Abstract—We report the dependence of the magnetization, anisotropy constant, and Kerr rotation on the Fe concentration in FeCo-Pd multilayer thin films, where the Fe concentration $x$ varies between 0 and 100 percent with maintaining the same sublayer thicknesses of 2A FeCo and 9A Pd. Perpendicular magnetic anisotropy existed for the films having Fe concentration less than about 80 atomic percent. Enhanced magnetization, possibly due to the polarization of Pd, was observed in the full range of Fe concentration. No simple proportional relation between the Kerr rotation and the magnetization was observed in this system.

I. INTRODUCTION

Transition - metal (TM) based multilayer thin films have been the subject of numerous recent studies because of their novel properties such as perpendicular magnetic anisotropy [1–4] and the giant magnetoresistance [5]. Potential application to magneto – optical recording on the materials with perpendicular magnetic anisotropy has triggered a lot of investigations on these systems [6–8]. So far the studies have been limited to TM element–based systems and little attention has been paid to FeCo alloy systems. In this paper, we report magnetic and magneto–optical properties of FeCo/Pd multilayer thin films and discuss a possibility to utilize these materials for magneto–optical recording media.

II. EXPERIMENT

Samples were prepared by e−beam evaporation of FeCo alloy and Pd element on glass substrates in a vacuum chamber maintained at about $2 \times 10^{-4}$ Torr during the deposition. The multilayer structure was achieved by alternately exposing the substrate to each of the two e−beam sources via a rotating substrate mount. Two e−beam sources were physically separated by stainless shields to prevent cross contamination of their evaporated fluxes. The deposition rates from the two sources were monitored by corresponding quartz crystal oscillators. The deposition rate was 1A/s with an average fluctuation of 10 % for FeCo and 4.5 A/s with an average fluctuation of 2 % for Pd. The Fe concentration in the FeCo sublayer was varied by evaporating FeCo alloys having different compositions. Although the composition was varied, the sublayer thickness of 2A FeCo and 9A Pd were kept constant in all samples.

The film composition was determined by inductively coupled plasma (ICP) atomic emission spectrometry and the film structure, was investigated by 0–2θ scanning x−ray diffractometry. Magnetization was measured using a vibrating sample magnetometer (VSM) calibrated against Ni standard. The magnetic anisotropy was measured using a torque magnetometer in an applied field of 15 kOe and the data was analyzed according to the method of Shin and Kim [9]. For both magnetization and anisotropy measurements, the small signal from the sample holder and uncoated substrate was subtracted out. The magneto–optical loops, composed of the polar Kerr rotation and ellipticity loops, were measured using a HeNe laser in an optical detection system.

III. RESULTS AND DISCUSSION

The growth parameters of FeCo/Pd multilayer thin films studied here are listed in Table I. The difference in the Fe concentration between the bulk alloy and the evaporated alloy film is due to the difference in the vapor pressures of Fe and Co. The sublayer thickness in Table I is a nominal value obtained by multiplying the deposition rate and the deposition time of each constituent. The bilayer thickness is an experimental value obtained by analyzing 0–2θ x−ray diffraction peaks. As seen in Table I, all samples have the sample bilayer thickness of 11 A within a 2 % variation.

In Fig. 1, we plot the dependence of the saturation magnetization on the Fe concentration in the FeCo sublayer. An observation of the maximum in the saturation magnetization (with an applied field strength of 15 kOe) at the Fe concentration of about 65 atomic % is similar to a well−known behaviour observed in iron−cobalt alloys [10]. It is interesting to note that the saturation magnetizations in FeCo/Pd multilayer films are enhanced in comparison with those in FeCo alloys. For example, Fe$_{0.65}$Co$_{0.35}$/Pd multilayer film has a 30% larger saturation magnetization than FeCo alloy having the same composition. Enhanced magnetization caused by the polarization of Pd has been reported in Co/Pd multilayer films by several investigators [4,11,12]. Broder et al. [11] assumed the layer of Pd adjacent to Co was polarized and found

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TABLE I

<table>
<thead>
<tr>
<th>Sample</th>
<th>Fe concen in FeCo alloy (at. %)</th>
<th>Sublayer thickness (FeCo/Pd)</th>
<th>Bilayer thickness (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0</td>
<td>2A / 9A</td>
<td>11.1</td>
</tr>
<tr>
<td>II</td>
<td>10</td>
<td>2A / 9A</td>
<td>11.0</td>
</tr>
<tr>
<td>III</td>
<td>20</td>
<td>2A / 9A</td>
<td>11.0</td>
</tr>
<tr>
<td>IV</td>
<td>30</td>
<td>2A / 9A</td>
<td>10.8</td>
</tr>
<tr>
<td>V</td>
<td>40</td>
<td>2A / 9A</td>
<td>11.2</td>
</tr>
<tr>
<td>VI</td>
<td>50</td>
<td>2A / 9A</td>
<td>11.1</td>
</tr>
<tr>
<td>VII</td>
<td>100</td>
<td>2A / 9A</td>
<td>10.9</td>
</tr>
</tbody>
</table>

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the magnetization per Pd atom to be 0.6 $\mu_B$ using a simple theory. Victora et al. [12] has obtained the magnetizations of 0.25 $\mu_B$ and 0.31 $\mu_B$ per Pd atom for a 2A Co9A Pd multilayer film using the layer Korringa–Kohn–Rostoker (KKR) technique. Enhanced magnetization due to the polarization of Pd has been also reported in Fe/Pd multilayer films [11]. Therefore, we tend to believe that the enhancement of magnetization in FeCo/Pd multilayer films has originated from the polarization of Pd.

We have observed that perpendicular magnetic anisotropy exists in Fe$_x$Co$_{1-x}$/Pd multilayer films until the Fe concentration $x$ reached about 80 atomic percent. Figure 2 shows the uniaxial anisotropy constant, $K_u$, and the effective anisotropy constant, $K_{ef}$, as functions of the Fe concentration in the FeCo sublayer. Here, we define $K_{ef} = K - 2\pi M_s^2$, where $M_s$ is the saturation magnetization. In Fig. 2, the result that the uniaxial anisotropy constant is positive in the full range of the Fe concentration is as expected since the perpendicular interface anisotropy exists in both Co and Fe monolayers on Pd [3]. A monotonic decrease of $K_u$ is understood by considering the fact that Co/Pd multilayer film has a larger surface anisotropy than Fe/Pd multilayer film [3]. Figure 2 shows that the effective anisotropy is negative for the Fe/Pd sample. In this case, even though the interface contribution is positive, it is not large enough to overcome the shape anisotropy demagnetization energy of $2\pi M_s^2$.

It was observed that Fe$_x$Co$_{1-x}$/Pd films have square magneto-optical hysteresis loops until the Fe concentration $x$ reached 0.52. Fig. 3 shows the polar Kerr rotation and ellipticity loops of an Fe$_{0.26}$Co$_{0.74}$/Pd film. The squareness of the hysteresis loops implies perpendicular magnetic anisotropy of the sample, which is an essential requirement to be suitable for magneto-optical recording. However, a slanted hysteresis loop was observed for an Fe$_{0.65}$Co$_{0.35}$/Pd film, even though the sample was expected to show a square hysteresis loop since it had perpendicular magnetic anisotropy according to Fig. 2. The result seems to be attributed to existence of stripe domains in the remnant magnetization state.

FeCo/Pd multilayer films generally develop the ellipticity as seen in Fig. 3b. The ellipticity is due to a phase difference in the $p$ and $s$ polarizations of the reflected beam. Therefore, the maximum Kerr rotation of a medium is obtained by eliminating the ellipticity using an appropriate phase plate in the reflected beam. For small degrees of Kerr rotation and ellipticity, the phase difference $\delta$ between two polarizing directions can be calculated by

$$\delta = \tan^{-1}(\epsilon/\theta_e)$$

(1)

where $\epsilon$ and $\theta_e$ are the ellipticity and the polar Kerr rotation measured without a phase plate, respectively. Then, the maximum Kerr rotation, obtainable at the zero ellipticity, is given by

$$\theta_{\text{max}} = (\theta_e^2 + \epsilon^2)^{1/2}$$

(2)
IV. CONCLUSIONS

We have studied magnetic and magneto-optical properties in Fe$_x$Co$_{1-x}$/Pd multilayer films where the Fe concentration, $x$, varied from 0 to 100 atomic percent while maintaining the same sublayer thicknesses of 2A FeCo and 9A Pd.

Perpendicular magnetic anisotropy was maintained until Fe was doped up to 80 atomic % in the FeCo sublayer. The magnetization was enhanced in comparison with an FeCo alloy having the same composition. This is believed to be caused by the polarization of the Pd atoms.

The Kerr rotation was kept nearly constant up to a 30 atomic % Fe concentration and then, decreased monotonically with increasing the Fe concentration. In this system, no simple proportional relation was observed between the Kerr rotation and the magnetization.

REFERENCES