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Hall effect-induced acceleration of electromigration failures in spin valve multilayers under magnetic field

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It was observed that electromigration (EM)-induced failures in spin valve multilayers were severely accelerated by an externally applied magnetic field. The theoretical and experimental analysis results confirmed that Hall effect-induced Lorentz force applied to the perpendicular-to-the-film-plane direction is primarily responsible for the severe acceleration of the EM failures due to its dominant contribution to abruptly increasing local temperature and current density. The proposed failure model and the theoretical calculations were demonstrated to agree well with the experimental observations. © *2011 American Institute of Physics*. [doi:10.1063/1.3581042]

Recently, research interests on the electrical and magnetic reliability of giant magnetoresistance spin valves (GMR SVs) and magnetic tunnel junctions (MTJs) induced by electromigration (EM) failures have been dramatically increased in spintronics devices, such as a GMR SV read sensor and a toggle switching GMR or MTJ based magnetic random access memory (MRAM), due to the geometrically-induced higher operating current density, $J > 2\times10^7$ A/cm^2, and larger local temperature gradient in the multilayered thin films.[1–3] Accordingly, systematic studies of EM-induced magnetic and electrical degradations of magnetic thin films,[4] SV multilayers (SV-MLs), GMR SVs, and MTJs have been intensively done for the past ten years to understand the EM failure mechanism and to find effective solutions enabling to improving the reliability of GMR SV and MTJ based spintronics devices.[5,6] However, all the research activities have been made so far entirely focused on studying the physical mechanism responsible for the EM-induced failures under the accelerated electrical stress and temperature conditions, there has been no report on the physical effects of applied magnetic field including dc magnetic field, H_{dc}, and pulsed-dc (Pdc) magnetic field, H_{Pdc}, on the EM-induced failure lifetimes and its characteristics, although most of the GMR SVs, the SV MLs, and the MTJ based spintronics devices are operated by an externally applied magnetic field.[7]

In this letter, we report on the EM-induced failure characteristics and physical mechanism of SV-ML devices stressed by both magnetic and electric fields. The effects of magnetic fields on the EM-induced failure characteristics were systematically investigated by measuring the mean-time-to-failure (MTTF) of SV-ML devices under the different H_{dc} and H_{Pdc} with different duty factors. In order to precisely understand the physical nature of EM-induced failure mechanism of SV-ML devices under magnetic field, a theoretical model describing electron and mass transport, Joule heating, and thermal (local temperature) gradient in the SV-ML devices under both electric and magnetic fields was developed based on the Boltzmann transport equation. The physical validity of the proposed model was experimentally and theoretically verified.

The NiFe(3)/Co(0.5)/Cu(2)/Co(0.5)/NiFe(3 nm) SV-MLs commonly used as a part of GMR SV devices were deposited on Si (100) substrate using a dc magnetron sputter. The SV-ML devices with a width of 2 μm and a length of 20 μm were patterned using standard electron beam lithography and photolithography with an ion miller. An electromagnet precisely calibrated was used to apply H_{dc} or H_{Pdc} to the SV-ML devices electrically stressed by a dc current density of $J = 1\times10^7 - 1\times10^8$ A/cm^2. The applied H_{dc} was changed from 200 to 600 Oe and the duty factor of the H_{Pdc}, which is orthogonally applied to the electric field, was changed from 0.3 to 1 (cycle time: 20 s) at the fixed magnetic field of 200 Oe. In order to exclude the influence of interlayer coupling and magnetostatic coupling energy on the EM-induced change in resistance under both magnetic and electric fields, the applied magnetic field was controlled to be larger than the saturation magnetic field of the SV-ML devices. The TTF and the MTTF (t_{50}) were defined as the time for the resistance of the devices to increase by 100% and the exponential of the mean of the logarithm of TTFs, respectively.[8] The EM-induced failures were analyzed using a high resolution transmission electron microscopy (HR-TEM).

Figures 1(a) and 1(c) show the resistance change versus time for SV-ML devices stressed by both electric and magnetic fields. The current density applied to the SV-ML devices was constant kept at $J = 5\times10^7$ A/cm^2 and the applied H_{dc} was varied from 200 to 600 Oe. The H_{Pdc} was kept constant at 200 Oe with different duty factors of 0.3, 0.8, and 1, respectively. As shown in Figs. 1(a) and 1(c), the TTF of SV-ML devices had a strong dependence on the strength and duty factor of the applied magnetic field. In order to obtain a full picture of the MTTF dependence on the applied magnetic field, the cumulative failure percent with different field strengths and duty factors were determined based on the TTF of the SV-ML devices. As can be clearly seen in Fig. 1(b), the MTTF of electrically stressed SV-ML devices was inversely proportional to the applied magnetic field. A significant decrease in MTTF from 128.22 to 16.08 h was observed by increasing the H_{dc} from 0 to 600 Oe. In order to investigate the effects of magnetic field on the EM-induced failure lifetime characteristics in an environment more close to

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