Transactions of the Materials Research Society of Japan 24 [4] 591-594 (1999)

Application of Spin-Valve Type Giant Magnetoresistive Material to Spin Device

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Abstract: A spin device consists of a multilayered structure that includes a spin-valve element and a bias current line. The micro-sized spin-valve element, fabricated by sputtering method and optical lithography, exhibits a step shape magnetoresistive (MR) loop. The magnetization and resistance of the spin-valve element is controlled by the magnetic field induced by the bias current. The spin device gets new and high performances by arranging the bias current. High magnetic sensitivity is, for example, realized by utilizing only the MR edge part. In a memory device, the information is stored as two memory states corresponding to the spin-valve resistance of a "high" and a "low", and these data do not volatilize. In addition, the electric resistance of the spin-valve element is operated by a small input signal, if the bias field is set to be slightly smaller than the two edge fields. A combined function of some performances, such as the sensing, the information storage and the electric operation, is likely to be realized by the presented spin device.

Keywords: giant magnetoresistance, spin-valve, spin device, spin-electronics

1. INTRODUCTION

Ten years have passed since giant magnetoresistive (GMR) effect was discovered [1], [2]. GMR effect is an electron scattering phenomenon dependent on the spin polarization. Electric conductivity is controlled by arranging the magnetic polarization between ferromagnetic layers constructing a magnetic multilayer. The MR ratio of GMR effect is much larger than a usual anisotropic MR effect. Moreover, GMR effect will be expanded over spin-electronics in the near future, in which the electron spin is actively utilized for electronic devices. Spin devices, such as a highly sensitive magnetic sensor, a magnetic random access memory and a spin transistor, have been recently presented [3]-[5]. Spin-valve type GMR material [6] is important for the application of these spin devices.

In this paper, we propose a spin device using spin-valve film, that has a combined function of some performances, such as a magnetic sense, an information storage and an electric operation. The figures used in this manuscript have been reproduced with permission from previous references.

2. SPIN-VALVE FILM [4]

Figure 1 shows the MR loops of a sputtered and a patterned spin-valve film: [NiO(25.0)/NiFeCo(2.2)/Cu(2.0)/NiFeCo(11.0)], where the value in () indicates the layer thickness in nm. The spin-valve film consists of a multilayered structure including an antiferromagnetic NiO layer and two ferromagnetic NiFeCo layers separated by a nonmagnetic Cu layer. The magnetization of the ferromagnetic layer in contact with the antiferromagnetic layer, is pinned along the unidirectional anisotropic direction, while the magnetization of the other layer is free. The electric resistance is changed between a "High" and a "Low" states

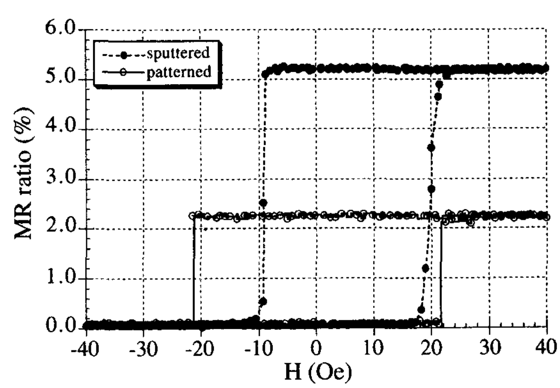

Fig. 1 MR loops of (a) a deposited and (b) a patterned spin-valve films. The patterned spin-valve film shows a step shape MR loop.

corresponding to the magnetic directions of the free and the pinned layers. The spin-valve element, patterned into a rectangular shape of 50 μm × 30 μm, exhibits a step shape MR loop. The magnetization of the free layer switches like a single domain, since the shape anisotropy effect is increased. The MR ratio decreased to approximately half of the patterned film. This is ascribed to the thermal deterioration in the microscopic fabrication and the shunt effect of a Cu surface layer. A 2.0 nm thick protection Cu layer, for inhibiting corrosion, was laminated on the patterned film surface alone.

3. DESIGN OF SPIN DEVICE

A spin device, as illustrated in Fig. 2, consists of a multilayered structure that includes the spin-valve element and a bias current line. The spin-valve element exhibits the step shape MR loop shown in Fig. 1. The magnetization and resistance of the spin-valve element are controlled by the magnetic field induced by the bias current. The spin device gets new and high performances by arranging the bias current.

3.1 Magnetic Sensor [3]

Figure 3 shows the operating principle of a magnetic sensor, where H_r and $-H_f$ are the rising and the falling magnetic fields of the MR loop, respectively. An AC bias magnetic field induced by the square-wave bias current: [plus or minus] is applied to the spin-valve element. The plus and the minus values of the bias field are set to be H_r-Δh and $-H_f$-ΔH respectively. In this case, the resistance of the spin-valve element is constant, because the plus value of the bias field is set to be smaller than the rising field of the MR loop *(solid line)*. An external magnetic field: H_{ex} is applied to the magnetic sensor, where $\Delta h<H_{ex}<\Delta H$. The output signal synchronized with the input bias current is observed, since the bias field goes across the rising of the MR loop *(dotted line)* by applying the external magnetic field. The sensitive magnetic sensor can be developed, if the magnetic field induced by the bias current is set to be slightly smaller than the rising field.

We have confirmed that the square-wave output signal synchronizing with the input bias current was observed by applying a magnetic field of 0.5 Oe. This magnetic sensitivity is approximately 40 times as high as the spin-valve film shown in Fig. 1.

3.2 Random Access Memory [4]

The information is stored into the spin-valve storage element as two memory states corresponding to the electric resistance of a "High" and a "Low", and this stored data does not volatilize. The free layer magnetization is switched by the bias current between parallel and antiparallel to the fixed layer. The memory cell of the differential type is shown in Fig. 4. The information is simultaneously stored at two storage elements constructing the memory cell, in which each bias current is in opposite directions. Thus, two electric resistance values, one corresponding to the "High" and the other to the "Low", are stored in each element. The readout of the memory states is accomplished by probing the differentiation of the two storage element outputs. The memory cell exhibits two memory states representing a "1" or a "0" according to whether the differen-

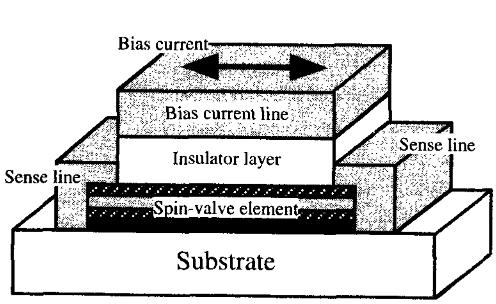

Fig. 2 Schematic structure of the spin device composed of a spin-valve element and a bias current line.

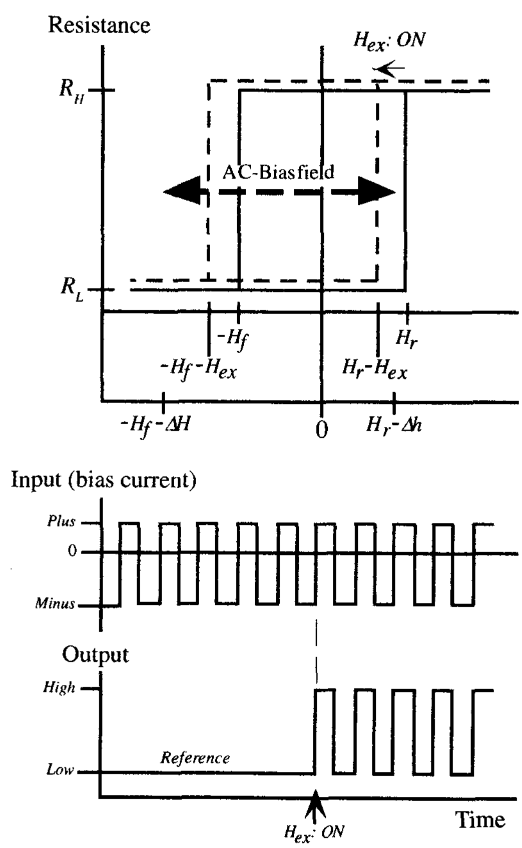

Fig. 3 Operation principle of the present magnetic sensor. High sensitivity is presented by using only the edge part of the MR loop.

tial output voltage is positive or negative, respectively. A magnetic field is not necessary for the readout process. It is possible to construct a nonvolatile memory device that has a number of highly efficient properties, such as a nondestructive readout, high-speed access, large output signal, and low electric power consumption.

The output voltage of the single spin-valve element indicated a step shape signal against a 3-step: [zero/plus/zero/minus] bias current. This result shows that the storage element stores the "High" state by the positive input signal, and that this state is maintained even when the bias current was switched from positive to zero. On the other hand, the element stores the "Low" state by the negative input signal, and the state is kept even when the current was switched to zero. In the differential type memory cell including two storage elements, the differential output signal indicated the voltage of a plus or a minus in response to the input signal, and this stored data did not volatilize. Magnetic field was not necessary for the data readout process and it was, of course, a nondestructive readout.

3.3 Electric Operating Device

The electric resistance of spin-valve element is controlled by using an input signal and a bias magnetic field, for an electric operating device. The AC bias magnetic field, which is a step shape and a high frequency, is induced by the bias current layer. The plus and minus values of the bias field, as shown in Fig. 5, are set to be H_r-Δh and -(H_f-Δh) respectively. The bias field is slightly smaller than the MR loop edges, so the magnetization of the spin-valve element is not changed by only the bias field. The input signal is applied to the metallic interlayer constructing the spin-valve element. The Cu layer is the interlayer of the spin-valve structure illustrated in Fig. 2. The input current mainly flows into the interlayer, if the interlayer resistance is smaller than other layers. Moreover, the input current flows into only the interlayer, if insulating layers are constructed at the interfaces between the interlayer and the ferromagnetic layers. This structure is better than one shown in Fig. 2. The direction of magnetic field induced by the input current is set to be parallel to the bias field. Therefore, the electric resistance of spin-valve element is changed, if the magnetic field direction induced by the input signal is equal to the bias field. The schematically output signal of this operating process is shown in Fig. 5. The input signal is estimated at less than several μA, if the Δh and the device size are set to be 0.1 Oe and 0.1 μm respectively. A switching device can be also realized by the differential type device design shown in Fig. 4.

3.4 Spin-Electronics

Semiconductor electronic devices usually make use of only the function of electron carrier, and nothing utilizes

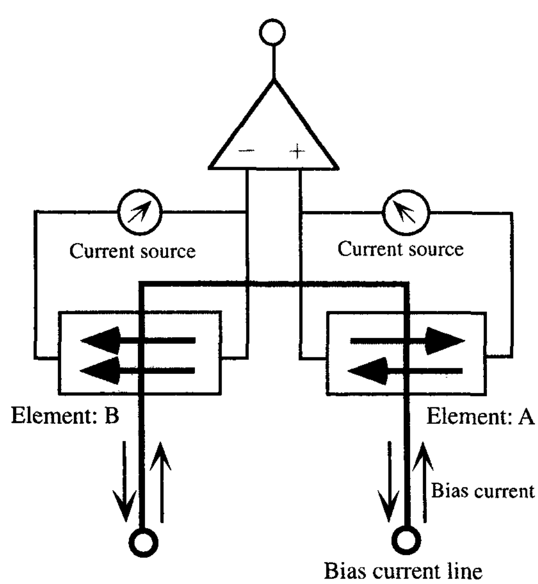

Fig. 4 Schematic structure of the GMR memory device of the differential type. The memory cell includes two storage elements of "A" and "B", and bias currents of each element are opposite in directions.

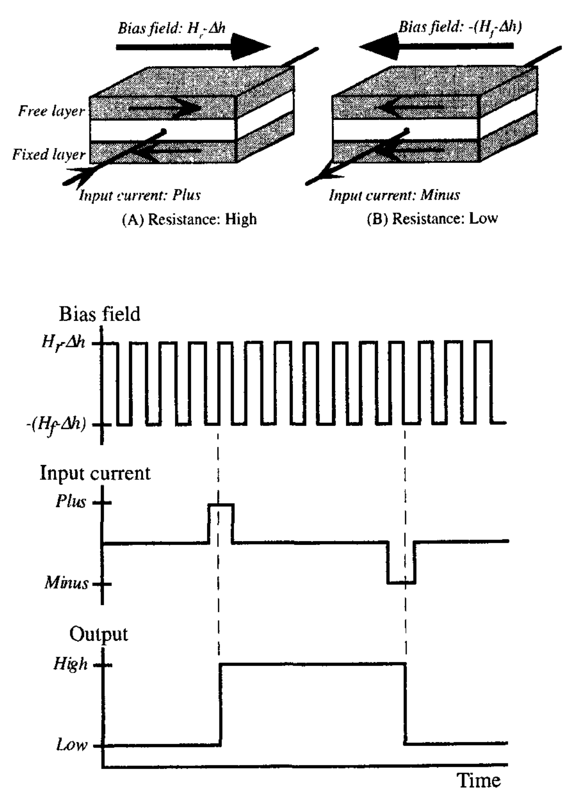

Fig. 5 Electric operating process of the spin device. The resistance of spin-valve element is controlled by the bias field and the input current.

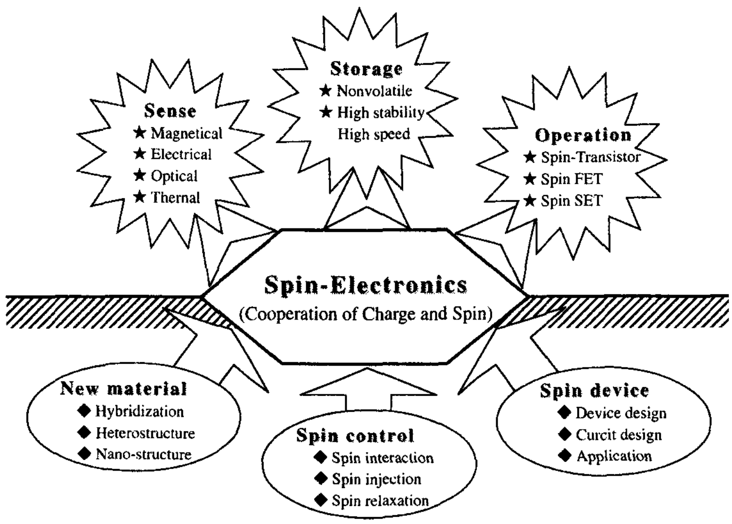

Fig. 6 Spin-electronics realizes high and new performance devices by utilizing the degree of electron spin-freedom.

the electron spin function. On the other hand, magnetic research and development had been restricted within passive devices, such as a recording medium and a sensor. Spin-electronics is that high-level and new performance devices are realized by actively using the degree of electron spin-freedom. Many new physical phenomena and devices, related electron spin, were reported in quite recently; such as the GMR, a tunnel MR [7], a spin blockade [8], the magnetic random access memory, the spin transistor [5], a spin-polarized field effect transistor [9] and a spin single electron transistor [10]. A combined function of some performances, such as the sensing, the information storage and the electric operation, is also likely to be realized by the single device, as shown in this paper. However, I think that it is very difficult to construct a new electronics instead of semiconductor device by spin device only. It might be possible to expand the semiconductor device by appending the spin dimension. Therefore, the harmonization of the magnetic and the semiconductor is important for the material development in spin-electronics, and will be achieved by a hybridized, a nano-structured and a diluted magnetic semiconductors. Spin control techniques, such as a spin interaction, a spin injection and a spin relaxation, are also an important keyword of course. And it is necessary to design the application and the device as capable of making the best of spin-electronics. Spin-electronics, as shown in Fig. 6, will attains new performances, which are impossible for semiconductor devices, on the basis of these fundamental factor.

4. CONCLUSION

We proposed a spin device having a combined function of some performances, such as the magnetic sensing, the information storage and the electric operation. The spin device consisted of the multilayered structure that includes the spin-valve element and the bias current line. The micro-sized spin-valve element, fabricated by sputtering method and optical lithography, exhibited the step shape MR loop. The magnetization and resistance of the spin-valve element was controlled by the magnetic field induced by the bias current. The spin device got new and high performances by arranging the bias current. Spin-electronics will be expanded over electronic device in the near future.

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(Received December 10, 1998; accepted April 14, 1999)