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主論文の要旨

論文題目　**Study of thermally-assisted spin-transfer torque switching of hybrid memory layer consisting of low Tc CoPd/Pd and high Tc Co/Pd MLs**
（低キュリー温度CoPd/Pd多層膜と高キュリー温度Co/Pd多層膜を用いたハイブリッドメモリ層の熱アシストスピン注入磁化反転についての研究）

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論文内容の要旨

Non-volatile memory (NVM) with properties of high writing endurance, high-speed, high-density, and low power consumption is required for the Internet of Things (IoT) society. Spin-transfer torque (STT) magnetoresistive random-access memory (MRAM) is considered to be a promising application as the universal memory.

Although MRAM using magnetic tunnel junctions (MTJ) with a perpendicular magnetized memory layer has a capacity of 1 Gbit, the dilemma of a high magnetic anisotropy K_u and a low switching current density J_c still impedes further increase in the memory density of STT-MRAM. The thermally-assisted (TA) writing method is considered as a promising writing scheme for the increase of the memory density, because no extra structure or processes is required for the writing operation.

Recently, a numerical study given by Machida *et al.* shows that low Curie temperature (T_C)/high T_C hybrid bi-layer memory layer is expected to have the gain ~4 of Δ/ I_c to realize high-density TA STT-MRAM, where Δ is the thermal stability factor and I_c is the critical STT switching current. In order to realize the hybrid memory layer (HML), the materials with low T_C and high perpendicular magnetic anisotropy (PMA) is required. In this study, a CoPd/Pd multilayer (ML) is proposed to be used as a low T_C layer of the HML, since it is expected to exhibit a large PMA and adjustable T_C by modifying the concentration of Co in the CoPd alloy layer. This dissertation summarizes the study on the TA effect of STT switching of current-perpendicular-to-plane (CPP) giant-magneto-resistance (GMR) structure with the HML with low T_C CoPd/Pd ML and high T_C Co/Pd MLs.

In chapter 1, traditional solid-state memories like DRAM, SRAM, and Flash memory were briefly introduced to understand the background of the memory market and requirements. The background of NVMs and the basics of MRAM were introduced, and some of the important previous studies for TA STT-switching were reviewed. The material candidates of high T_C and low T_C layers for the HMLs were summarized, and the objective of this research was described.

In chapter 2, the sample preparation, micro-fabrication, and measurement methods were reviewed. The magnetron sputtering method for the growth of GMR films, and the sputtering equipments for this study are introduced. The GMR films were micro-fabricated to the CPP pillar structure, and the procedure of the micro-fabrication was summarized. The principles measurements, alternating gradient magnetometer (AGM), torque magnetometer, and magneto-optical Kerr effect, to characterize the magnetic properties of the as-deposited film were described. The measurement setups for magneto-resistive (MR) effect and STT switching of CPP-GMR pillars were also described. Furthermore, the basics of magnetization dynamics and time-resolved magneto-optical Kerr effect (TRMOKE) measurement to understand the dynamical behaviors of HMLs were introduced in the last part of this chapter.

In chapter 3, the properties of Co/Pd MLs and CoPd/Pd MLs were investigated, including the magnetization, PMA, etc. From the result, it is concluded that these MLs are suitable for high and low T_C structures in the proposed HML. Then the TA field-induced magnetization switching (TA-FIMS) of Co/Pd ML exchange coupled with CoPd/Pd ML is discussed. The Co/Pd and CoPd/Pd MLs were confirmed to be exchange-coupled for $t_{Pd} \leq 1$nm, and the TA-FIMS was confirmed for the HML with $t_{Pd} \leq 1$nm. In the last section, a tri-layered HML was proposed as a potential memory layer to increase the TA gain.

In chapter 4, the STT-switching of CPP-GMR cell consisting HML $[Co(0.4)/Pd(1.2)]_{3-N}$ / $[CoPd(0.4)/Pd(1.2)]_N$ (N= 0, 1, 2, 3) was investigated. The composition of the HML was varied with the repetition number N of low T_C ML while keeping the total layer number of 3. STT switching of the HMLs was confirmed by using CPP-GMR pillars with diameters from Φ120 nm to Φ300 nm. The critical current density J_{c0} and thermal stability factor Δ were estimated from the pulse width dependence of the STT switching current, and all HMLs have J_{c0} = 40~70 MA/cm^2 and Δ = 50~80 at room temperature (RT). Moreover, the temperature dependences of J_{c0} and Δ for all samples were analyzed to confirm the TA effect using HMLs. The J_{c0} and Δ of the HMLs were found to decrease with increasing temperature. The efficiency of TA STT-switching could be defined as the ratio of Δ at RT and J_{c0} in MA/cm^2 at high temperature of ~150˚C. The efficiency was evaluated to be 2.6 and 4.5

for the HML with N = 0 and N = 2, respectively. Thus the density gain by using HML can be estimated to be ~2, indicating that the memory density could be doubled by using the HML. Thus, a HML with low T_C CoPd/Pd MLs is a promising candidate as a memory layer of the TA STT-MRAM.

In chapter 5, the interface high T_C Co/Pd layer in the HML was modified by changing the thickness ratio of Co and Pd, and the STT switching of the HML is discussed. CPP-GMRs with a stack of $[\mathrm{Co}(x)/\mathrm{Pd}(1.6–x)]_1/[\mathrm{CoPd}(0.4)/\mathrm{Pd}(1.2)]_2$ (x = 0.4, 0.6, 0.8 nm) were fabricated and the temperature dependences of J_{c0} and Δ were analyzed to evaluate the TA effect using different interface layers. The J_{c0} and Δ of all samples gradually decreased with increasing temperature. The memory density gain is expected to be tripled by using $[\mathrm{Co}(0.6)/\mathrm{Pd}(1.0)]_1/[\mathrm{CoPd}/\mathrm{Pd}]$ HML. Moreover, the J_{c0} at RT of the HML with x = 0.8 was found to drastically decrease compared to the other samples. The temperature dependence of effective anisotropy constant K_{eff} and magnetization dynamics of the HMLs were investigated to explain the temperature dependence of the STT-switching of HMLs. The magnetization dynamics and STT-switching of HMLs assuming a variable exchange coupling between low T_C and high T_C multilayers are also studied by simulation. When the exchange coupling strength S between the interface high T_C ML and low T_C ML was is reduced from 100% to 3%, only one precessional angular frequency of $\omega \sim 340$ Grad/s was confirmed, indicating a simultaneous precession of the two MLs. On the other hand, two precessional frequencies were observed when $S < 3\%$, indicating independent precessions of interface ML and low T_C CoPd/Pd ML. The STT switching of HMLs has also been simulated to confirm the relationship between the exchange coupling strength S and J_{c0} of the HML. In the region of S from 100% to 3%, J_{c0} of the HML was roughly constant. With decreasing S from 3 to 1%, J_{c0} was found to significantly increase due to the decoupling between the interface and low T_C MLs during the STT switching. From the simulation as well as experiments of magnetization dynamics, the increase in J_{c0} at RT and large TA effect of STT switching for the $[\mathrm{Co}(x)/\mathrm{Pd}(1.6\text{-}x)]_1/[\mathrm{CoPd}/\mathrm{Pd}]_2$ HML when $x \leq 0.6$ nm were concluded to be explained by the decoupling at the interface between high T_C Co(x)/Pd(1.6-x) and low T_C CoPd/Pd MLs.

In the last chapter, the experimental and simulation results was summarized, and the discussion for further investigations was described. Density gain of 3 by using HML was realized, but further understand of HML is still required to reach the density gain of 10, which can enable the MRAM density compete with the current DRAM for main memory application.