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Spin dynamics of polycrystalline Ni films on Si substrate

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ABSTRACT

We have prepared thin Ni films by direct electrodeposition onto Si substrates and investigated the magnetization dynamics up to 9 GHz. Films with typical thickness of 200 nm show good adhesion to the substrate. Experimental absorption spectra were fitted using a model, which combines the magnetization dynamics according to Landau–Lifshitz–Gilbert and eddy current contribution. Damping parameters ranging from 0.12 to 0.08 were obtained. These values are larger than the intrinsic damping parameter of 0.064 for Ni, which indicates that the effect of eddy current is the prime contribution to line broadening in the electrodeposited Ni/Si structure. The dependence of damping parameter on applied field also supports this idea, the larger the applied field the smaller the damping parameter is.

1. Introduction

Recently, the integration of magnetic components onto silicon has added a renewed interest in the development of soft magnetic materials to operate at high frequencies [1–3]. The basic material requirements for recording head and microinductor/microtransformer applications are high-magnetization saturation, low coercivity and high resistivity. The use of magnetic components is particularly attractive for power conversion operating at frequencies close to and beyond the GHz range. At these frequencies, passive component value requirements are significantly reduced so that integration onto the integrated circuit can be considered [4].

Among the various techniques currently being exploited for integration, electrodeposition shows advantages over vacuum deposition, sputtering and high-temperature sintering techniques because it is fast, relatively inexpensive, operates at low temperature and it is integration compatible. However, electrochemical deposition usually requires a conductive seed layer, which may affect high-frequency performance. The possibility of plating directly a magnetic layer onto semiconductor substrate offers an attractive avenue for simplifying the integration process and has been demonstrated in the literature for NiFe [5–7]. The static magnetic properties of these NiFe‖Si structures is far from optimum with film thickness limited to a fraction of micron due to stress and coercivities larger than 318 A m^{-1} (4 Oe) [6,7]. Furthermore, very little is known about the dynamic behavior of these structures at high-frequency operation.

Here, we investigated experimentally the spin dynamics of Ni films electroplated directly onto Si substrate. This simple system was chosen to avoid the complication of composition inhomogeneity, which may arise from electrodeposited alloy and cannot be easily de-convoluted from other sources of line broadening. As shown, by using a single metal we found a clear correlation between line broadening and eddy current reflected on the damping parameter(α) for electrodeposited Ni. Furthermore, we compare our results to numerical predictions using the Landau–Lifshitz–Gilbert (LLG) equation combined with eddy current.

2. Experiment

The electrodeposition of Ni films was carried out using a solution containing 0.7 M of $NiSO_4$, 0.4 M of boric acid, 0.02 M of $NiCl_2$ and 0.016 M of saccharin, which is used as a stress reducing agent. The use of saccharin proved necessary for obtaining compact and smooth deposits with shiny appearance and good adhesion to the substrate. Solutions were prepared using deionised water with resistivity of 18 MΩ cm and the pH was adjusted to 3.5 by adding small amounts of sulfuric acid. Deposit thickness was determined using a Tencor Alpha-Step 200 surface profilometer

Ni films were electrodeposited onto Si substrate with a working area of 5×5 mm^2 defined by varnish from electrolytes at room temperature. The Si substrates were activated by etching in a commercial HF solution for a period of 30 s prior to deposition. Given the corrosive nature of HF, robber gloves, fume hood, acid-proof vest and face shield were used during substrate activation, which is used to remove any residual layer of Si-oxide. Then the substrate was washed in a continuous flow of

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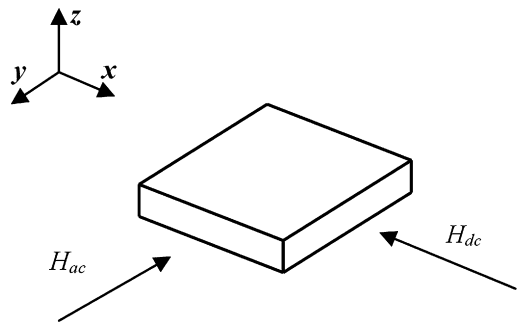

Fig. 1. Schematic diagram showing the direction of applied field (H_{dc}), laboratory reference axis and alternating field (H_{ac}) used in the high-frequency permeability experiments.

deionised water for 30 s. Films with thickness of 100–500 nm were galvanostatically deposited with current densities of 8–32 mA cm^{-2}.

Magnetization measurements were carried out at room temperature using a commercial 5 T SQUID magnetometer (MPMS-XL5), whereas the dynamic response of the films was characterized using 0.001–9 GHz permeameter Ryowa PMM 9G-1. In this wide band high-frequency permeability measurement an AC magnetic field is applied in plane of a strip sample as illustrated in Fig. 1. We studied the line broadening of ferromagnetic resonance peak (FMR) of the deposits by applying an in-plane magnetic field ranging from 0 to 30 mT orthogonally to the AC exciting field.

3. Results and discussion

We have varied the film thicknesses of Ni by controlling deposition time and current density. Films plated at current density between 8 and 32 mA cm^{-2} were smooth, shiny and only showed good adhesion for thickness typically smaller than 250–350 nm. We observed a similar behavior when varying the plating time for a fixed current density of 8 and 16 mA cm^{-2}. After a threshold of about 350 nm, the films had the tendency to peel-off the Si substrate. We classified the electroplated films into two categories: adhesive and non-adhesive films. The transition from one category to the other occurs roughly in accordance with a critical surface normalized thickness given by a simple relation $J \cdot t = 300\,\mathrm{C\,cm^{-2}}$, where J is the current density and t is the deposition time. This correlation is valid as long as current efficiency does not vary much with plating current density. The thickness threshold of 350 nm can be understood in terms of stress in the films, once the force due to stress is larger than the adhesion force between film and substrate the film will peel-off.

We focus our analysis on films with thickness of 200 nm, which is below the peeling off threshold. A typical in-plane room temperature magnetization curve on Ni film is shown in Fig. 2. We observed that the magnetization curves measured with an applied field in the plane were identical regardless of the direction of the applied field in relation to film orientation. This indicates that the films are isotropic in the film plane. Coercivities ranged between 1.36 to 2.4 kA m^{-1} (17–30 Oe) with saturation magnetization of 0.58 T.

The spin dynamics are described by the Landau–Lifshitz–Gilbert equation of motion of magnetization [8,9] as

$$dM/dt = -\gamma' M \times H_{eff} + (a\gamma'/M_s) M \times (M \times H_{eff}) \tag{1}$$

Here, $\gamma' = \gamma/(1+\alpha^2)$, where $\gamma = 2\pi g \mu_B / h$ is the gyromagnetic ratio, g is the g-factor, μ_B is the Bohr magneton, h is the Planck's constant and α is dimensionless damping constant. The effective field (H_{eff}) is composed of anisotropy field (H_{ansi}), exchange field (H_{exch}), AC field (H_{ac}) and applied field (H_{dc}). The net contribution of eddy current is generally assumed to be already included in the damping parameter of the LLG equation and good representation is obtained for materials with small conductivities. However, as the conductivity increases the material will experience induced circulating currents, which in turn will produce a extra magnetic field (H_{eddy}). Therefore further refinement can be obtained by coupling the LLG with Maxwell's equation [9] for better representation of highly-conductive magnetic layer. This correction due to eddy current is obtained by introducing an extra field term to the effective field that is equivalent to $H'_{eff} = H_{eff} + H_{eddy}$. This additional term is calculated by solving the LLG equation simultaneously with the Poisson type equation deduced from Maxwell's equation as [9]

$$\nabla^2 H_{eddy} = \sigma \mu_0 \left(\frac{\partial H_{eddy}}{\partial t} + \frac{\partial M}{\partial t} \right) \tag{2}$$

As can be seen from Eq. 2, the correction to the effective field due to eddy current becomes relevant in materials with large conductivity (σ) and at high operation frequencies.

We simulated susceptibility spectra based on Eqs. (1) and (2) using a built-in software package, which comes together with the Ryowa permeameter. The effect of eddy currents is reflected in-line broadening of the ferromagnetic resonance peak and can be accessed via the damping parameter, α, thickness and conductivities of the film, which are the coefficients of Eqs. (1) and (2). A typical permeability measurement of 200 nm films is shown in Fig. 3 with an applied field of 5 mT. The ferromagnetic resonance frequency is about 1.5 GHz. In a permeability measurement, the

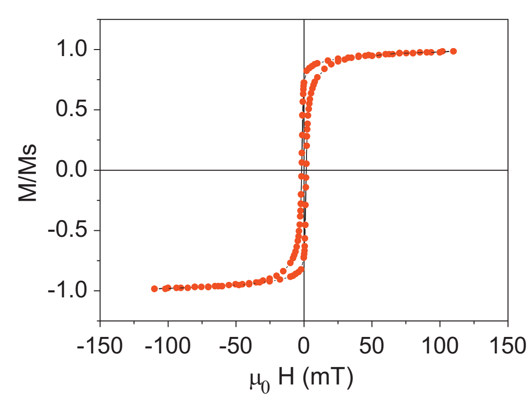

Fig. 2. In-plane room temperature magnetization of electrodeposited Ni(200 nm)||Si film.

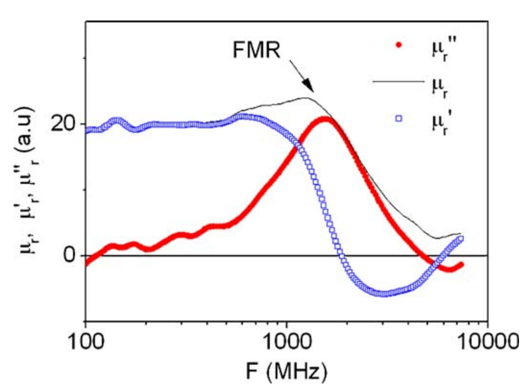

Fig. 3. Permeability spectra of 200 nm films measured with an applied field of 5 mT in the plane of the film.

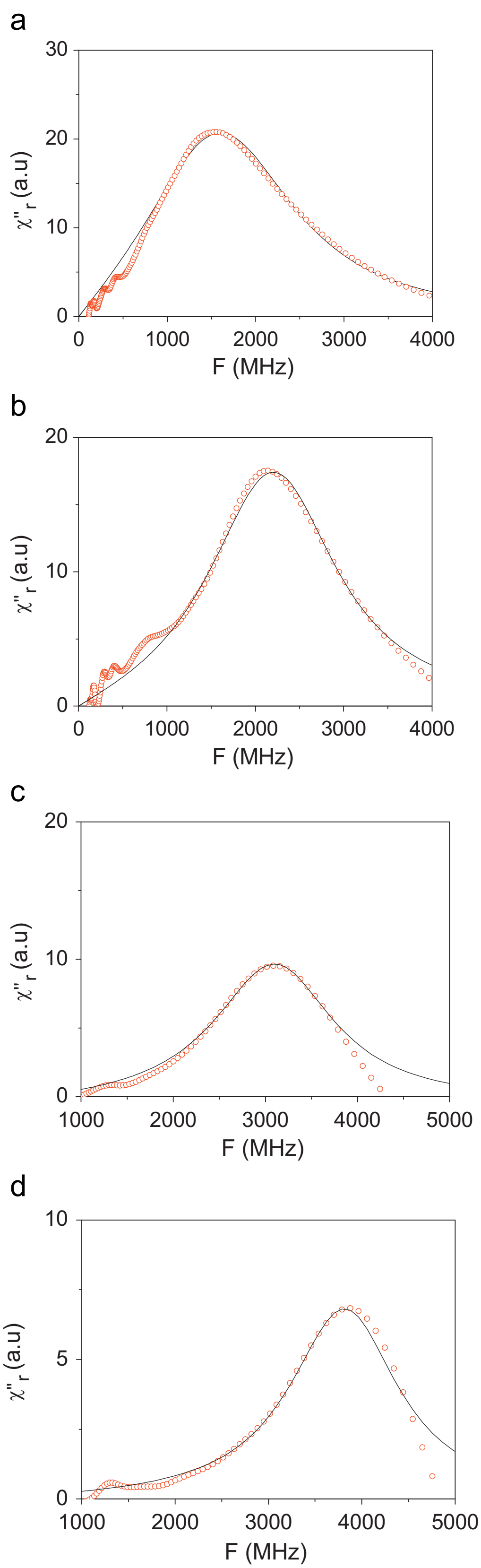

Fig. 4. Absorption peaks (χ_r'') for Ni for applied field of (a) 5 mT, (b) 10 mT, (c) 20 mT and (d) 30 mT. The continuous lines are simulations using LLG+eddy current.

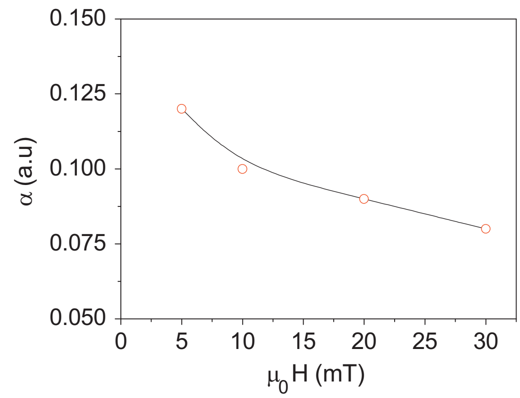

Fig. 5. Damping parameter (α) dependence on applied field. Values were obtained from the best fitting of the absorption lines (χ_r'') shown in Fig. 4.

relative magnetic permeability, $\mu_r = \mu_r' + j\mu_r''$, has two components a real (μ'_r) and an imaginary (μ''_r) part. The real part of permeability is associated with non-dissipative processes, whereas the imaginary part of permeability, μ''_r, represents irreversible processes associated with dissipation via Joule effect (eddy current) and/or ferromagnetic resonance. Susceptibility values ($\mu_r = 1+\chi_r$) were extracted from permeability measurements of Ni films at different applied fields and are compared to simulated values in Fig. 4.

All susceptibility curves shown in Fig. 4 were fitted using α as a free parameter and the following fixed bulk parameters for Ni: $g = 2.2$, $\sigma = 14.3 \times 10^6\,\Omega^{-1}\,\mathrm{m}^{-1}$, $\mu_0\ M_s = 0.6\,\mathrm{T}$ and $\mu_0 H_k = 4.7\,\mathrm{mT}$. Fig. 5 shows the dependence of the damping parameter on the applied field. This dependence is related to decreasing effect of eddy current losses, which result in sharper peaks at larger applied field. The dependence of the damping parameter on applied field can be rationalized by comparing with an ideal case: a thin film with in-plane uniaxial anisotropy. When the applied field is aligned with the easy axis the susceptibility can be written in first approximation as $\chi_r = M_s/(H_k+H_{dc})$. The classical dissipation due to eddy currents is given by

$$P_{eddy} = (1/4\rho\delta)(\omega B d)^2 \tag{3}$$

Here P_{eddy} is dissipated power (loss) per unit volume ($\mathrm{W\,m^{-3}}$), ρ is the resistivity ($\Omega\,\mathrm{m}$), δ is the geometry factor (6 for films), B is the magnetic flux density (T), ω is the angular frequency (rad/s) and d is the film thickness (m). The magnetic field B can be written as

$$B = [1 + M_s/(H_k + H_{dc})]\mu_0 H_{ac} \tag{4}$$

Therefore, the losses due to eddy currents reduce as the H_{dc} field increases and asymptotically approaches $(1/4\rho\alpha)(\omega d)^2\mu_0^2 H_{ac}^2$ for larger value of H_{dc}. In fact this trend is expected as permeability should reduce to 1 at very large applied field. As the damping parameter α is correlated to eddy current losses it will also reduce as the H_{dc} is increased. Although, our Ni films do not show uniaxial anisotropy the asymptotic dependency on H_{dc} is similar to the thin film with in-plane uniaxial anisotropy, hence a similar trend of the damping parameter is expected as shown in Fig. 5. The larger values of damping parameter compared to the intrinsic damping parameter for Ni films, which is 64×10^{-3} [10,11], also supports the idea of eddy current contribution to the line broadening in electrodeposited films.

4. Conclusion

We have studied the effect of eddy current on the ferromagnetic resonance of Ni films plated directly onto Si substrate. The electrodeposition without the need of a seed layer allows us to directly probe the contribution of eddy current to ferromagnetic resonance line broadening of electroplated Ni/Si structure in permeability experiments. Data was fitted using the LLG equation in combination with eddy current and resulted in damping parameter of 0.08 for an applied field of 30 mT ($6360\,A\,m^{-1}$). Structures prepared by direct deposition of magnetic layer onto Si may find application in high-frequency devices provided that low coercivity and high anisotropy can be obtained.

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