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Kerr effect enhancement by photon tunneling and possible application to a new scanning probe magnetic microscope

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Magneto-optical effects are calculated for the film stack consisting of hemisphere glass/magnetic film (10 nm)/air gap (*d* nm)/glass plate. Polarized light (wave length=800 nm) is irradiated through the hemisphere glass in the total internal reflection configuration. A typical amorphous rare earth-transition metal alloy is used for the magnetic layer. We find a large monotonic change in the figure of merit (product of the reflected amplitude of light and the Kerr rotation angle) as a function of the air gap, ranging from 1 to 800 nm. Similar results are obtained for a magnetic film with a 10 nm SiO_2 protective layer and for a 1-nm-thin magnetic film. This phenomenon is mostly caused by a change in the reflectivity at magnetic film/air interface due to photon tunneling. The difference in the figure of merit between perpendicular and longitudinal magnetization is about 0.6°. These results imply that it might be possible to obtain an image of perpendicular magnetic moment with photon scanning tunnel microscopy (STM). This method can be combined simultaneously with a conventional atomic force microscope or STM.
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I. INTRODUCTION

In the total internal reflection (TIR) mode, light irradiated from the first medium with refractive index n_1 to the second medium with n_2 $(n_1>n_2)$ is completely reflected at the boundary,[1] and the electromagnetic field in the second medium, which is called an evanescent field, decreases exponentially with the distance from the boundary. However, when a third medium with refractive index n_1 exists close to the first medium, the evanescent wave is converted to a propagating wave at the second boundary. This phenomenon is called photon tunneling.[2] The photon scanning tunnel microscope (STM)[3] utilizes this phenomenon. A scanned fine tip is used as the third medium, and the morphology of the first boundary (distance form the tip) is detected as a change in the intensity of the converted light.

When the incident light is linearly polarized and the first medium is a magnetic film, magneto-optical (MO) effect, that is, a rotation of the polarization angle, will be observed both in the reflected and the converted light and also will be changed with the distance from the tip. This leads to a scanning probe magnetic microscope, which has the advantages of being sensitive to low magnetization materials and having no magnetic interaction between probe and sample. Safarov *et al.* reported such a microscope using a pulsed magnetic field to a Co thin film sample.[4] However, no static magnetization image was reported. A weak MO signal in the converted light appears to be a problem in this microscope system.

In this article, we calculate MO effects in a hemisphere glass/magnetic film/air gap/glass plate system in the TIR condition and estimate them from the view point of the figure of merit, which corresponds to the detected intensity. Then we discuss the possibility of a new scanning probe magnetic microscope using the photon tunneling phenomenon.

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II. CALCULATION

Numerical calculations were performed by the program MULTILAYER™[5] with a configuration shown in Fig. 1. This program solves Maxwell's equations at flat interfaces without any approximations. A linearly polarized light (wavelength 800 nm) irradiated through the hemisphere glass at an angle θ greater than the critical angle. The values of the dielectric tensor of a typical amorphous rare earth-transition metal alloy with perpendicular and longitudinal magnetization were used for the magnetic layer.

III. RESULTS AND DISCUSSION

A change in the figure of merit [(FOM): $E\times\theta_k$, E: amplitude of light, θ_k: Kerr rotation angle] of the reflected light

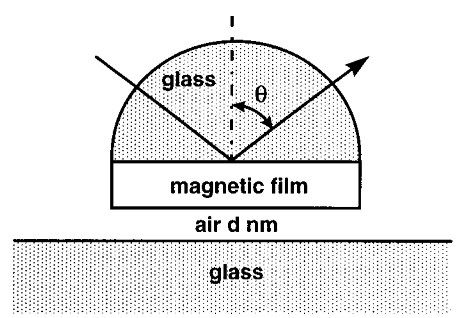

FIG. 1. Configuration used for the calculations.

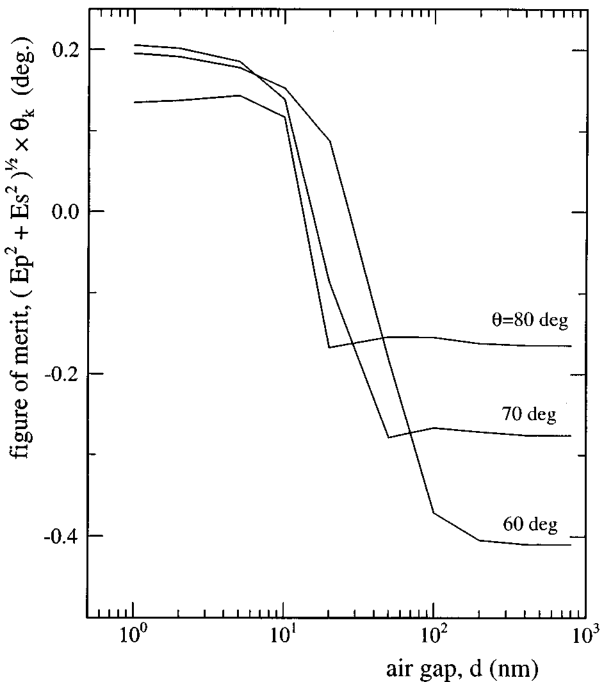

FIG. 2. Figure of merit (=amplitude$\times\theta_k$) of the reflected light vs the air gap for glass/MO material (10 nm)/air (d nm)/glass plate. P-polarized incident light and perpendicular magnetization were assumed.

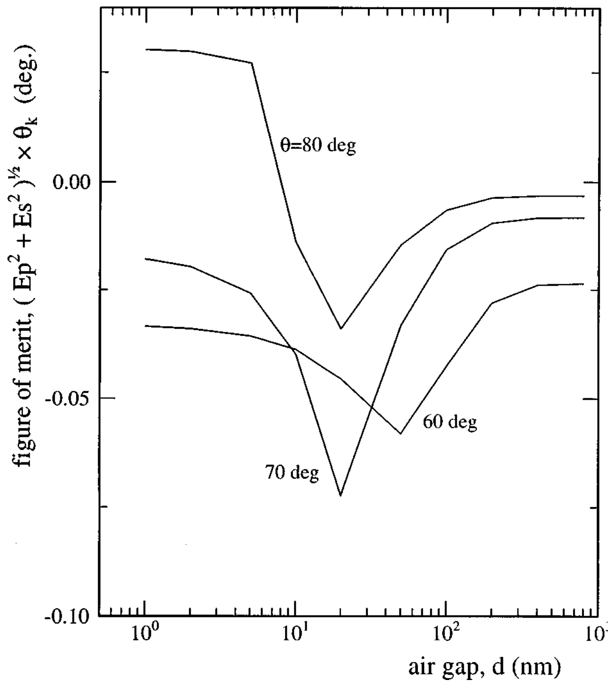

FIG. 3. Figure of merit vs d, for the longitudinal magnetization case.

against the air gap d for $\theta=60°$, 70°, and 80° is shown in Fig. 2. The magnetic film is a perpendicular magnetized MO material with thickness of 10 nm. The incident beam has a unit intensity and is p polarized, that is, the direction of the polarization is perpendicular to the film surface. Although a large θ_k, more than 2°, is obtained at a couple of specific conditions, E tends to be small in such cases, so the FOM is small. As can be seen, the FOM increases monotonically with decreasing d. For $\theta=60°$, the change in the FOM is as large as 0.6°, which is larger than the FOM for the case of normal incidence of 0.13°. The result for the longitudinal magnetization is shown in Fig. 3. FOM has rather complex d dependence but the change in the FOM is less than 0.1.

It is clear that the detected MO signal almost corresponds to the perpendicular magnetic moment from the results of Figs. 2 and 3. A difference in the FOM between perpendicular and longitudinal magnetization cases is shown in Fig. 4. When the direction of an analyzer is set to be crossed to that of the polarization for large d case, the signal intensity becomes large with decreasing d. Therefore, it might be possible to utilize this phenomenon for a new scanning probe magnetic microscope by using a fine glass tip instead of the glass plate.

The change in FOM is caused by the change in the reflectivity at magnetic film/air interface according to the extent of photon tunneling. That is, FOM changes from the value of glass/magnetic film/glass configuration ($d=0$) to that of TIR configuration ($d=\infty$). In the calculation of FOM, a contribution of multiple-beam interference within magnetic film and air gap is included. When a fine glass tip is used for the glass plate in Fig. 1, such an interference does not expect to occur. However, FOM change is not thought to decrease so much even when the tip completely scatters the evanescent wave. FOM from hemisphere glass/magnetic film interface is estimated to be $+0.1°$ and that from magnetic film/glass interface ($d=0$) is estimated to be more than 0.03° for $\theta=60°$. Since FOM for large d value is independent of the occurrence of the scattering, FOM change is expected to be more than 0.57° for $\theta=60°$.

Though a possible problem is that almost all of the detected light comes from the area where the tip is not positioned, this light can be eliminated when the direction of an

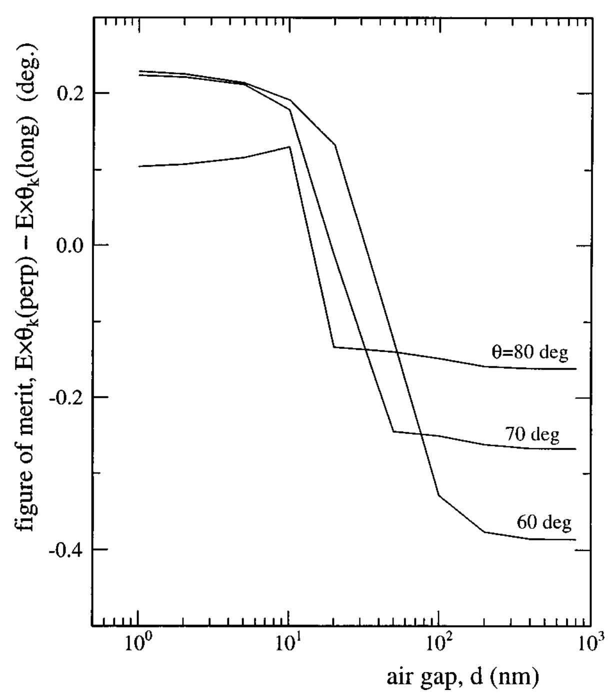

FIG. 4. Difference in FOM between the perpendicular and longitudinal magnetization cases for glass/MO material (10 nm)/air (d nm)/glass.

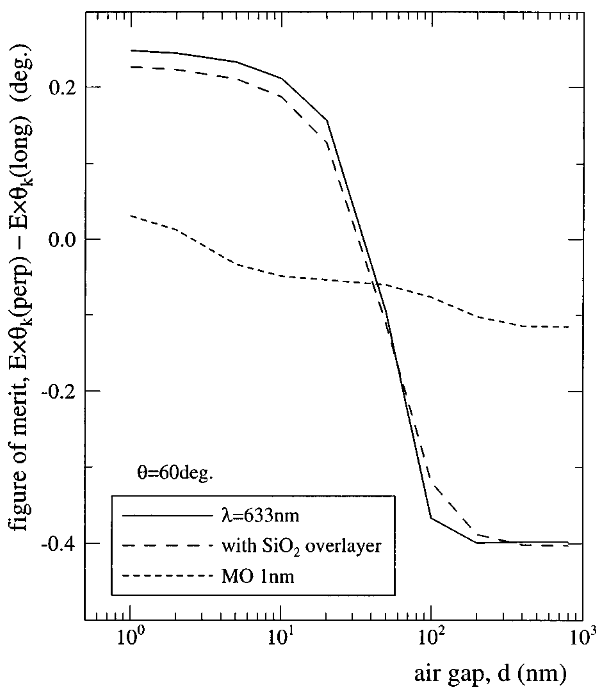

FIG. 5. The difference in FOM between the perpendicular and longitudinal magnetization cases for the case of $\lambda=633$ nm, for magnetic film with 10 nm SiO_2 protective layer and for 1 nm magnetic film. Conditions are p-polarized incident, $\theta=60°$ and perpendicular magnetization.

analyzer is set as mentioned above. As for the case of collecting the evanescent wave, large FOM (about 0.3° at maximum) is obtained but it includes much contribution of the multiple-beam interference in air gap and also this method has a problem of poor coupling efficiency between photon and glass probe. Moreover, our method could employ a couple of signal enhancement method such as an ac method with photoelastic modulation optics[6] or by vibrating the tip.

Since a tip need not collect the light, a metal tip can be used. A change in FOM with air gap for glass/magnetic film/air/Pt is 0.5°. This means that simultaneous measurement of magnetization and morphology would be possible by combining our method with a conventional STM or atomic foce microscope.

In order to examine the feasibility of this method, MO effects were calculated for various film configurations. Figure 5 shows the results for 633 nm wavelength, for a magnetic film with a 10 nm SiO_2 protective layer and for 1 nm magnetic film. Similar results to that shown in Fig. 4 are obtained. This method is useful for magnetic film with a dielectric overcoat and might have the capability for ultrathin magnetic film.

IV. SUMMARY AND CONCLUSION

A magneto-optical effect for the film stack of hemisphere glass/magnetic film/air gap/glass plate is calculated in the total internal reflection condition. It is found that the figure of merit (FOM) of reflected light changes monotonically as a function of the air gap. This phenomenon is caused by the change in the reflectivity at magnetic film/air interface due to photon tunneling through the air gap. The monotonic air gap dependence of FOM and a FOM difference as large as 0.6° between perpendicular and longitudinal magnetization are found, so it might be possible to apply this phenomenon to a new scanning probe magnetic microscope.

ACKNOWLEDGMENTS

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