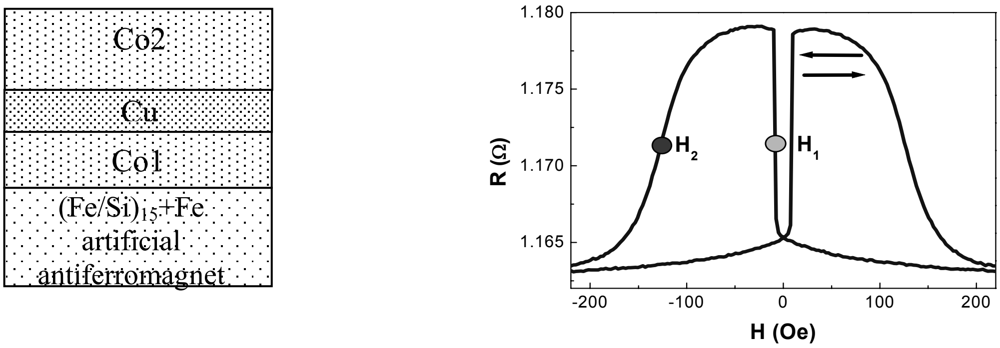

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Fig. 4. Magnetoresistance effect of $(Fe/Si)_{15}$/Fe/Co1/Cu/Co2 pseudo-spin-valve structure with Fe/Si multilayer used as the artificial antiferromagnet.

Fe/Co1 bilayer is AF coupled to the rest of Fe/Si Ml structure it reverses at higher fields than the top Co2 layer and an antiparallel arrangement between magnetizations of the Fe/Co1 bilayer and the Co2 layer occurs between H_1 and H_2.

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