Determination of the saturation magnetization of ion irradiated Py/Ta samples using polar magneto-optical Kerr effect and ferromagnetic resonance

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Based on polar magneto-optical Kerr effect and frequency dependent ferromagnetic resonance measurements, a method has been found that allows for the quantitative determination of the saturation magnetization of samples with unknown effective magnetic volume. Conventional magnetometry cannot be used for this purpose. Thin Py/Ta multilayers with an overall Py thickness of 20 nm but different number of interfaces are used as test systems. By means of Ne ion irradiation the magnetic moment and the saturation magnetization are affected due to interfacial mixing. With both increasing ion fluence and increasing number of Py/Ta interfaces, a decrease of saturation magnetization is observed. © 2010 American Institute of Physics. [doi:10.1063/1.3291051]

Ion beam irradiation and ion implantation of ferromagnetic films, multilayers, and nanostructured samples have proven to be a smart tool to tailor their magnetic properties and structural composition (see Refs. 1–3 and references therein). Transition metals like Ta are widely used as seed and cap layers in the design of spintronic devices like giant magnetoresistance effect sensors or magnetic random access memory. As Ta is chemically stable, it also helps to tune the post switching precessional motion of the magnetization. In this context the structural and magnetic properties of various kinds of Py/Ta structures have been investigated. It was shown experimentally and verified theoretically that Ta intermixing leads to magnetically dead layers of 0.6–1.2 nm in thickness. These dead layers make it difficult to determine the magnetic moment of the Ni atoms in Py. These dead layers make it difficult to determine the correct magnetic volume, which is needed to obtain the saturation magnetization. The saturation magnetization of Py/Ta samples using polar magneto-optical Kerr effect (MOKE) and vector network analyzer ferromagnetic resonance (VNA-FMR) measurements even in the case of interfacial mixing due to ion irradiation, where SQUID magnetometry fails. We do not evaluate \( \mu_0 M_s \) from calibrated MOKE measurements nor from its proportionality to the FMR amplitude, as these methods are cumbersome and error-prone. Instead, \( \mu_0 M_s \) is directly determined from the magnetic anisotropy energy.

To test this method, three different sets of Py=5 \( \times \) 1013 to 5 \( \times \) 1016 Ne/cm².

Figure 2(a) shows the ferromagnetic resonance frequency \( f \) of the 1 \( \times \) Py samples as a function of the applied magnetic field \( B_{ext} \) along the easy axis. While there is virtually no difference between the unirradiated sample and the samples irradiated with fluences up to 1 \( \times \) 1015 Ne/cm², a significant decrease of the resonance frequency \( f \) can be observed for fluences of 2.5 \( \times \) 1015 Ne/cm² and higher. Figure 2(b) presents the decay of Py/Ta samples. Here, the ferromagnetic resonance frequency \( f \) strongly decreases with an increasing number of Py/Ta repetitions, i.e., increasing number of interfaces. The frequency versus field dependence, also known as Kittel equation, is given by

\[
f = \frac{|\gamma|}{2\pi} \sqrt{B_{ext} \left( B_{ext} + \mu_0 M_{eff} + \frac{K_{eff}}{M_s} \right)}.
\]

The key to determine \( \mu_0 M_s \) from FMR measurements is the

FIG. 1. Sketch of the Py/Ta thin film systems: (a) 1 \( \times \) Py, (b) 5 \( \times \) Py, and (c) 10 \( \times \) Py.
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**TABLE I.** Uniaxial in-plane anisotropy field $K_{2\parallel}/M_s$ and saturation magnetization $\mu_0M_s$ (both in millitesla) determined from FMR.

<table>
<thead>
<tr>
<th>Ion fluence (Ne/cm²)</th>
<th>$1 \times$ Py</th>
<th>$5 \times$ Py</th>
<th>$10 \times$ Py</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K_{2\parallel}/M_s$</td>
<td>$\mu_0M_s$</td>
<td>$K_{2\parallel}/M_s$</td>
</tr>
<tr>
<td>Unirradiated 0.67</td>
<td>0.70</td>
<td>1018</td>
<td>0.64</td>
</tr>
<tr>
<td>1.0 x 10¹⁴</td>
<td>...</td>
<td>...</td>
<td>0.31</td>
</tr>
<tr>
<td>1.5 x 10¹⁴</td>
<td>...</td>
<td>...</td>
<td>0.00</td>
</tr>
<tr>
<td>2.5 x 10¹⁴</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>5.0 x 10¹⁴</td>
<td>0.71</td>
<td>1022</td>
<td>...</td>
</tr>
<tr>
<td>1.0 x 10¹⁵</td>
<td>0.65</td>
<td>1016</td>
<td>...</td>
</tr>
<tr>
<td>2.5 x 10¹⁵</td>
<td>0.64</td>
<td>987</td>
<td>...</td>
</tr>
<tr>
<td>5.0 x 10¹⁵</td>
<td>0.67</td>
<td>920</td>
<td>...</td>
</tr>
<tr>
<td>1.0 x 10¹⁶</td>
<td>0.74</td>
<td>805</td>
<td>...</td>
</tr>
</tbody>
</table>

**FIG. 2.** (Color online) Microwave frequency squared vs the resonance field of (a) the irradiated $1 \times$ Py type samples and (b) the unirradiated samples.

The effective magnetization $\mu_0M_{\text{eff}} = \mu_0M_s - 2K_{2\perp}/M_s$, which is the difference between shape anisotropy field and the uniaxial perpendicular anisotropy field, of Py. From the polar MOKE curves of selected $1 \times$ Py samples shown in Fig. 3 one can see that the samples do not have a perpendicular anisotropy, because there is no hysteresis. Hence, one can replace $\mu_0M_{\text{eff}}$ by $\mu_0M_s$ in Eq. (1) in order to determine $\mu_0M_s$ by FMR. Now it becomes clear that a drop in saturation magnetization $\mu_0M_s$ is responsible for the reduced resonance frequencies. From polar MOKE loops $\mu_0M_s$ is obtained independently by determining the shape anisotropy field of the samples. This is the field value at which two imaginary lines drawn to the horizontal “saturation branch” and steep “reversal region” of the hysteresis loop intersect (see Fig. 3).

SQUID magnetometry, like any other type of magnetometry, measures the magnetic moment $\vec{m}$ only. But calculating $\mu_0M_s$ from $\vec{m}$ requires the knowledge of the exact effective Py volume, which is very difficult—if not impossible at all—to determine due to the increasing number of interfaces and their intermixing induced by ion irradiation. However, in our case, FMR and polar MOKE measurements allow $\mu_0M_s$ to be determined without the knowledge of any effective Py thickness. The good agreement with the SQUID data of the unirradiated samples confirms this.

Using Eq. (1) the uniaxial in-plane anisotropy field $K_{2\parallel}$ and $\mu_0M_s$ have been fitted. For the FMR analysis a $g$-factor for Py of $g = 2.10$ (Ref. 15) was assumed for all samples as exact values for the irradiated samples are unknown. However, increasing $g$ by 0.01 would decrease $\mu_0M_s$ by 1% only. The results are given in Table I.

The samples possess a small uniaxial in-plane anisotropy that is slightly larger for the $1 \times$ Py samples than for the other two systems. It is virtually independent of the ion fluence and has only a minor contribution to the ferromagnetic resonance frequency $f$. Comparing the saturation magnetization of the unirradiated $1 \times$ Py and $10 \times$ Py samples, a reduction by a factor of 2 is found though all samples contain the same amount of Py. This behavior can be explained by taking into account the number of neighboring Ta atoms. In the $1 \times$ Py samples, the are only two interfaces and the number of neighboring Ta atoms is the smallest. However, in the $10 \times$ Py samples, there are already 20 interfaces and so many more Ni and Fe atoms have Ta atoms as neighbors. In this way, the deleterious effect of Ta on the ferromagnetic properties is becoming much stronger and leads to a reduction of the effective ferromagnetic film thickness by creating so-called magnetically dead layers close to the interfaces.

**FIG. 3.** (Color online) Polar MOKE measurements of selected $1 \times$ Py samples. The curves show no hysteresis which means that the samples do not have a perpendicular anisotropy.

**FIG. 4.** Shows $\mu_0M_s$ as a function of the ion fluence of the samples determined independently from FMR, polar MOKE, as well as SQUID magnetometry. Data obtained from FMR and MOKE are consistent within error and also agree well with the SQUID data of the unirradiated samples. Note that no sort of normalization or scaling is involved in the determination of $\mu_0M_s$.

In the case of $5 \times$ Py and $10 \times$ Py the decrease of $\mu_0M_s$ already starts at very small ion fluences, whereas for $1 \times$ Py
having a total Py thickness of 20 nm, were irradiated with Ne ions in order to modify their magnetic properties. With increasing ion fluence as well as an increasing number of Py/Ta interfaces, a decrease of saturation magnetization can be observed. However, the small uniaxial anisotropy of the samples remains virtually unaffected. Ne ion irradiation leads to a mixing and broadening of the interfaces and the Py/Ta stack undergoes a transition from being polycrystalline to amorphous at a critical fluence depending on the number of interfaces. The saturation magnetization is found to vanish at a Ta concentration of about 10–15 at. % in the Py layers.

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