Numerical simulation of current density induced magnetic failure for giant magnetoresistance spin valve read sensors

Ding Gui Zeng,[1] Kyung-Won Chung,[2] Jack H. Judy,[3] and Seongtae Bae[1,a)]
[1]*Department of Electrical and Computer Engineering, Biomagnetics Laboratory (BML), National University of Singapore, Singapore 117576*
[2]*Daion Co. Ltd., Incheon 405-846, South Korea*
[3]*Department of Electrical and Computer Engineering, The Center for Micromagnetics and Information Technology (MINT), University of Minnesota, Minneapolis, Minnesota 55455, USA*

(Received 10 June 2010; accepted 14 June 2010; published online 16 July 2010)

It was numerically demonstrated that current-in-plane (CIP) and current-perpendicular-to-plane (CPP) $Ir_{20}Mn_{80}$ based giant magnetoresistance spin valve read sensors operating at an extremely high current density ($J \geq 1 \times 10^8$ A/cm^2) show completely different electrical and magnetic failure mechanisms: (1) CIP read sensors, electromigration-induced Cu spacer diffusion and correspondingly degraded interlayer coupling were primarily responsible for the failures; while, (2) CPP read sensors, the deterioration of exchange bias due to thermomigration-induced Mn interdiffusion at the $Co_{80}Fe_{20}/Ir_{20}Mn_{80}$ interface was found to be dominant. The different temperature and current distribution resulting in different mass-transport mechanisms are the main physical reasons for the failure. © *2010 American Institute of Physics*. [doi:10.1063/1.3463380]

I. INTRODUCTION

As the magnetic recording density has been incredibly increased beyond 1 Tbit/in.^{2}, the geometry of exchange biased giant magnetoresistance (EBGMR) spin valve (SV) read sensors is dramatically reduced down to a few tens of nanometers and the current density for the sensor operation is correspondingly increased beyond $J = 1 \times 10^8$ A/cm^2.[1] Accordingly, the electrical and magnetic failures of EBGMR SV read sensors accelerated by the substantial electron wind force and joule heating, which are directly relevant to electromigration (EM) and thermomigration (TM)-induced mass-transport, become critical in the stability issue of EBGMR SV read sensors.

The research concern on the magnetic and electrical stabilities of EBGMR SV read sensors operating at the high current density were initiated approximately one decade ago for the current-in-plane (CIP) configuration.[2,3] However, all of the research efforts made so far were focused on the phenomenological observation of GMR degradation, thermally induced magnetic degradation due to joule heating, and EM-induced failure lifetime,[2,4] there have been no systematic studies to elucidate the physical failure mechanism. The main reason for this technical limitation is that the read sensors are completely encapsulated by the insulator as well as top and bottom magnetic shields. Therefore, it was not easy to analyze the fluctuation of temperature rise and the current density distribution inside the read sensors. Furthermore, as the configuration of EBGMR SV read sensor has been recently changed from CIP to current-perpendicular-to-plane (CPP) for the ultrahigh density of magnetic recording beyond 1 Tbit/in.^{2}, two major concerns directly relevant to the extremely high operating current density are critically raised: (1) which mass-transport mechanism (failure mode), either EM or TM, would be dominant for each configuration of EBGMR SV read sensor, and (2) which sensor configuration, either CIP or CPP, would be better for an ultrahigh density recording read sensor in terms of electrical and magnetic reliability.

In this work, we report on the numerically confirmed electrical and magnetic failure mechanism of CIP and CPP read sensors operating at an extremely high current density beyond $J = 1 \times 10^8$ A/cm^2 targeted for 1 Tbit/in.^{2} of magnetic recording density. In order to compare and to investigate the temperature and current density distribution for the understanding of EM and TM-induced mass-transport mechanism and the corresponding magnetic failure characteristics in the both CIP and CPP-EBGMR SV read sensors, three-dimensional (3D) thermoelectrical models based on finite element method were employed for the detailed quantitative analysis.[5]

II. NUMERICAL MODEL

The CIP and CPP-EBGMR SV read sensors with identical magnetic shields (Permalloy) and geometry but different shield-to-shield gap were considered for the numerical calculation. The CIP read sensor had an 80 nm thick Al_2O_3 layer for the dielectric gap.[6] The dimension of magnetic shields was fixed at a 2 μm(W, width) $\times$ 2 μm(L, length) $\times$ 2 μm(thickness) and the EBGMR SV consisted of Ta (2.7)/$Ni_{80}Fe_{20}$ (3.6)/$Co_{80}Fe_{20}$ (0.9)/Cu (2.7) /$Co_{80}Fe_{20}$ (3.6)/Ru (0.9)/$Co_{80}Fe_{20}$ (3.6)/$Ir_{20}Mn_{80}$ (14.4)/Ta (4.5 nm) had the same geometry of 40 nm(W) $\times$ 80 nm(L) for both CIP and CPP configuration. In order to analyze the different temperature rise and current distribution inside the CIP and CPP read sensors, 3D electrical-thermal calculations of GMR spin valve systems were done using a numerical finite element method by solving following equations:

$$\nabla \cdot J = 0,$$

[a)]Electronic mail: elebst@nus.edu.sg.

