Adjust the resonance frequency of $(Co_{90}Nb_{10}/Ta)_n$ multilayers from 1.4 to 6.5 GHz by controlling the thickness of Ta interlayers

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(Received 19 November 2009; accepted 15 December 2009; published online 7 January 2010)

In this work, the static and high frequency magnetic properties of $(Co_{90}Nb_{10}/Ta)_n$ multilayers have been investigated. The results show that the in-plane uniaxial magnetic anisotropy fields can be adjusted from 12 to 520 Oe only by decreasing the thickness of Ta interlayers from 8.0 to 1.8 nm. As a consequence, the resonance frequencies of the multilayers continuously increased from 1.4 to 6.5 GHz. It was found that the changes in the in-plane uniaxial anisotropy field are ascribed to the interlayer interactions among the magnetic layers by investigating the $\delta M(H)$ curves. © *2010 American Institute of Physics*. [doi:10.1063/1.3290252]

Recently, high permeability of magnetic materials at high frequency is a persistent requirement for planar inductor, microtransformer, electromagnetic interference suppressor, and even metamaterials.[1–5] As operating frequency has reached gigahertz with a wide band to increase the data transition rate in modern technology, e.g., 2.4 and 5.8 GHz are typical frequencies for bluetooth technology.[6] Most of recent works found kinds of films with unitary high resonance frequency, however, most of them cannot adjust the resonance frequency with a wide band with same composition.[7–9] So it is valuable to find a sample whose resonance frequency can be adjusted in a wide band. According to some early works, microwave properties can be significantly affected by the magnetic anisotropy.[10,11] Thin films with in-plane uniaxial magnetic anisotropy (IPMUA), which can extend the Snoek's limit,[12–16] have a static permeability $\mu_s = 1 + 4\pi M_s/H_k$, and a resonance frequency $f_r = \gamma/2\pi(4\pi M_s H_k)^{1/2}$, where M_s is the saturation magnetization, H_k is the IPUMA field, γ is the gyromagnetic factor. With the relationships, μ_s and f_r can be optimized by tailoring the magnitude of the IPUMA field H_k. It is essential for the high frequency application of soft magnetic thin films.[17]

For single layer films, the IPUMA field can be controlled in several ways. Such as ex situ annealing in a magnetic field,[18] *in situ* depositing on prestressed substrates[19] changing oblique angles and so on.[20] However, any post fabrication treatment may affect the other components of the entire circuit into which the magnetic films have been integrated; it is difficult to employ the stress induced method in films deposited on hard substrates; while in the case of changing the oblique angles, it may lead to the nonuniformity in the thickness of film for a large oblique angle (>30°, for example). In this work, we have found a simple and effective method to control the H_k of multilayers from 12 to 520 Oe just by decreasing the thicknesses of interlayers from 8.0 to 1.8 nm. As a consequence, an improvement of f_r of the $(Co_{90}Nb_{10}/Ta)_n$ multilayers from 1.4 to 6.5 GHz could be achieved.

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The multilayers were prepared by radio frequency (rf) sputtering onto 10 mm × 20 mm × 0.42 mm (111)-oriented Si substrates, which is attached to a water-cooling system, with background pressure lower than 5×10^{-5} Pa. A Ta target, 70 mm in diameter and 3 mm in thickness, was used to deposit Ta layers; and a Co target, the same size as Ta target, on which Nb chips were placed in a regular manner, was used to deposit $Co_{90}Nb_{10}$ layers. Magnetic layers were deposited at an angle 24° to attain uniaxial anisotropy.[20,21] The composition of the deposited magnetic layers was adjusted by controlling the number of the Nb chips. During sputtering, an Ar flow rate of 20 SCCM (SCCM denotes cubic centimeter per minute at STP) was needed to maintain an Ar pressure of 0.15 Pa, and the rf power density was kept at 1.7 W/cm^2. The structures of $(Co_{90}Nb_{10}/Ta)_n$ multilayer thin films with a Ta buffer layer was shown in Fig. 1. Thickness of each $Co_{90}Nb_{10}$ layers is 11.5 nm and Ta interlayers are changed from 8.0 to 1.8 nm for different samples. The static magnetic properties were measured by vibrating sample magnetometer (Lakeshore model 7304), H_k was determined by calculating the measured easy axis and hard axis loops of the reduced magnetization. The microwave permeability measurements of the films were carried out with a PNA E8363B vector network analyzer using the microstrip method from 100 MHz to 8 GHz.[22] f_r and damping parameter α were determined by fitting the permeability spectrum with Landau–Lifshitz–Gilbert equation.[23]

The static magnetic hysteresis loops reveal that these samples were well defined IPUMA form. The in-plane hys-

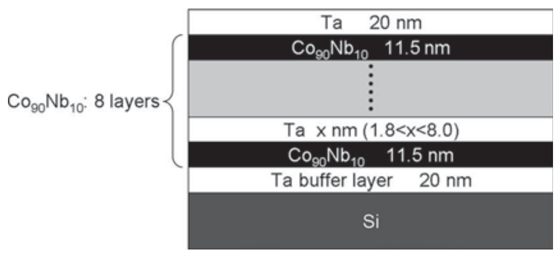

FIG. 1. The structure of $(Co_{90}Nb_{10}/Ta)_n$ multilayers on a 20 nm Ta buffer layer. Thickness of each $Co_{90}Nb_{10}$ layers is 11.5 nm and Ta interlayers change from 8.0 to 1.8 nm for different samples.

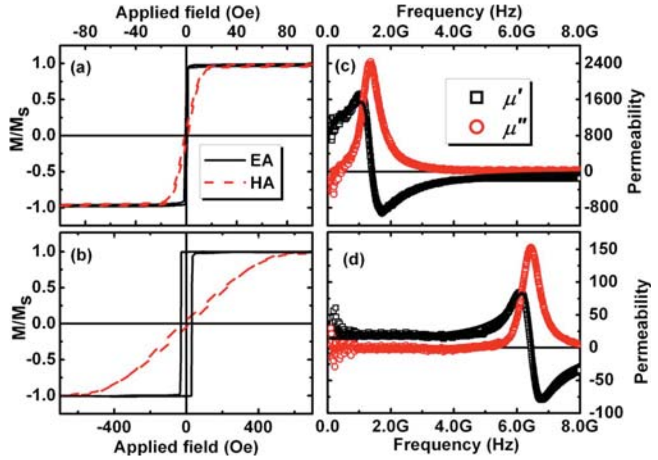

FIG. 2. (Color online) In-plane hysteresis loops (left column) and frequency dependences of the real (μ') and imaginary (μ'') components of the permeability (right column) of the $(Co_{90}Nb_{10}/Ta)_n$ multilayers with different thickness of Ta interlayers with $x=8.0$ nm [(a) and (c)] and $x=1.8$ nm [(b) and (d)]. The lines in [(c) and (d)] mean the fitting curves with LLG model.

teresis loops of the $(Co_{90}Nb_{10}/Ta)_n$ multilayers with Ta interlayer thickness of 8.0 and 1.8 nm are shown in Figs. 2(a) and 2(b), respectively. The loops along the easy axis are basically a rectangle for both samples with lower H_c and the remanent magnetization ratio $M_r/M_s \sim 1$; the loops along the hard axis (HA) demonstrate obvious magnetic anisotropy with 12 and 520 Oe. The high frequency performances of these multilayers are shown in Figs. 2(c) and 2(d), where the static permeability $\mu_s=894$ and $f_r=1.4$ GHz is achieved for sample with thickness of Ta interlayers $x=8.0$ nm as well as $\mu_s=21$ and $f_r=6.5$ GHz for $x=1.8$ nm. All these permeability spectrums can be well fitted by using Landau–Lifshitz–Gilbert model,[23] which proved that the resonance modes are natural resonances. The high frequency performance of $(Co_{90}Nb_{10}/Ta)_n$ multilayers can be controlled by adjusting the thicknesses of the Ta interlayers. As shown in Fig. 3, the values of f_r, and H_k adjust from 6.5 GHz and 520 Oe to 1.4 GHz and 12 Oe while thicknesses of the Ta increase from 1.8

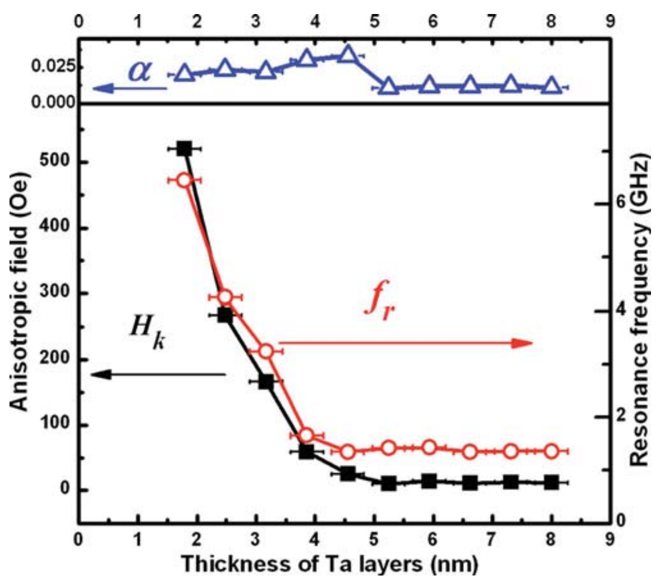

FIG. 3. (Color online) The experimental results of resonance frequency f_r, damping parameter α and IPUMA field H_k of $(Co_{90}Nb_{10}/Ta)_n$ multilayers with different thickness of Ta interlayers.

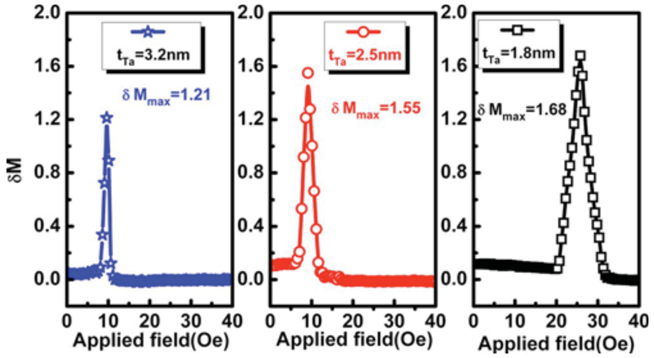

FIG. 4. (Color online) The $\delta M(H)$ plots for $(Co_{90}Nb_{10}/Ta)_n$ multilayers with different thickness of Ta interlayers as 3.2, 2.5 and 1.8 nm.

to 8.0 nm with small changes of damping parameters.

In the series of $(Co_{90}Nb_{10}/Ta)_n$ multilayers, every $Co_{90}Nb_{10}$ layer with same thickness of 11.5 nm was deposited on the Ta layer alternately, so, the structure and magnetic properties of each $Co_{90}Nb_{10}$ layer should be the same with each other. As the only difference of these multilayers is the spacing of the magnetic layers, the change of the magnetic properties might derive from the interlayer interactions. The $\delta M(H)$ curve is often employed to analyze the interaction in permanent magnetic materials and magnetic recording materials.[24,25] According to Stoner–Wohlfarth's theory,[26] for an assembly of noninteracting single domain granule with uniaxial anisotropy, the relationship between the isothermal remanent magnetization $M_r(H)$ and the dc demagnetization remanence $M_d(H)$ is shown as follows:

$$M_d(H) = 1 - 2M_r(H), \tag{1}$$

where $M_r(H)$ is measured starting from a demagnetization state, after the initial application and subsequent removal of a field H, whereas $M_d(H)$ is obtained after technical saturation in one direction and the subsequent application and removal of a field H in the reverse direction. However, for an interacting system, the Eq. (1) is not valid because of the interaction between granules and interlayers,[27] which can be quantitatively expressed by a $\delta M(H)$ curve as follows:[28]

$$\delta M(H) = M_d(H) - [1 - 2M_r(H)]. \tag{2}$$

Positive $\delta M(H)$ represents that the interaction forces the magnetizations parallel, while negative $\delta M(H)$ means that interaction tends the magnetizations antiparallel.[26,27] Furthermore, the maximum value of $\delta M(H)$ [$\delta M(H)_{max}$] reflects the intergranular or interlayer interaction intensity.[26–30] As the structure and magnetic properties are same for each $Co_{90}Nb_{10}$ layer, the difference of $\delta M(H)_{max}$ should be only caused by the interlayer interactions. The $\delta M(H)$ curves for samples with Ta interlayers 1.8, 2.5, and 3.2 nm are shown in Fig. 4. It can be seen that the δM are positive which implies the existence of interlayer interactions between $Co_{90}Nb_{10}$ layers that forces the magnetizations parallel. So the large IPUMA fields may be caused by the strong interlayer interaction between $Co_{90}Nb_{10}$ layers. And $\delta M(H)_{max}$ decrease while thickness of Ta layer increasing, means that the interlayer interaction decrease while the thickness of Ta layer increasing. As a sequence the IPUMA fields increase with the increasing interactions between $Co_{90}Nb_{10}$ layers. The tendency is more like the long-range exchange interaction in exchange bias system.[31] But here, we have to note that this is only the experimental result, the detail of the mechanism need to be studied with more evidences.

In summary, this work provide an approach to modify the resonance frequency of $(Co_{90}Nb_{10}/Ta)_n$ multilayers over a wide range. Moreover, the multilayers with adjustable IPUMA field can be conveniently obtained only by changing the thicknesses of the Ta interlayers. For high frequency application of soft magnetic thin films, it is essential to obtain IPUMA and control over the magnitude of the IPUMA *in situ*. Our work provides a feasible and simple approach to control the IPUMA field of the samples with certain compositions, which can further promote the application of soft magnetic thin films in the gigahertz region.

The authors should thank Dr. Qingqing Pan for English revision. This work is supported by National Natural Science Foundation of China (NSFC) (Grant No. 10774062), National Science Fund for Distinguished Young Scholars (Grant No. 50925103), and Keygrant Project of Chinese Ministry of Education (Grant No. 309027).

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