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AC MOKE Measurements of Yttrium Iron Garnet Thin Films

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The traditional magneto-optical Kerr effect (MOKE) measurements involve measuring the intensity of a light reflected off the samples subjected to a DC magnetic field. By superimposing an AC field to the sweeping DC field, and measuring the AC component of the light intensity, we achieved a high signal-to-noise ratio and a better resolution in determining the Curie temperatures of magnetic samples. For a demonstration, we have determined the Curie temperature of a 350 nm thick YIG (yttrium iron garnet, $Y_3Fe_5O_{12}$) thin film to be 511.0 +/– 0.5 K using this method.

Keywords : MOKE, hysteresis, Curie temperature, AC, YIG, $Y_3Fe_5O_{12}$

1. Introduction

Magneto-optical Kerr effect (MOKE) is widely used in probing the magnetic properties of magnetic thin films, due to its simplicity, sensitivity, and *in situ* feasibility [1, 2]. The Kerr rotation angle and the Kerr ellipticity are obtained by measuring the intensity of a polarized light reflected off the sample through an analyzing polarizer. Magnetization of a sample is generally proportional to its Kerr rotation angle and ellipticity. Thus, a hysteresis diagram can be drawn by plotting the light intensity versus the strength of the applied magnetic field.

A common usage of MOKE is to determine the Curie temperatures of magnetic thin film samples [3]. The standard procedure is to obtain the MOKE hysteresis loop of the sample as a function of temperature. Then, the Curie temperature is found as the temperature when the hysteresis loop disappears. However, in this way, the signal is susceptible to noise from various origins such as fluctuation and drift of the light source. Therefore, it is rather difficult to locate the exact Curie temperature since, near the Curie point, the height of the hysteresis is too small to be distinguishable from the noise. The problem is especially true for transparent magnetic samples due to their low reflectivity.

We have devised an AC method, after Rayleigh's work on butterfly-shaped hysteresis loops [4]. This method employs a DC magnetic field with a superimposed AC component, and the AC magnetization of a sample is recorded as the DC field is swept back and forth. The resulting AC hysteresis loop resembles the shape of a butterfly since it is mathematically just the differentiation of the DC hysteresis loop. By looking at the AC signal, the bandwidth of the noise is reduced, whence a higher resolution in determination of the Curie temperature is expected.

Recently, YIG (yttrium iron garnet $Gd_3Ga_5O_{12}$) gains much attention due to its applications in spintronics [5-7]. YIG is a ferrimagnetic substance with a Curie temperature of 553 K for the bulk. YIG is transparent in the visible spectrum; furthermore, its magnetization is relatively weak compared to ferromagnetic materials. Therefore, YIG thin films serve as good test samples to examine the sensitivity of our AC MOKE system in the determination of the Curie temperature.

2. Experimental Details

The YIG thin film, 350 nm thick, was grown by pulsed laser deposition (PLD) on GGG (111) substrates (gadolinium gallium garnet, $Gd_3Ga_5O_{12}$). The sample, 5 mm x 5 mm in size, was placed parallel to the magnetic field produced by a pair of Helmholtz coils, 40 cm in diameter. A current source capable of supplying a DC current with AC modulation was used to drive the coils. The field produced consisted of a DC bias ranging from −8 to +8 Oe and an AC component with a frequency of 200 Hz and a maximum r.m.s. amplitude of 2.0 Oe. The light

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source was a xenon lamp powered by a regulated power supply, ripple ~ 0.25 %. The light was guided through an optical fiber to focus onto the sample surface at 15 degrees incident angle after passing through a calcite polarizer, extinction ratio > $10^5 : 1$. The direction of polarization was parallel to the sample surface, as is in the case of LMOKE (longitudinal MOKE). The reflected light from the sample again passed through a calcite analyzer, whose polarization angle was set at 5 degrees away from extinction at zero magnetic field. This offset angle is to shift the Kerr hysteresis loop so that it will appear monotonic with respect to the applied DC field [8]. The final light intensity was measured by a photodiode amplified by a low noise transimpedance amplifier with a gain of 10^6 V/A. A lock-in amplifier with reference to the AC modulating field was used to extract the AC part of the signal, while the DC part of the signal was simultaneously read by a precision digital voltmeter. To minimize the non-uniformity of the applied AC field, no metallic parts were allowed in the Helmholtz coils except for a miniature thermocouple for measuring the sample temperature. To maintain a stable temperature, the sample was enclosed in a BN (boron nitride) block with openings for the incident and the reflected light. The block was then heated by the radiation of a 400 watt focused halogen lamp located outside the coils. The temperature was controlled between 298 K and 543 K by a PID temperature controller with a stability of 0.1 K.

3. Results and Discussion

In order to display the virtue of the AC method, we compare it with the DC hysteresis loop method. Figure 1 shows the DC hysteresis loops of the YIG film at different temperatures. The DC magnetic field is swept from positive to negative and back to positive to complete a loop. The loop is not further averaged by repeating the magnetic field sweep. It can be seen from the plots that, in general, the initial value of the signals do not match well with the end value. As mentioned in the introduction, the light source is vulnerable to the fluctuations of the environment, leading to the intensity noise and drift, which would easily wipe out the small MOKE signals. Moreover, when the sample temperature approaches the Curie point, the signal is even weaker and noisier. Consequently, although the hysteresis loop seems to vanish at 507 K, it is still difficult to judge whether or not the Curie point has been reached.

To determine the Curie temperature more precisely, we can observe the change of the AC hysteresis signals with steps of temperature. In Fig. 2 we have the AC amplitude plotted against the applied DC field, where pronounced peaks are observed near zero magnetic field. The peak positions are slightly biased left due to the zero-drift drift of the Gauss meter.

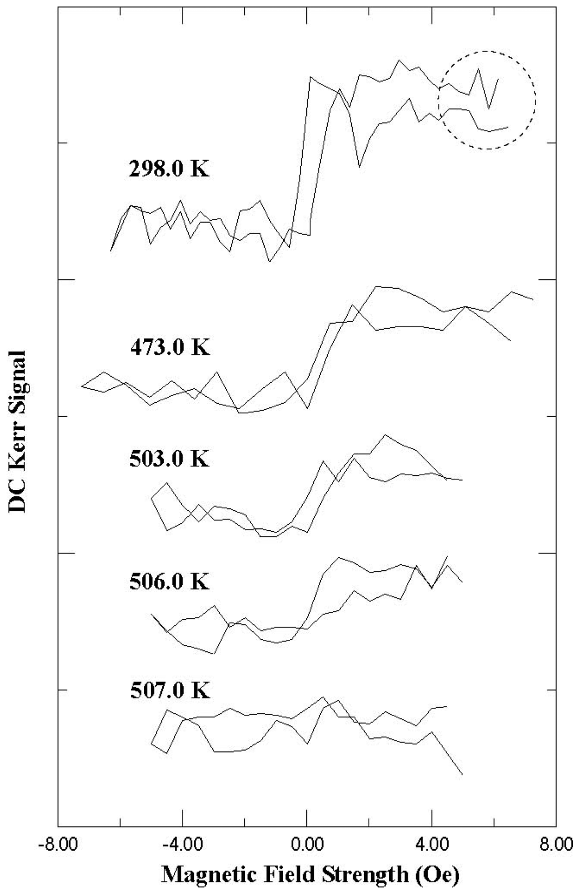

Fig. 1. DC MOKE hysteresis loops measured at different temperatures. The height of the hysteresis loops diminishes as the temperature rises to near the Curie temperature. The dashed circle indicates that the initial and the end values of the loop do not match in general.

The height of the peaks decreases while the temperature is raised, and finally, the peak disappears completely at the Curie temperature. With the AC nature of the method, uncertainties due to the drift and noise of the light source are reduced, so the resolution is promoted to within 0.5 K without resorting to elaborate signal averaging techniques. The Curie temperature thus determined is 511 K, which is significantly higher than 507 K by the previous DC method. The Curie temperature of our deposited thin film is considerably lower than the bulk value of 553 K. This might be due to less ideal sample quality. The Arrott plot method is another way to determine the Curie temperature, but it requires a large magenetization signal with high S/N ratio near the Curie temperature to have a good analysis. For MOKE measurements, the uncertainty in T_C

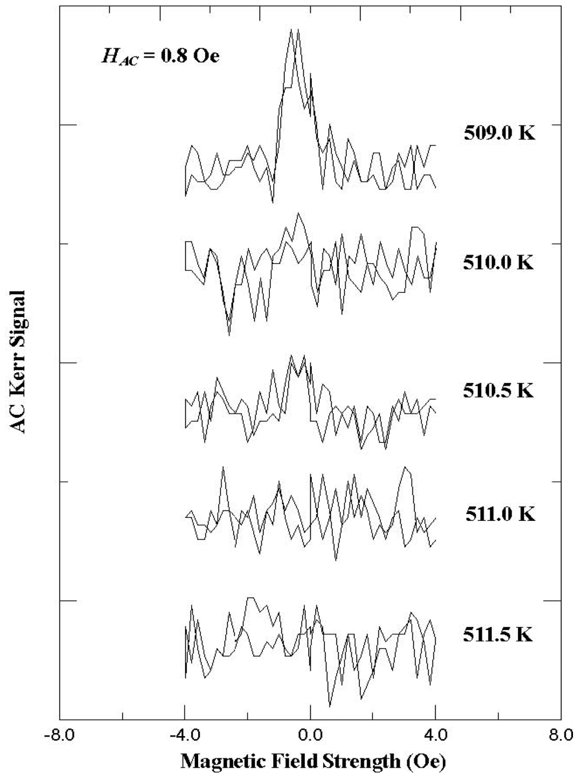

Fig. 2. AC MOKE hysteresis loops measured at different temperatures. The r.m.s. amplitude of the AC applied field (H_{AC}) is 0.8 Oe. As the temperature increases, the signal decreases, and finally vanishes at the Curie temperature, 511 K. Resolution of the Curie temperature up to 0.5 K is achieved here.

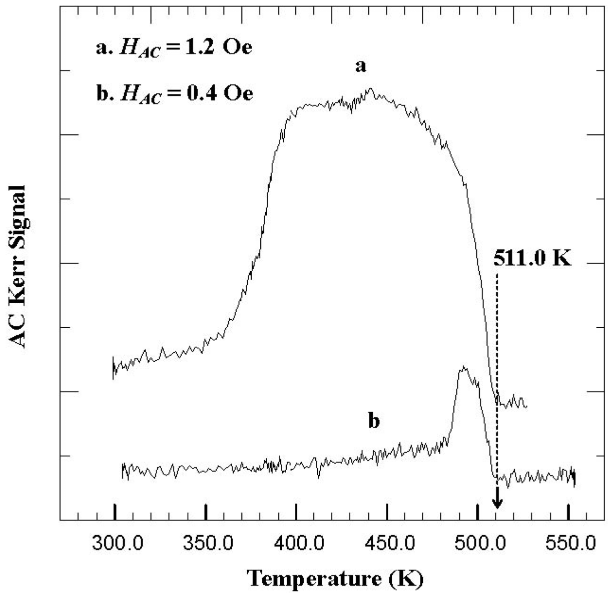

Fig. 3. AC MOKE signal versus temperature at zero DC field. For the two applied AC fields of different r.m.s. amplitudes, 0.4 and 1.2 Oe, respectively, both curves drop sharply near 511 K and level off at higher temperatures. The Curie temperature is estimated to be 511 ± 1 K by this method.

using the Arrott method can be as large as ± 5 K [9, 10].

To speed up the AC measurement, we have the AC light amplitude measured against the temperature with the DC field set to zero (Fig. 3). The AC MOKE measures the differential change of the magnetization within the amplitude of the applied field. At low temperatures, the coercivity of the sample is larger than the r.m.s. amplitudes of the applied AC field, 1.2 and 0.4 Oe, respectively, so the differential (AC) MOKE signals are small. As the temperature is raised, the coercivity is weakened, so the differential changes of the MOKE signals become pronounced. For H_{AC} = 1.2 Oe, 370 K is the temperature when the coercivity approaches 1.2 Oe, so the signal starts increasing. While for H_{AC} = 0.4 Oe, 485 K is the temperature when the coercivity is further reduced to 0.4 Oe. Finally, as the temperature approaches the Curie point, the AC signals acquire the minimum values and remain unchanged above the Curie temperature. The two plots corresponding to AC fields of 1.2 and 0.4 Oe, respectively, show close Curie temperatures of the YIG thin film. Thus, the Curie point located directly from the graph is 511 ± 1 K, which is consistent with the Curie temperature obtained with the more deliberate method involving the full AC hysteresis measurement.

4. Conclusion

Since the magnetic transition depends only on the temperature, light of any frequency is bound to show a hysteresis in the DC and AC MOKE measurements. The light source in our setup is a xenon lamp with a wide range of frequency distribution rather than a monotonic laser. Moreover, the AC signal measured is invulnerable against DC noise, granting a more precise result. In fact, in our setup, the ambient light leaking to the photo diode does not affect the results at all. Finally, for the purpose of a quick scan of the Curie temperature, it can be done more efficiently with only a small sacrifice in precision by doing the AC measurement at zero DC field.

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