# Dielectric tensor characterization of $Mn_{0.53}Bi_{0.47}$ and $Mn_{0.52}Bi_{0.44}Sb_{0.04}$ films

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We have grown $Mn_{0.53}Bi_{0.47}$ and $Mn_{0.52}Bi_{0.44}Sb_{0.04}$ alloy films on glass substrates under UHV conditions. These films exhibit good magneto-optical (MO) properties. Unfortunately, the measurements of Kerr rotation and ellipticity cannot by themselves provide reliable evaluation of the MO properties of a layer capped with a dielectric SiO film. The purpose of the present work was to determine the dielectric tensor in the $MnBi_{1-x}Sb_x$ films within a multilayer stack, using a combination of ellipsometric, reflection/transmission, and polar MO Kerr effect measurements in the wavelength range of 360–860 nm. We have evaluated the $Mn_{0.53}Bi_{0.47}$ and $Mn_{0.52}Bi_{0.44}Sb_{0.04}$ films based on the intrinsic MO figure of merit (FOM) defined by $\mathrm{FOM}=|\epsilon_{xy}|/(2\ \mathrm{Im}\ \epsilon_{xx})$, where $\epsilon_{xy}$ and $\epsilon_{xx}$ are the diagonal and off-diagonal elements of the dielectric tensor of the MO material. For short wavelengths (360–550 nm) the measured FOM in the $Mn_{0.53}Bi_{0.47}$ and $Mn_{0.52}Bi_{0.44}Sb_{0.04}$ films is significantly larger ($\geq$factor of 2) than that commonly observed in TbFeCo films ($\sim$0.01).

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For quite some time, MnBi films have attracted considerable attention as a possible high-density magneto-optical (MO) media.[1] The large Kerr rotation and perpendicular anisotropy have maintained the interest in this material among physicists despite its severe problem, lack of thermodynamical stability. Two phases of MnBi exist, a low-temperature phase (LTP) and high-temperature phase (HTP), which exhibit different MO response. During thermomagnetic writing the HTP phase is quenched and causes a rapid reduction of MO signal. One of the approaches to stabilize the low-temperature phase of MnBi, a phase which exhibits very good MO response, was to substitute a fraction of the Bi atoms with Sb atoms.[2–4]

The aim of the present article is to determine the diagonal and off-diagonal elements of the dielectric tensor for the $Mn_{0.53}Bi_{0.47}$ and $Mn_{0.52}Bi_{0.44}Sb_{0.04}$ films and evaluate the figure of merit (FOM) of these MO layers. To determine the elements of the dielectric tensor of a MO film one must measure thickness and optical constants for all the layers within the structure. To do this, we have performed ellipsometric, reflectance, and polar MO Kerr effect measurements, and analyzed the data using the MULTILAYER computer program. Detailed descriptions of apparatus, measurement procedures, and the computer program can be found in the article by Hong Fu *et al.*[5]

To evaluate the performance of any MO media one should use parameters which do not depend upon the geometry of the studied structures. The intrinsic FOM, introduced for the first time by Mansuripur,[6] provides the best way to compare different media. The FOM, which is solely determined by the dielectric tensor of the MO material, is given by

$$\mathrm{FOM}=\frac{|\epsilon_{xy}|}{2\ \mathrm{Im}\ \epsilon_{xx}}.$$

Frequently, the off-diagonal reflectivity, $r_{xy}$, has been used in the literature to describe the efficiency of a sample in rotating polarization. The incident, linearly polarized beam has only an $x$ component and the reflected beam has both $x$ and $y$ components. The absolute value of the off-diagonal reflectivity is defined by ratio $|E_y^{\mathrm{ref}}/E_x^{\mathrm{inc}}|$, where $E_y^{\mathrm{ref}}$ and $E_x^{\mathrm{inc}}$ are the $E$-field amplitudes of the $y$ component of the reflected light and the $x$ component of the incident light, respectively. The measurements of Kerr rotation $\Theta_k$, ellipticity $\epsilon_k$, and total reflectivity $\mathbf{R}$ can be used to calculate the absolute value of the off-diagonal reflectivity from the following formula:[7]

$$|\mathbf{r}_{xy}|=\sqrt{R(\Theta_k^2+\epsilon_k^2)}.$$

Since values of $\Theta_k$, $\epsilon_k$, and $\mathbf{R}$ strongly depend on the thicknesses of the layers in the studied structure, the value of $|\mathbf{r}_{xy}|$ for the same MO layer may vary significantly. It can be shown,[6] however, that $|\mathbf{r}_{xy}|$ is upper bounded by the FOM. In addition, it is possible to design a structure for which $|\mathbf{r}_{xy}|$ approaches the FOM of the MO material. For these reasons, we will quote both $|\mathbf{r}_{xy}|$ and FOM in our article.

We grew our samples on glass (Corning 7059) substrates under UHV conditions. Sample preparation and systematic studies of the structural, magnetic, and magneto-optical properties of the $MnBi_{1-x}Sb_x$ films have been recently reported elsewhere by Celinski *et al.*[4] The substitution of Bi atoms by Sb does not improve the thermal stability of these MnBi based layers. To avoid ambiguities during analysis of optical measurement data we also grew a single layer of SiO on glass and determined its optical constants independently.

Utilizing a multiwavelength variable-angle ellipsometer we measured the polarization rotation and ellipticity as a function of incident angle $\Theta_{\mathrm{inc}}$ for linearly polarized light with wavelengths $\lambda$ within the range 360–860 nm. The measurements of total reflectance $R$, $\Theta_k$, and $\epsilon_k$ at normal incidence were carried out on a MO Kerr spectrometer. All measurements were taken from the film side. The thickness and diagonal elements $\epsilon_{xx}$ of the various layers were determined by using the ellipsometric and total reflectance $R$ data. Off-diagonal elements, $\epsilon_{xy}$, were determined by using Kerr effect and ellipsometric data.

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TABLE I. The calculated values of diagonal and off-diagonal elements of the dielectric tensor for the $Mn_{0.53}Bi_{0.47}$ and $Mn_{0.52}Bi_{0.44}Sb_{0.04}$ samples. Then $n$ and $k$ values for the SiO layers are presented for the film grown on top of the $Mn_{0.53}Bi_{0.47}$ layer.

| Wavelength (nm) | $Mn_{0.53}Bi_{0.47}$ | | $Mn_{0.52}Bi_{0.44}Sb_{0.04}$ | | SiO | |
|---|---|---|---|---|---|---|
| | $\epsilon_{xx}$ | $\epsilon_{xy}$ | $\epsilon_{xx}$ | $\epsilon_{xy}$ | $n$ | $k$ |
| 360 | $0.01+i2.65$ | $-0.04-i0.09$ | $-1.80+i4.03$ | $-0.09-i0.19$ | 1.735 | 0.109 |
| 400 | $-0.10+i3.19$ | $-0.07-i0.09$ | $-0.84+i4.22$ | $-0.10-i0.11$ | 1.712 | 0.053 |
| 450 | $-0.58+i4.03$ | $-0.09-i0.10$ | $-0.16+i4.71$ | $-0.13-i0.08$ | 1.694 | 0.025 |
| 500 | $-0.86+i5.97$ | $-0.15-i0.12$ | $-0.19+i6.21$ | $-0.18-i0.09$ | 1.719 | 0.014 |
| 550 | $-1.37+i7.53$ | $-0.23-i0.14$ | $-1.26+i7.66$ | $-0.29-i0.12$ | 1.746 | 0.013 |
| 600 | $-2.12+i9.52$ | $-0.34-i0.13$ | $-2.70+i6.71$ | $-0.30-i0.13$ | 1.788 | 0.010 |
| 633 | $-2.75+i10.6$ | $-0.40-i0.11$ | $-4.00+i10.5$ | $-0.54-i0.12$ | 1.805 | 0.007 |
| 650 | $-2.61+i10.9$ | $-0.44-i0.07$ | $-3.19+i10.9$ | $-0.58-i0.03$ | 1.807 | 0.0 |
| 700 | $-4.09+i12.2$ | $-0.57-i0.06$ | $-3.81+i12.2$ | $-0.70+i0.12$ | 1.815 | 0.0 |
| 750 | $-0.89+i16.5$ | $-0.74+i0.35$ | $-5.01+i13.2$ | $-0.843+i0.22$ | 1.835 | 0.0 |
| 780 | $0.48+i16.0$ | $-0.67+i0.52$ | $-5.30+i14.5$ | $-0.92+i0.34$ | 1.814 | 0.0 |
| 820 | $1.38+i15.9$ | $-0.55+i0.63$ | $-1.51+i13.6$ | $-0.61+i0.65$ | 1.827 | 0.0 |
| 840 | $3.71+i17.5$ | $-0.55+i0.96$ | | | 1.830 | 0.0 |
| 860 | $3.91+i17.1$ | $-0.46+i1.02$ | | | 1.835 | 0.0 |

Table I shows results of our analysis of the dielectric tensor elements for both MO layers, $Mn_{0.53}Bi_{0.47}$ and $Mn_{0.52}Bi_{0.44}Sb_{0.04}$. We estimated that the error associated with our analysis does not exceed 5%. The quality of our analysis can be assessed by analyzing Fig. 1 which shows a typical set of ellipsometric data. The open and solid symbols represent rotation and ellipticity, respectively, as a function of incident angle for 400 nm wavelength. The solid lines depict the best theoretical fit to this data. In order to obtain such a good fit at short wavelengths values of $n$ and $k$ for the SiO layer had to be slightly modified from those obtained for a SiO layer grown on glass. Table I also contains the $n$ and $k$ values for the SiO layer grown on top of $Mn_{0.53}Bi_{0.47}$ film.

From our measurements we determined that the $Mn_{0.53}Bi_{0.47}$ film was 70 nm thick and the SiO layer was 65 nm thick. These results are in good agreement with values obtained from the thickness monitor during deposition. The Kerr hysteresis loops are fairly squared with a coercive field of 840 Oe (see inset in Fig. 2). Figure 2 shows the wavelength dependence of the Kerr rotation and ellipticity. The observed extrema in $\Theta_k$ and $\epsilon_k$, at 600 nm, are related to the interference effect due to the SiO overcoating. As expected, we observed a significant decrease in total reflectivity $R$ at this wavelength. For a wavelength of 400 nm, far from the interference condition, the Kerr rotation and ellipticity still have significantly high values, 0.9° and 0.35°, respectively, indicating good MO response at short wavelength. Figure 3 shows the wavelength dependence of $n$ and $k$ for $Mn_{0.53}Bi_{0.47}$ film. The lines were added to guide the reader's eye. Our values of $n$ and $k$ are comparable with those previously reported in the literature.[5] Figure 4 shows the calculated FOM and off diagonal reflectivity, $\mathbf{r}_{xy}$, as a function of the wavelength for $Mn_{0.53}Bi_{0.47}$ film. Determined values of FOM are smaller than those previously reported.[5] This indicates that measured parameters, such as FOM, are not universal for a given compound but strongly depend on the growth conditions, procedure, and small changes in stoichiometry for the MnBi based compounds.

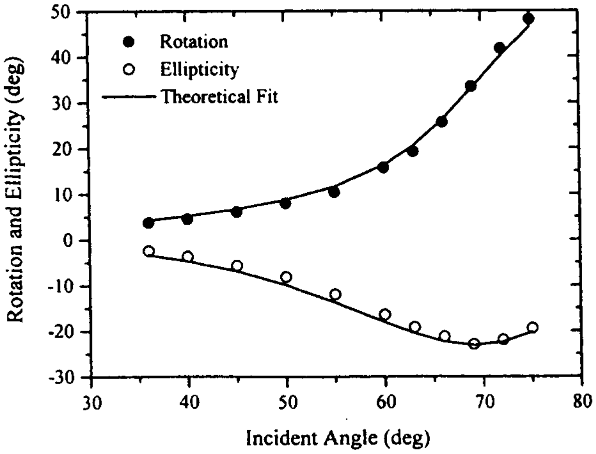

FIG. 1. Measured rotation and ellipticity, open and solid circles, respectively, as a function of incident angle $\Theta_{inc}$ at 400 nm wavelength for the $Mn_{0.53}Bi_{0.47}$ sample. The solid lines represent the best fit.

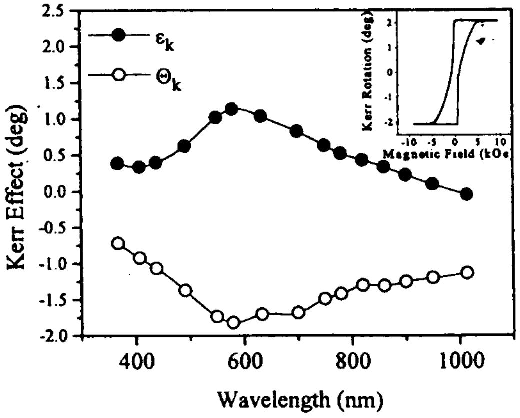

FIG. 2. Measured Kerr rotation $\Theta_k$ and ellipticity $\epsilon_k$, open and solid circles, respectively, as a function of wavelength for the $Mn_{0.53}Bi_{0.47}$ sample. The solid lines were added to guide the reader's eye. Measurements were performed from the film side.

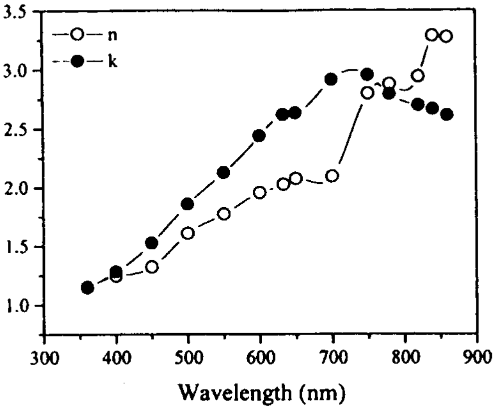

FIG. 3. The best estimate values of *n* and *k* as a function of wavelength for the Mn$_{0.53}$Bi$_{0.47}$ sample.

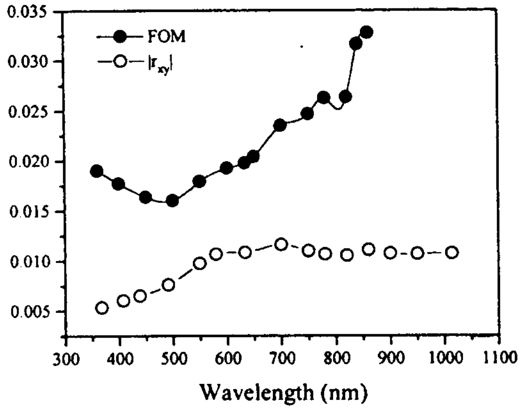

FIG. 4. Measured $|r_{xy}|$ (solid symbols) and the computed FOM (open symbols) for the Mn$_{0.53}$Bi$_{0.47}$ sample as a function of wavelength.

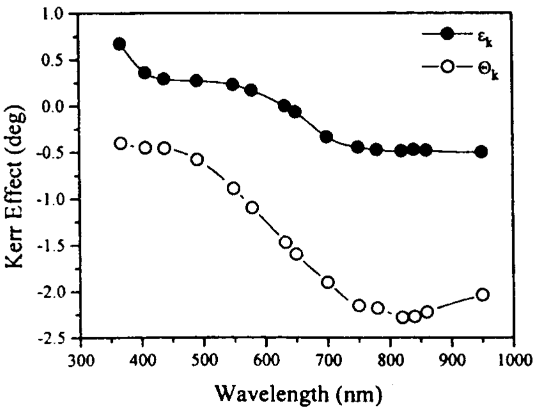

FIG. 5. Measured Kerr rotation $\Theta_k$ and ellipticity $\epsilon_k$, open and solid circles, respectively, as a function of wavelength for the Mn$_{0.52}$Bi$_{0.44}$Sb$_{0.04}$ sample. The solid lines were added to guide the reader's eye. Measurements were performed from the film side.

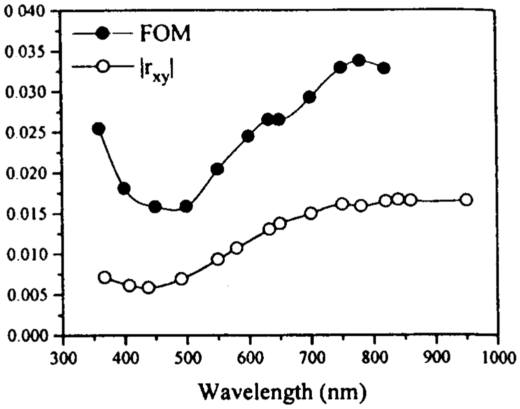

FIG. 6. Measured $|r_{xy}|$ (solid symbols) and the computed FOM (open symbols) for the Mn$_{0.52}$Bi$_{0.44}$Sb$_{0.04}$ sample as a function of wavelength.

Our Mn$_{0.52}$Bi$_{0.44}$Sb$_{0.04}$ film was also 70 nm thick, capped with a 95 nm SiO layer. The Kerr hysteresis loops are fairly square with a coercive field of 3 kOe. Figure 5 shows the wavelength dependence of $\Theta_k$, and $\epsilon_k$. The observed extreme in Kerr rotation at 800 nm is again related to the interference effect due to SiO overcoating (the total reflectivity also shows a broad minimum at this wavelength). At short wavelengths, the measured values of the Kerr rotation and ellipticity, −0.4° and 0.67°, respectively, indicate again a good MO response in this material. The determined values of *n* and *k* for the Mn$_{0.52}$Bi$_{0.44}$Sb$_{0.04}$ film are very similar to that observed for Mn$_{0.53}$Bi$_{0.47}$ film. This indicates that the presence of Sb atoms does not modify the values of *n* and *k*. Figure 6 shows the FOM as a function of wavelength for the Mn$_{0.52}$Bi$_{0.44}$Sb$_{0.04}$ film. Only for a narrow range, between 400 to 500 nm, the determined values of FOM are equal to those determined for Mn$_{0.53}$Bi$_{0.47}$. For all other wavelengths the values of FOM are 25% larger than these determined for Mn$_{0.53}$Bi$_{0.47}$. At 360 nm, the FOM for Mn$_{0.52}$Bi$_{0.44}$Sb$_{0.04}$ is equal to 0.025, more than twice the value observed for TbFeCo, which is currently used for MO recording. This would make our films a good candidate for future MO data storage medium if the thermodynamic stability problem could be solved in MnBi based layers.

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[1] D. Chen, J. F. Ready, and E. Bernal, J. Appl. Phys. **39**, 3916 (1968).
[2] M. Takahashi, Y. Kikuchi, and T. Wakiyama, IEEE Trans. J. Magn. Jpn. **4**, 673 (1989); M. Takahashi, Y. Kikuchi, T. Tanaka, and T. Wakiyama, *ibid.* **5**, 998 (1990).
[3] Y. J. Wang, J. X. Shen, and Q. Tang, J. Magn. Magn. Mater. **74**, 365 (1988).
[4] Z. Celinski, Dino Pardo, Brad N. Engel, and Charles M. Falco, IEEE Trans. Magn. **31**, 3233 (1995).
[5] Hong Fu, Zheng Yan, Seh Kwang Lee, and M. Mansuripur, J. Appl. Phys. **78**, 4076 (1995).
[6] M. Mansuripur, Appl. Phys. Lett. **49**, 19 (1986).
[7] M. Mansuripur, *The Physical Principles of the Magnet-Optical Recording* (Cambridge University Press, Cambridge, 1995), p. 206.
[8] A. F. Anderson, J. E. Engebretsen, and J. Refsnes, Acta Chem. Scand. **26**, 175 (1972).