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著者(和文)	許 欣星
Author(English)	Xinxing Xu
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論 文 要 旨

THESIS SUMMARY

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学生氏名： Student's Name	Xu Xinxing	指導教員（主）： Academic Supervisor(main)	中村 吉男
		指導教員（副）： Academic Supervisor(sub)	史蹟

要旨（英文 800 語程度）
Thesis Summary（approx.800 English Words ）

Soft magnetic materials are defined as the materials whose coercivity is smaller than 1000 A/m, and they are widely applied in electronic devices, such as magnetic recording head, planar inductor. FeCo based thin films are extraordinary candidate soft magnetic materials due to their large saturation magnetization, high permeability and high curie temperature properties. However, the coercivity of the FeCo thin film is relatively large, and the magnetostriction is strong, the electrical resistivity is low, which limits its application, especially in high-frequency area. Nitrogen doping is supposed to resolve these problems. Up to now, various works have been conducted on Fe-N system, while few studies have reported on Fe-Co-N system. For this reason, we prepared a series of FeCoN thin films sandwiched by AlN layer using direct current reactive magnetron sputtering method in this work. The nitrogen content in the FeCoN thin films is controlled by adjusting the N_2 gas flow ratio. First, the formation of iron cobalt nitrides, and the effect of nitrogen contents on film structure and film properties are systematically investigated. Second, in order to decrease the coercivity of FeCoN films at high temperature, the exchange coupling behavior between soft/hard FeCo(N) layer with different nitrogen contents are studied. Third, an abnormal angle-dependent inverted hysteresis loop in the FeCoN films are observed, and the corresponding mechanisms are discussed. Details are summarized as follows:

First, we have systematically investigated the effects of nitrogen concentration, annealing temperature and Fe-Co ratios on microstructure and magnetic properties of FeCoN films. The nitrogen gas flow ratio (N_2/Ar+N_2) is set from 0%-50%. It is revealed that the main phase of films transforms from polycrystalline α-FeCo(N) to amorphous-like γ'-$(Fe,Co)_4N$, polycrystalline ε-$(Fe,Co)_3N$ and ξ-$(Fe,Co)_2N$ with increasing N_2 flow ratio. The amorphous-like γ'-$(Fe,Co)_4N$ films possess the optimal soft magnetic performance, since they have a relatively high saturation magnetization (986-1431 emu/cc), low coercivity (8-10 Oe), almost zero magnetostriction coefficient and high electrical resistivity (> 170 μΩ·cm). The formation of amorphous-like phase with extremely fine microstructure account for the low coercivity. Furthermore, vacuum annealing has been carried out over a temperature range of 100 to 600 °C for the films with N_2 ratios ranging between 20%-40%. The saturation magnetization of the films largely increases after the films are annealed at 350 °C, which is caused by the decomposition of the nitride phases into α-FeCo(N) during the annealing process. The coercivity of the 20% and 30% N_2 films shows strong annealing temperature dependence, and it increases at first and then decreases. The changes in film stress and the formation of new phase during annealing account for the variation of coercivity.

Second, we found the thermal stability of amorphous-like FeCoN films is poor, the coercivity of the films will largely increase after annealing at high temperature, though they have optimal properties in the as-deposited state. This problem is solved by exchange coupling with FeCo layers. The FeCoN layer is deposited with 20-30% N_2 gas flow ratio, and the film structure includes FeCo/FeCoN bilayer, FeCo/AlN/FeCoN trilayer. The crystal information and magnetic properties of these multilayer films are studied. For the FeCo/FeCoN bilayer films with different FeCo layer thickness, a single-phase hysteresis loop without kinks can be observed, indicates the strong exchange coupling between the FeCo layer and the FeCo layer. The coercivity of the bilayer films increase with the increase of FeCo layer thickness. After annealing at 200-250 °C for 1 hour, The coercivity of annealed films largely decreases as the FeCo layer thickness is greater than 3 nm, and the saturation magnetization increases as well. Moreover, the phase transition ($\gamma' \rightarrow \varepsilon$) of FeCoN films during annealing is suppressed. For the FeCo/AlN/FeCoN trilayer films with different non-magnetic AlN spacer layer thickness, The FeCo layer and FeCoN layer become

decoupled when the spacer layer is thick, while a magnetic exchange spring occurs for the thickness of AlN layer is 1-2 nm. Two layers are in contact through the holes in the AlN spacer layer, leads to an weaken exchange coupling. When the AlN spacer layer thickness decreases to 0.5 nm, two layers are strongly exchange coupled.

Final, an abnormal phenomenon of inverted hysteresis loop (IHL) has been observed when we measuring the out-of-plane magnetic hysteresis loop of FeCoN amorphous films using VSM equipment. In addition, IHL shows angle dependence. The sample plane deviates from the center plane by a small angle during VSM measurement, causing the differences in magnetic properties when rotate the sample around film normal direction. The mechanism of IHL is clarified by measuring the film anisotropies and full-angle out-of-plane hysteresis loops. It revealed that uniaxial planar-anisotropy and biaxial anisotropies co-exist in the FeCoN film. The uniaxial anisotropy of the FeCo film is induced by the sputtering field, and the bi-axis anisotropy is originated from the inclined deposition in the facing-targets-sputtering system. The inverted hysteresis loop is caused by the anti-ferromagnetic coupling of two different magnetization components at low applied field, and the two components originate from the inhomogeneous compositions in the film. The angular dependence is determined by the rotation of in-plane magnetization component under the competition of the anisotropies.