Numerical failure analysis of current-confined-path current perpendicular-to-plane giant magnetoresistance spin-valve read sensors under high current density

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Thermomigration (TM)-induced failures occurred in the current-confined-path (CCP) current perpendicular-to-the plane (CPP) giant magnetoresistance spin valve (GMR SV) read sensors with Cu nanopillar metal paths (~5 nm in diameter) operating at a high current density ($J > 2 \times 10^7$ A/cm^2) have been numerically studied to explore the magnetic and electrical stability. The Cu interdiffusion (migration) from nanopillars into adjacent magnetic layers (e.g., CoFe) due to thermally induced mass transport was found to be the main physical reason for the magnetic failures of CCP-CPP GMR SV read sensors including the change in interlayer coupling and the reduction in exchange bias field as well as MR. Furthermore, it was numerically verified that the TM-induced failures are more dominant than the electromigration-induced failures at the higher current density beyond $J = 6 \times 10^7$ A/cm^2 in the CCP-CPP GMR SV read sensors. However, all the numerical calculation results demonstrated in this study clearly suggest that these undesirable electrical and magnetic failures occurred in the CCP-CPP GMR SV read sensors can be improved by tuning the path density, the purity (electrical resistivity), and the uniformity of Cu nanopillar metal paths.
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I. INTRODUCTION

In recent, giant magnetoresistance spin valves (GMR SVs) with current-perpendicular-to-plane (CPP) configuration have been drawn huge attraction due to their technical promises to the future read sensors for ultrahigh density magnetic recording. In particular, the low resistance-area (RA) product (<0.1 Ω μm^2) value of the metallic CPP GMR SVs leading to the lower noise level as well as the faster data transfer rate has been considered as the most crucial technical advantage over magnetic tunnel junctions in recording read sensor applications. However, the conventional metallic CPP GMR SVs has too low ΔRA and relatively too small GMR ratio (usually <2%) to be applied for the read sensors.[1] Therefore, how to effectively enhance the area resistance directly relevant to the increase in ΔRA has been considered as a key issue in practically applying the CPP-GMR SVs to the recording read sensors. Two major technical approaches have been recently attempted to improve the ΔRA as follows: (1) inserting novel materials with high spin polarization such as Heusler alloys in the free (or pinned) layers and between the nonmagnetic spacer and the magnetic layers to improve the spin-dependent interface and bulk scattering,[2] and (2) utilizing well-defined conducting channels within the spacer layer, which is known as the current-confined-path (CCP), to reduce the effective current flowing area resulting in the increase in effective resistance of the sensor.[3] However, the former approach was found to be technically limited by the easy loss of magnetization at room temperature for CPP GMR SV read sensor applications.[4] Hence, the latter approach has been considered potentially as one of the future generation of read sensors in ultrahigh density of magnetic recording technology. However, although the metallic nanopillar CCP was confirmed to effectively enhance the effective resistance and the GMR performance, the suddenly increased joule heating, and correspondingly induced large temperature gradient across the nanopillar CCP due to the geometrically accelerated current density, "current crowding effects" (typically, $J > 1 \times 10^8$ A/cm^2),[5] could give rise to severe electrical and magnetic degradation of the CCP-CPP GMR SV read sensors. Accordingly, the intensive studies on thermomigration (TM), which is defined as thermally-driven mass transport (atomic migration), and its failure mechanism occurred in the CCP-CPP GMR SV read sensors have been recently done to improve the electrical and magnetic stability. However, despite huge research efforts, the physical characteristics of TM-induced failures of the CCP-CPP GMR SV read sensors operating at a high current density have been still remained unclear up to now.

In this study, the TM-induced failure characteristics of CCP-CPP GMR SV read sensors operating at the different operating current densities have been numerically analyzed to evaluate the electrical and magnetic stability. The density, the distribution pattern, and the resistivity of the metallic (Cu) nanopillar CCP were considered as the main physical parameters in characterizing the TM behavior in the CCP-CPP GMR SV read sensors. In particular, in order to further clarify which failure mode, electromigration (EM) or TM,

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