Ferromagnetic resonance properties of Fe$_{81-x}$Ni$_x$Ga$_{19}$/Si(100) and Fe$_{81-y}$Ni$_y$Ga$_{19}$/glass films

Chi-Ching Liu, Shien-Uang Jen, Jenh-Yih Juang, Chi-Kuen Lo

Abstract

Two series of Fe$_{81-x}$Ni$_x$Ga$_{19}$/Si(100) and Fe$_{81-y}$Ni$_y$Ga$_{19}$/glass films, where $x$ or $y = 0–26$, were made by the magnetron sputtering method. The film thickness ($t_f$) was fixed at 100 nm. We have performed three kinds of experiments on these films: (i) the saturation magnetostriction ($\lambda_S$) measurement; (ii) the easy-axis and hard-axis magnetic hysteresis loop measurements; and (iii) the ferromagnetic resonance (FMR) experiment to find the resonance field ($H_R$) with an X-band cavity tuned at $f_X = 9.6$ GHz. The natural resonance frequency, $f_{FMR}$, of the Kittel mode at zero external field $(H=0)$ is defined as $f_{FMR} = \gamma(H_\text{K} - \pi M_S)/2$, where $\gamma = 2\pi v$ is the gyromagnetic ratio, $H_\text{K}$ and $4\pi M_S$ are the uniaxial anisotropy field and saturation magnetization, and $H_\text{R} = -4\pi M_S$. The Gilbert damping constant, $\alpha$, is calculated from the formula, $\alpha = [v(AH)_\text{exp}]^2/(4K)$, where $(AH)_\text{exp} = (AH)_\text{sym} + (AH)_\text{asym}$ is the half-width of the absorption peak around the resonance field $H_\text{R}$, $(AH)_\text{sym}$ is the symmetric part of $(AH)_\text{exp}$, and $(AH)_\text{asym}$ is the asymmetric part. The degree of asymmetry, $(AH)_\text{sym}/(AH)_\text{asym}$, is associated with the structural and/or magnetic inhomogeneities in the film. The main findings of this study are as follows: (A) $f_{FMR}$ tends to decrease, as $x$ or $y$ increases; (B) $\lambda_S$ decreases from 0.052 to 0.020 and then increases from 0.020 to 0.050, as $x$ increases, and $\lambda_S$ decreases from 0.060 to 0.013 in general, as $y$ increases; and (C) $H_\text{R}$ reaches a local maximum when $x = 22$. We conclude that the Fe$_{81}$Ni$_{22}$Ga$_{19}$/glass film should be the most suitable for application in magneto-electric microwave devices.

1. Introduction

The desirable properties of a soft magnetic material are high permeability ($\mu$) and low loss. Hysteresis loss is the most important loss in ferromagnetic substances at low driving frequency. However, at the high driving frequency hysteresis loss becomes less important, because the domain-wall-displacement mechanism, is mostly damped and is replaced by the rotation-magnetization mechanism. Thus, the next important loss in ferromagnetic metals and alloys is the eddy current (EC) loss. Since a power loss of this type increases in proportion to the square of the frequency, it plays an important role at high frequencies, usually in the range of radio frequencies [1,2]. Moreover, if the frequency is increased further into the microwave range, one will encounter both the ferromagnetic resonance (FMR) and the EC phenomena.

In this study, we wish to find soft magnetic materials that can be used in a tunable magneto-electric microwave device [3] or other rf/microwave magnetic devices. In these devices, the basic requirements for the soft ferromagnetic film are low coercivity ($H_C$), high saturation magnetization ($4\pi M_S$), high saturation magnetostriction ($\lambda_S$), high rotational permeability ($\mu_r$), high limiting (or natural resonance) frequency ($f_{FMR}$), high electrical resistivity ($\rho$), and low Gilbert damping parameter ($\alpha$).

From Ref. [3], we find that the Fe–Ga alloys seem to be good soft magnetic materials for the device applications mentioned above. For example, they may have low saturation field ($H_C$), about 100 Oe for single crystals (SCs) and about 50 Oe for polycrystals (PCs) [4,5], high saturation magnetization, about 18 kG [4], and high saturation magnetostriction, about 200–400 ppm for SC and about 40–100 ppm for PC sample [6,7]. Notice that although the FeGa single crystal has a large value of $\lambda_S$, which is favorable in terms of magneto-electric coupling, its ferromagnetic resonance line-width ($AH$), about 450–600 Oe [8] at X-band, is, however, too large for tuning efficiency. In other words, $\alpha$ of a FeGa single-crystal film is too large. Moreover, from an economic point of view, it is usually more laborious (or expensive) to grow a single-crystal than a polycrystal film. Hence, in this paper we shall concentrate only on the polycrystalline film. Besides, it has been found that incorporation of about 12 at.% of a metallic element, such as boron (B) or carbon (C), into the Fe$_{81}$Ga$_{19}$ alloy improves...
\(\xi_S\), i.e., \(\xi_S\) reaches maximum in the B range from 1 to 10 at.\% [3,9–11]. Notice, however, there is a discrepancy between \(\xi_S\approx 70\) ppm for the (FeGa)_{0.8}B\_10 film in Ref. [3] and \(\xi_S\approx 45\) ppm for the as-quenched (FeGa)_{0.8}B\_10 bulk in Ref. [9].

In this study, we chose one series of the Fe\_81 - Ni\_x Ga\_19/Si(100) and another series of the Fe\_81 - Ni\_x Ga\_19/glass films, where \(x\) or \(y\) ranges from 0 to 26. Hopefully, we can achieve combinations of the following favorable features, such as low \(H_c\) or \(H_M\), high \(4\pi M_s\), high \(\xi_S\), high \(\mu\), and low \(\Delta H\) or \(x\), from one of these FeNiGa films [12–14].

2. Experimental details

Fe\_81 - Ni\_x Ga\_19/Si(100) and Fe\_81 - Ni\_x Ga\_19/glass films, with \(0 \leq x \leq 26\) at.\% Ni, were made by the magnetron sputtering method. The various fabrication conditions are summarized below: the base pressure \((p)\) was \(5 \times 10^{-7}\) Torr; the Ar working gas pressure \((pAr)\) was 5 mTorr; the sputtering power \((P_{sput})\) was 80 W; the deposition temperature \((T_d)\) was room temperature \((RT)\); and the film thickness \((d)\) was fixed at 100 nm.

The field-in-plane magnetic hysteresis loops was obtained from vibrating sample magnetometer (VSM) measurements. When the squareness ratio \((SQR = M_s/|M_p|)\) is the largest, we define the easy-axis (EA), and when SQR the smallest, the hard-axis (HA). In most cases, the angular dependence of SQR is roughly sinusoidal and the magnetometer \((VSM)\) measurements. When the squareness ratio \((SQR = M_s/|M_p|)\) is the largest, we define the easy-axis (EA), and when SQR the smallest, the hard-axis (HA). In most cases, the angular dependence of SQR is roughly sinusoidal with a period of \(180^\circ\). As an example, the HA hysteresis loop of the Fe\_81 - Ni\_x Ga\_19/glass film in Fig. 1a shows that \((SQR)_{HA} = 0.72\), \(H_p = 20\) Oe, and the anisotropy field \((H_A \equiv (1/2)H_{HA} + H_{KS}) \approx 6.3\) Oe. For the same film, its EA hysteresis loop in Fig. 1b shows that the saturation magnetization \((4\pi M_s)\) is the largest, \((SQR)_{EA} = 0.99\), and coercivity \((H_c \approx 13.8\) Oe). Here, it is interesting to note that since \(H_c \leq H_M\) for all the films, they may be classified as the “inverted” films [15]. A brief summary is listed below: as \(x\) or \(y\) increases from 0 to 26, \(4\pi M_s\) remains almost constant, 16.8–15.8 K, and \(H_c\) decreases, 34.4–13.8 Oe.

The series of Fe\_81 - Ni\_x Ga\_19/Si(100) and Fe\_81 - Ni\_x Ga\_19/glass films, in a circular or disk shape, were studied with the FMR experiments. The microwave resonant cavity used was a Bruker ER4102SST X-band resonator, which was tuned at \(f_M = 9.6\) GHz. The film samples were oriented such that EA// and HA//, where \(H\) was an in-plane external field, which varied from 0 to 2 K.Oe, and \(h_M\) was the microwave field. A typical FMR absorption spectrum of the Fe\_81 Ni\_x Ga\_19/glass film is shown in Fig. 2, where we can spot an FMR event or an absorption peak at \(H = H_k\) and define the half-peak width \((\Delta H)_\text{peak}\). In this case, \(H_k = 637\) Oe and \((\Delta H)_\text{peak} = 144\) Oe.

The longitudinal and transverse magnetostrictions \((\xi_L\) and \(\xi_T\)) were measured in an optical-cantilever system [16]. The Young’s modulus \((E)\) of the each film, which is required in the estimations of \(\xi_L\) and \(\xi_T\), was obtained from nanoindentation measurements. Finally, \(\alpha\) was calculated using the formula \(\alpha \\equiv (H_{HA} - H_{KS})/(H_{KS} - H_{EA})\), where \(H_{HA}\) and \(H_{KS}\) are the \(H_c\) and \(\xi_S\) values above \(H_c\).

The electrical resistivity \((\rho)\) was measured by the standard four-point-probe method. The structural properties were characterized by X-ray diffraction (XRD) using Cu K\_\alpha\ line.

3. Results and discussion

Table 1 lists the X-ray structure data of the (FeNi)\_81 Ga\_19 films deposited on glass substrates. Briefly speaking, when \(y = 22\) at.% Ni, there is only one single A2 phase, and when \(y = 0–17\) and 26 at.% Ni, there are mixed phases with A2 (major) and D\_0\_19, L\_12, and/or unidentified (minor) phases. In general, we consider that all the FeNiGa films are highly \(\{110\}\) textured.

Fig. 3 shows the main resonance field \((H_k)\) at \(f_M = 9.6\) GHz as a function of the Ni concentration \((x\) or \(y\)) for the two series of (FeNi)\_81 Ga\_19 films, respectively. From this figure, we find that \(H_k\) increases as \(x\) or \(y\) increases. When at the Kittel mode resonance, the relationship among \(H_k\), \(H_{Kc}\), \(f_M\), and \(4\pi M_s\) for a flat film can be written as [17–19].

\[
\left(\frac{f_M}{c}\right)^2 = H_k^2 + (2H_k + 4\pi M_s)H_{Kc} + H_k(H_k + 4\pi M_s) \equiv X^2
\]

where \(Y = y/(2\pi)\) is in MHz, \(4\pi M_s\), and \(H_s\) in Gauss, \(Y\) is the gyromagnetic ratio of the material and \(g = \gamma/(1.40X)\), with 1.40 in unit of MHz/G. From Eq. (1), we found that \(g\) of the FeNiGa films varies from 2.21 to 2.01, as \(x\) or \(y\) increases. Then, based on Eq. (1) and the \(g\) value, the natural (or FMR–K) resonance \((H = 0)\) would occur at \(f_{EMR} = \sqrt{H_k(H_k + 4\pi M_s)}\) where \(H_k < 4\pi M_s\). The plot of the \(f_{EMR}\) vs. \(x\) or \(y\) is shown in Fig. 4D. As discussed in the next paragraph, \(f_{EMR}\) should serve as the cut-off (or limiting) frequency \((f_c)\) for these series of ferromagnetic films.

In general, the complex permeability, \(\mu = \mu_R - i\mu_I\), has an anomalous behavior; the real part, \(\mu_R\), drops off and the imaginary part, \(\mu_I\), exhibits an absorption peak at a certain high frequency, e.g., \(f_c\). For a non-metallic ferromagnet, \(f_c\) is mainly determined by FMR. For a metallic ferromagnet, according to Fig. 4, 17 of Ref. [1], \(f_c\) should depend on the smallest dimension, i.e., \(t_f\) of the sample. For example, if \(t_f < \delta\), where \(\delta = (\pi/\mu_0\mu)^{1/2}\) is the skin depth, the \(\mu_R\) or \(\mu_I\) anomaly at \(f_c\) is related to the FMR effect, and if \(t_f > \delta\), \(f_c\) is related to the eddy-current effect [1]. In our case, \(t_f = 100 - 650\) nm < \(\delta = 560 \mu\text{m} (f_c = 1\) GHz). Thus, we would have \(f_c < f_{EMR}\) for all the FeNiGa films in general. Here, since we do have metallic films, the eddy-current effect is not negligible, and should be considered in the resonance cases, as discussed later.

![Fig. 1.](image1.png)

![Fig. 2.](image2.png)
Next, at low frequency, the definition of rotation permeability for an in-plane uniaxial film, such as any FeNiGa film in this study, is 

$$ l_r = \frac{4pM_s}{H_K}. $$

Then, in Fig. 5, we can calculate $l_r$ of the FeNiGa films and plot it as a function of $x$ or $y$. From this figure, we conclude that in general $l_r$ increases, as $x$ or $y$ increases. It is easy to understand this result; i.e., the Snoek’s law, followed from the Landau–Lifshitz equation, can be written as [2,20],

$$ (l_r - 1)f_{\text{FMR}} = \frac{(\nu 4\pi M_s)^2}{M_s H_K}. $$

Eq. (2) is used in a shorted micro-strip transmission line perturbation experiment [20]. Alternatively, Eq. (3) can also be written as [18],

$$ \alpha = \frac{(\Delta H)_s}{2f_{\text{FMR}}}. $$

where $(\Delta H)_s$ is the theoretical full width at half maximum of the absorption peak around the main resonance field ($H_R$). In the following, we shall give a reason for this argument. The LLG equation with Kittel mode can be expressed in the following form [18,19,21]:

$$ \tan \phi = \frac{4\pi M_s H_K}{H_R}, $$

and

$$ \mu_K \sim \chi' = \frac{M_s}{2H} \sin \phi \cos \phi, $$

$$ \mu_K \sim \chi'' = \frac{M_s}{2H} \sin^2 \phi. $$

For a ferromagnetic film, high speed magnetization switching means a low Gilbert damping parameter ($\alpha$). From the Landau–Lifshitz–Gilbert (LLG) equation, the magnetic damping parameter ($\alpha$) can be written as [20],

$$ \alpha = \frac{\Delta f_{1/2}}{4\pi M_s}, $$

where $\Delta f_{1/2}$ is the full width at half maximum for the absorption peak of $\mu_K$ at resonance. Eq. (3) is used in a shorted micro-strip transmission line perturbation experiment [20]. Alternatively, Eq. (3) can also be written as [18],

$$ \alpha = \frac{\nu (\Delta H)_s}{2f_{\text{FMR}}}. $$

Table 1

<table>
<thead>
<tr>
<th>y (at.% Ni)</th>
<th>2θ (deg.)</th>
<th>phase (hkl)</th>
<th>d (Å)</th>
<th>a (Å)</th>
<th>$l_{\text{I max}}$ (%)</th>
<th>$(\Delta H)<em>{\text{A}}/ (\Delta H)</em>{\text{exp}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>27.707</td>
<td>?</td>
<td>3.217</td>
<td>–</td>
<td>16.8</td>
<td>3.6</td>
</tr>
<tr>
<td>4</td>
<td>38.300</td>
<td>D0$_{00}$ (200)</td>
<td>2.348</td>
<td>–</td>
<td>14.3</td>
<td>5.0</td>
</tr>
<tr>
<td>11</td>
<td>24.374</td>
<td>L1 (100)</td>
<td>3.649</td>
<td>–</td>
<td>17.0</td>
<td>14.5</td>
</tr>
<tr>
<td>17</td>
<td>24.371</td>
<td>L1 (100)</td>
<td>3.649</td>
<td>–</td>
<td>17.0</td>
<td>14.5</td>
</tr>
<tr>
<td>22</td>
<td>24.217</td>
<td>A2 (110)</td>
<td>3.032</td>
<td>–</td>
<td>79.9</td>
<td>14.5</td>
</tr>
<tr>
<td>26</td>
<td>29.522</td>
<td>A2 (110)</td>
<td>2.037</td>
<td>–</td>
<td>100</td>
<td>14.5</td>
</tr>
</tbody>
</table>

Fig. 3. The main resonance field ($H_K$), at $f = 9.6$ GHz, of the various FeNiGa films.

Fig. 4. Natural resonance frequency ($f_{\text{FMR}}$) of the FeNiGa films plotted vs. the Ni concentration ($x$ or $y$).

Fig. 5. Static rotational permeability ($l_r$) increases, as $x$ or $y$ increases in the FeNiGa films.
where $\mu_0 = 4\pi \times 10^{-7} \text{H/m}$, $\phi$ is a finite azimuthal angle between the rotating field vector $h_R$ and the magnetization vector $M_S$, $x = (x V_{M0})/(4\pi \mu_0)$, and $H$ is an in-plane field with $EA/H$. From Eq. (5), $\tan(\phi)$ reaches the maximum value, when $H = H_R$ or $\phi = 90^\circ$. Similarly, from Eq. (6), the maximum $\chi'$ also occurs at $\phi = 90^\circ$. In other words, if Eqs. (5) and (6b) are combined, we obtain,

$$\mu_1 \propto \sin^2 \phi \propto \left[ \frac{H^2}{H^2 + \left( \frac{1}{2} \right)^2 (H - H_R)^2} \right] \left[ \frac{M_S}{2H} \right]$$

(7)

In Eq. (7), the Lorentzian part, $H^2/[H^2 + (1/2)^2(H - H_R)^2]$, of $\mu_1$ must be symmetric with respect to $(\text{w.r.t.} \ H_R)$. However, the $\left(1/H\right)$ part of $\mu_1$ is not. Fortunately, when $H$ is near $H_R$, the dependence of $\mu_1$ is more characterized (or affected) by the Lorentzian part, if $x$ is small, which is exactly the case for our films. Thus, we can still consider $\mu_1$ to be symmetric w.r.t. $H_R$. Further, since the FeNiGa films are metallic, due to the eddy current (or the surface impedance) effect, the power absorption of microwave at $H_R$ should be expressed as [22],

$$\Delta P_{\text{abs}} = \left( \mu^2_1 + \mu^2_2 + \mu^1_1 \right)^{1/2},$$

(8)

Thus, unlike a ferromagnetic insulator, there is an admixture of $\mu^1_1$ and $\mu^2_1$ in $\Delta P_{\text{abs}}$ for a ferromagnetic FeNiGa metal. From Eq. (6a), $H_R$ is mainly anti-symmetric w.r.t. $H_R$. But, $(\mu^2_1)^2$ in Eq. (8) is still symmetric w.r.t. $H_R$. As a result, no matter if the film is metallic or not, $\Delta P_{\text{abs}}$ is symmetric. Moreover, when $H$ is near $H_R$, $(\mu^2_1)^2 >> (\mu^1_1)^2$, which leads to the result,

$$\Delta P_{\text{abs}} \approx \left( 2\mu_1 \right)^{1/2},$$

(9)

from Eq. (8). Thus, we believe that in our case the theoretical $\Delta P_{\text{abs}}$ is symmetric w.r.t. $H_R$. Also, whether we used $\mu_1$ or $\mu_2$ in $\Delta P_{\text{abs}}$ for a ferromagnetic FeNiGa, from Eq. (6a), $H_R$ is mainly anti-symmetric w.r.t. $H_R$. But, $(\mu^2_1)^2$ in Eq. (8) is still symmetric w.r.t. $H_R$. As a result, no matter if the film is metallic or not, $\Delta P_{\text{abs}}$ is symmetric. However, in reality, as shown in Fig. 2, the experimental width $(\Delta H)_{\text{exp}}$ is not ideally symmetric. Hence, $(\Delta H)_{\text{exp}}$ is composed of two parts: $(\Delta H)^2_{\text{exp}} = (\Delta H)^2_{\text{sym}} + (\Delta H)^2_{\text{asym}}$, where $(\Delta H)^2_{\text{sym}}$ and $(\Delta H)^2_{\text{asym}}$ are the symmetric and asymmetric parts in $(\Delta H)_{\text{exp}}$ in general. In general, three sources may contribute to $(\Delta H)^2_{\text{sym}}$: one is from the structural inhomogeneity, and the other two are from the magnetic inhomogeneities [21]. As discussed previously, Table 1 shows that for $y = 22$ at.% Ni (range A), the films are structurally homogenous (i.e., containing only one A2 phase), and if $y = 0–17$, and 26 at.% Ni (range B), they are structurally homogenous (i.e., containing mixed phases). Thus, we expect that for the former film its $(\Delta H)^2_{\text{sym}}$ is smaller, while for the latter films their $(\Delta H)^2_{\text{sym}}$s are larger. In agreement with the experimental data from FMR experiments (Table 1), for the film in range A, the degree of asymmetry of the linewidth, $(\Delta H)^2_{\text{sym}}/(\Delta H)_{\text{exp}} = 0.99$, is smaller, while for those in range B, the degree of asymmetry, $(\Delta H)^2_{\text{sym}}/(\Delta H)_{\text{exp}} = 3.6–19.7\%$, is larger in general. As to the magnetic inhomogeneity, one mechanism is due to the asymmetric distributions of the magnitude and/or angle dispersion of $H_R$. The other is associated with the local inhomogenous demagnetizing field $(H_d)$ near edges of the film sample. Here, we are unable to assess how much the magnetic-inhomogeneity mechanisms would affect $(\Delta H)^2_{\text{sym}}/(\Delta H)_{\text{exp}}$ quantitatively.

Fig. 6 shows that as $y$ increases, $x$ decreases from 0.060 to 0.013 for the FeNiGa films deposited on glass substrates, and as $x$ increases, $x$ first decreases from 0.052 to 0.020 and then increases from 0.020 to 0.050 for the FeNiGa films deposited on Si(100) substrates. All these Gilbert damping parameters were extracted, as described previously, from each FMR measurement made along the easy-axis. We like to emphasize that since all our films are poly-crystalline, as shown in Fig. 6 may or may not be from the minimum or maximum linewidth of each sample [23]. In addition, one may notice that there is discrepancy between $x$ data of the $x$- and $y$-series films in the range $17 \leq x$ or $y \leq 26$ at.% Ni. In the following, we shall explain why the $x$ data from the $y$-series (Fe$_{81}$-$y$.Ni$_{22}$Ga$_{19}$/glass) films should be more reliable. The $p$-doped Si(100) semiconductor substrate conducts with electrical resistivity ($\rho$), about 5–10 $\Omega$ cm. On the other hand, $\rho$ is about 120–150 $\mu$cm for FeNiGa films deposited on insulating glass. Further, the thickness ratio of $\epsilon_{\text{Si}}/\epsilon_{\text{FeNiGa}}$ is about 10. A simple calculation shows that the electrical resistance ratio, $R_{\text{Si}}/R_1$, for the $x$-series (Fe$_{81}$-$y$.Ni$_{22}$Ga$_{19}$/Si(100)) films is of the order of one. Thus, the current shunting effect must be significant in the case of FeNiGa films deposited on Si(100). As observed, the (apparent) $\rho$ of the $x$-series films is in general smaller than the (real) $\rho$ of the $y$-series films. In an FMR situation, the eddy current, $i_{\text{ec}}$, induced by $h_{\text{rf}}$, must be flowing in the most conducting FeNiGa film at least. For the $y$-series film, because glass is an insulator, $i_{\text{ec}}$ is mainly limited inside the film region. However, for the $x$-series films, due to the current shunting effect, $i_{\text{ec}}$ will flow across the film/Si interface. Moreover, the spin injection across the interface indicates that the proximity region on the Si side, which is partially magnetized, will also absorb microwave, and make an extra contribution to the main FMR signal from the film. As a result, for the $x$-series (Fe$_{81}$-$y$.Ni$_{22}$Ga$_{19}$/Si(100)) films, there is an additional broadening of the FMR peak width due to the extraneous eddy-current effect near the film/Si interface [20]. Thus, in general $x$ of the Fe$_{81}$-$y$.Ni$_{22}$Ga$_{19}$/Si(100) films, as shown in Fig. 6, should be less accurate (or meaningful) than that of the Fe$_{81}$-$y$.Ni$_{22}$Ga$_{19}$/glass films.

Fig. 7 shows $\lambda_S$ of the $x$- and $y$-series FeNiGa films as a function of the Ni concentration ($x$ or $y$). The general trend in Fig. 7 is that as $x$ or $y$ increases, $\lambda_S$ increases, and $\lambda_S$ reaches a local maximum when $x$ and/or $y = 22$ at.% Ni. For Fe$_{59}$Ni$_{22}$Ga$_{19}$/Si(100), $\lambda_S = 19$ ppm, and for Fe$_{59}$Ni$_{22}$Ga$_{19}$/glass, $\lambda_S = 27$ ppm. Also, notice that the saturation field of these films is quite low, about 15 Oe only. Hence, its magnetostriction sensitivity, defined as $S_H = (3/2)(\lambda_S/H_S)$, can be quite high, about 1.9–2.7 ppm/Oe, which is suitable for the low field and high frequency application.
4. Conclusion

We have made two series of Fe$_{81-x}$Ni$_{x}$Ga$_{19}$/Si(1 0 0) and Fe$_{81-y}$Ni$_{y}$Ga$_{19}$/glass films, with 0 $\leq x$ or $y$ $\leq$ 26 at.% Ni, at room temperature by the magnetron sputtering method. Magnetic hysteresis loop, magnetostriction, and FMR measurements were performed on these films. We observed that $(\Delta H)_{\exp}$ of each film is in general asymmetric. Hence, $(\Delta H)_{\exp}$ is composed of two parts: $(\Delta H)_{\exp} = (\Delta H)_S + (\Delta H)_A$, where $(\Delta H)_S$ and $(\Delta H)_A$ are the symmetric and asymmetric parts. We believe this asymmetry is related to the degrees of the structural and/or magnetic inhomogeneities in each film. As $x$ or $y$ increases from 0 to 26 at.% Ni, we found that (I) $4\pi M_S$ decreases only slightly, 16.6–15.0 KG, (II) $H_C$ is small, 34.4–13.8 Oe; (III) $\delta_S$ first increases and reaches a local maximum at $x$ or $y = 22$ at.% Ni; (IV) $f_{\text{FMR}}$ tends to decrease, 1.6–0.8 GHz; (V) $\mu_r$ tends to increase, 1212–3993; and (VI) $\alpha$ decreases in general, 0.060–0.013.

Thus, from this study we conclude that among all the FeNiGa/glass films, the Fe$_{59}$Ni$_{22}$Ga$_{19}$/glass film should be the most suitable, due to its highest $\delta_S$, $S_H$, $\rho$, $(\text{next to the highest})$ $\mu_r$ and the lowest $H_S$ and $(\text{next to the lowest})$ $\alpha$, for application in the magneto-electric microwave devices. However, $4\pi M_S$ and $f_{\text{FMR}}$ of the Fe$_{59}$Ni$_{22}$Ga$_{19}$/glass film are relatively smaller.

Acknowledgement

This work is supported by a Grant No. NSC 100-2112-M-001-017-MY3, from the National Science Council.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jallcom.2013.01.169.

References