Thermal stability of low dose Ga\textsuperscript{+} ion irradiated spin valves

Xian-jin Qi, Yin-gang Wang, Guang-hong Zhou and Zi-quan Li

College of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

E-mail: qxjmsc@nuaa.edu.cn

Abstract. The thermal stability of low dose Ga\textsuperscript{+} ion irradiated spin valves has been investigated and compared with that of the as-prepared ones. The dependences of exchange field, measured using vibrating sample magnetometer at room temperature, on magnetic field sweep rate and time spent at negative saturation of the pinned ferromagnetic layer, and training effect were explored. The training effect is observed on both the irradiated spin valves and the as-prepared ones. The magnetic field sweep rate dependence of the exchange bias field of the irradiated spin valves is nearly the same as that of the as-prepared ones. For the as-prepared structure thermal activation has been observed, which showed that holding the irradiated structure at negative saturation of the pinned ferromagnetic layer for up to 28 hours results in no change in the exchange field. The results indicate that the thermal stability of the ion irradiated spin valves is the same as or even better than the as-prepared ones.

1. Introduction

The effect of ion irradiation on magnetic properties of thin films and multilayers has recently attracted considerable interest and a wide variety of phenomena have been reported [1]. For example, in perpendicularly magnetized Co/Pt multilayers [2], ion irradiation introduces in-plane magnetization. For exchange-biased IrMn/CoFe bilayers [3], decreases in exchange field and coercivity along with a change in the magnetization reversal mechanism with increasing ion dose was reported. For NiFe/CoFe/Cu/CoFe/IrMn spin valves, on both continuous films and patterned elements, it is observed that the Ga\textsuperscript{+} ion irradiation results in dramatic decreases in the GMR and the exchange bias field together with an increase in the film resistance [4,5]. Since the ion irradiation can modify the microstructure and thus properties of magnetic films, it can be used for maskless patterning of magnetic elements by altering magnetic properties of given regions instead of removing materials in conventional patterning such as photolithography and electron beam lithography [6,7].

In maskless patterning, the edge of the ion beam has a low dose effect on the edge of magnetic elements and will inevitably affect the thermal stability of the devices. On the other hand, spin valves are practically applicable systems in the information storage industry. In this work, we investigate the magnetization reversal of CoFe/Cu/CoFe/IrMn spin valves to gain a clear insight into how the thermal stability is affected by Ga\textsuperscript{+} ion irradiation at a low dose.
2. Experimental procedure
The spin valve structure Seed Ta (5nm) / Co₇₅Fe₂₅ (5nm) / Cu (2.5nm) /Co₇₅Fe₂₅ (5nm) /Ir₂₀Mn₸₀ (12nm) / Cap Ta (8nm) was deposited by magnetron sputtering on thermally oxidized silicon wafer substrates. It is in the “top” configuration, where the antiferromagnetic (AFM) layer was deposited onto the FM layer. The deposition conditions were: base pressure <5×10⁻⁷ Pa, Ar sputtering pressure 7×10⁻² Pa, deposition rate 0.03~0.12 nm/s. A magnetic field of 100 Oe was applied in order to induce magnetic anisotropy during FM and AFM films sputtering. Irradiation was performed in an FEI Strata 200XP FIB system using Ga⁺ ions of 30 keV and ion currents of 1 nA. The stack was evenly subjected to a dose of 10¹³ ions/cm².

The magnetic properties of the spin valve structures were investigated using a vibrating sample magnetometer at room temperature. The field range of loop measurement is set to be -800 Oe ~ +800 Oe. In training effect and waiting time measurements, the sweep rate of magnetic field was kept constant at 3 Oe/s in order to avoid different contributions from time-dependent effects. The magnetic field was applied parallel or antiparallel to the unidirectional easy axis, which coincides with the direction of the field applied during film growth. This indicates that there is little or no spin flop coupling between the AFM and FM moments at the interface.

3. Results and discussion
Figure 1 shows two series of hysteresis loops recorded sequentially showing the training effect for both the as-prepared and the Ga⁺ ion irradiated spin valves. As reported in ref. [8], the training effect on the forward branch of the loop is believed to be a result of thermal activation of AFM moment with a small time constant. Before starting the loop, all the AFM regions are aligned along or close to the positive direction. The exchange field induced by the FM layer at negative saturation results in some proportion of the AFM regions reversing and thus the exchange anisotropy decreases. As the number of magnetization cycles increases this reversed proportion approaches some equilibrium value so that the difference between one loop and the next becomes smaller.

![Figure 1](image)

**Figure 1.** Series of hysteresis loops for CoFe/Cu/CoFe/IrMn top spin valves recorded sequentially. (a) as-prepared. (b) Ga⁺ ions irradiated with a dose of 10¹³ ions/cm².

The dependences of the reverse fields $H_{c1}$ and $H_{c2}$ for the forward and recoil loops respectively on sweep rate of magnetic field $dH/dt$ are shown in Figure 2. One can see similar sweep rate dependences on both the as-prepared and the Ga⁺ ion irradiated spin valves. On the other hand, one can see that the coercivity increases as the sweep rate increases. A slow sweep rate permits the magnetization to decay during the measurement, driven by thermal activation. Hence, a slow sweep rate leads to a narrowing of the hysteresis loop. This dynamical behavior can be explained by a competition between the domain nucleation and domain wall propagation process [9]. At low sweep rates of magnetic field only a few inverse domains nucleate and the magnetization tends to switch by thermally activated domain wall
motion. While at high sweep rates, domain wall propagation becomes relatively slow compared to the variation of the applied magnetic field, thermally activated reversal becomes less effective and therefore more domains nucleate. Since the activation energy for domain nucleation is larger than that for domain wall propagation, for both the as-prepared and ion irradiated spin valves with the $dH/dt$ increasing the absolute values of $H_{c1}$ increase while those of $H_{c2}$ decrease.

![Figure 2](image1.png)  
**Figure 2.** Sweep rate dependences of $H_{c1}$ and $H_{c2}$ of the as-prepared and the ion irradiated spin valves.

Figure 3 shows the exchange field of both as-prepared and ion irradiated spin valves as functions of time spent at negative saturation of the pinned ferromagnetic layer. Firstly, one can see that the exchange field of ion irradiated spin valve is slightly lower than that of the as-prepared spin valve. This can be attributed to the modification of interface between the pinned FM layer and the AFM layer caused by ion irradiation [4]. The exchange field of the as-prepared spin valve decreases as the waiting time increases while that of the ion irradiated spin valve remains nearly unchanged, which indicates the thermal stability of the ion irradiated spin valve is better than that of the as-prepared spin valve. The decrease of the exchange field of the as-prepared spin valve with the waiting time increasing is believed to result from the reversal of regions of magnetization in the AFM layer driven by thermal activation over a high energy barrier (with large time constant) [8,10,11]. With the waiting time increasing, the exchange coupling between the pinned FM and AFM layers causes more of the AFM layer magnetization to rotate antiparallel to the unidirectional easy axis, which reduces the original unidirectional anisotropy, resulting in the exchange field decrease. The stable exchange field of the Ga⁺ ion irradiated spin valve is believed to result from the decrease of the degree of texture and the intermixing of atoms between various layers. Ga⁺ ion irradiation modifies the interface between the pinned FM layer and the AFM layer and thus the AFM spins are tied strongly to its crystal structure. Therefore the reversal or rotation of moments in bulk regions of the AFM layer has to overcome a much higher energy barrier and the energy induced by the applied field is not high enough to overcome this barrier.

![Figure 3](image2.png)  
**Figure 3.** $H_{ex}$ as a function of waiting time for the CoFe/Cu/CoFe/IrMn top spin valves.
4. Conclusion
In summary, the thermal stability of low dose Ga⁺ ion irradiated spin valves was investigated and compared with that of the as-prepared ones. The training effect is observed on both the irradiated spin valves and the as-prepared ones. The magnetic field sweep rate dependence of the exchange bias field of the irradiated spin valves is nearly the same as that of the as-prepared ones. For the as-prepared structure thermal activation has been observed while holding the irradiated structure at negative saturation of the pinned ferromagnetic layer for up to 28 hours results in no change in the exchange field. The results indicate that the thermal stability of the ion irradiated spin valves is the same as or even better than the as-prepared ones. This work demonstrates that Ga⁺ ion irradiation is a feasible technique to fabricate magnetoelectronic devices without a mask.

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