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Cite as: AIP Advances 9, 125335 (2019); https://doi.org/10.1063/1.5130182
Submitted: 12 October 2019 . Accepted: 08 November 2019 . Published Online: 27 December 2019

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Manipulations of the coercivity and the Kerr signal of the NiFe films by a ZnO underlayer

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Note: This paper was presented at the 64th Annual Conference on Magnetism and Magnetic Materials.

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ABSTRACT
In this study, Ni$_{50}$Fe$_{50}$ films with different thicknesses were prepared on a ZnO(0001) film that was grown on a conductive Si(100) substrate. The ZnO(0001) film was characterized to be a ferroelectric layer with a value of piezoelectric constant, $d_{33}$, equal to 5.0pm/V. Monotonic decreases in the coercivity of the NiFe films can be observed while the ZnO layer exposed to an electric field. As the applied potential equal to 10V, the coercivity of the NiFe films reduced 64% and 41% for the thickness equal to 10nm and 50nm, respectively. The strength of the strain field established inside the NiFe films was strongly correlated with the decreasing ratio of the coercivity. Moreover, the Kerr signal of the NiFe films can be well modulated by the electric fields established across the ZnO layer while the potential lower than 10V. The lattice distortion and dislocation formation inside the ZnO layer controlled the highest potential that can be applied and, consequently, the reliability of the modulation of the Kerr signal.

I. INTRODUCTION
The magnetic states of traditional spin electronic devices usually controlled by a magnetic field or a small current. In such devices, the performance, signal-to-noise ratio, and dimension are strongly influenced by their thermal stability. To overcome the thermal disaster, magnetic devices through voltage control have been developed. One of the methods to manipulate the magnetic state of a ferromagnetic layer is through the strain effect (magnetostriction) of the layer. In such a case, the strain of the ferroelectric layer is provided by a nearby piezoelectric (ferroelectric) material.

In 2007, S. Sahoo et al. prepared a 10-nm-thick Fe film on BaTiO$_3$(100) substrate. A clear change of the coercivity ($H_c$) of the Fe film as the BaTiO$_3$ subjected a ±2 kV/cm electric field. In 2014, W.-C. Lin et al. using Kerr effect to monitor the coercivity of the ZnO/Fe bilayers, the $H_c$ of the Fe also decreased as elevating the bias voltage across the ZnO layer. Besides, the value of the $H_c$ of Fe film was enhanced through the annealing due to the leakage current. In this study, the permalloy (NiFe) films with thicknesses, $t$, equal to 10 and 50nm were fabricated on ZnO(0001) layers. The hysteresis loops of the NiFe films were monitored while the ZnO layer subjected to an electrical potential.

II. EXPERIMENTAL PROCEDURE
The films were grown on the conductively N-type Si(100) substrates with a resistivity ranged from 0.001 - 0.005 Ω-cm. Before the film deposition, the Si substrates were etched by dilute HF (20%) for 2 mins to remove the native oxide. Then, the ZnO layer was prepared by the RF sputter using a ZnO target with a power of 100 W under a mixed gas of Ar and O$_2$ at a ratio equal to 3:1. During the growth of the ZnO layer, the substrate temperature and the deposition pressure were kept at 600°C and 2x10$^{-2}$ Torr, respectively. Subsequently, the NiFe films were deposited on the ZnO layer at room temperature by using the RF sputter with a power of 40 W and a processing gas of Ar under a pressure of 6x10$^{-2}$ Torr.

The structures of the films were characterized by the θ-2θ X-ray diffraction (XRD) with Cu K$_\alpha$ radiation in the Rigaku IV system. The thicknesses and the compositions of layers were measured by
a secondary electron microscope (SEM) and an energy dispersive spectroscopy (EDS) purchased from JEOL Inc. The morphology and vertical piezoresponse of the ZnO layer were detected by a Ti-Pt coated NSC36C cantilever operated in the DC-EFM mode, which is the piezoresponse mode (PFM) named by other brands, of the XE-100 scanning probe microscope purchased from the Park Systems Inc. The frequency and root-mean-square (RMS) amplitude of the AC voltage that applied on the AFM tip were set at 10 kHz and 2 V, respectively to obtain the piezoresponse. The magnetic hysteresis loops of the NiFe films were obtained by a home-build magneto-optical Kerr effect (MOKE) under a longitudinal configuration with voltage applications by a Keithley 2400 source meter.

III. RESULTS AND DISCUSSION

The thickness and crystal structure of the ZnO layer were 320nm and a strong (0001) texture as extracting from the cross-section SEM (not shown here) and the θ-2θ XRD (Fig. 1), respectively. Figures 2(a)–2(c) were the morphology, PFM amplitude and PFM phase images of the ZnO film. Because the Zn\textsuperscript{2+} and O\textsuperscript{2-} sublattices do not have a common center but separate a small distance along the c-axis, the ZnO possessed a permanent electric dipole moment along the c-axis. From the population of the light and dark areas in the phase image, we concluded that the c\textsuperscript{+} and c\textsuperscript{-} ferroelectric domains were almost equivalent for the as-deposited film. And the dark stripes in the amplitude image indicated the ZnO film possessed multiple ferroelectric domains in a single grain.

The piezoelectric constant, $d_{33}$, of the ZnO film was obtained by measuring the curve of piezoresponse versus the applied AC voltage. By comparing the slope of the piezoresponse curve of the ZnO in Fig. 3(c) with the curve of the X-cut quartz in Fig. 3(b), with a value of $d_{11}=2.3$ pm/V, the $d_{33}$ value of ZnO can be extracted by

$$d_{33_{\text{ZnO}}} = \frac{\text{slope}_{\text{ZnO}}}{\text{slope}_{\text{quartz}}} \times d_{11_{\text{quartz}}}$$  \hspace{1cm} (1)
FIG. 3. The curves of piezoresponse versus bias voltage of (a) the ZnO film and (b) the X-cut quartz.

where \( d_{33, \text{ZnO}} \) is the value of the \( d_{33} \) piezoelectric constant of the ZnO, and \( d_{11, \text{quartz}} \) is the \( d_{11} \) piezoelectric constant of the X-cut quartz, and slope_{ZnO} and slope_{quartz} denote the slopes of the linear fitted curves of the curves of piezoresponse versus bias AC voltages for ZnO and X-cut quartz, respectively. Because such a measurement was a local detection, we measured \( d_{33} \) at ten different grains and got an average value of 5.0 pm/V. Such a \( d_{33} \) value was lower than the previous reports of other researchers and possibly resulted by the strong clamping effect from the underlying Si substrate and the repellent effect between the highly textured ZnO grains. In addition, by measuring the piezoelectric response curve (not shown here), it can be known that the coercive field of the ZnO ferroelectric thin film is around \( \pm 2 \) V. Therefore, for the bias voltage larger than \( \pm 2 \) V, the NiFe film will suffer a compressive stress resulted from the lattice elongation of the ZnO along the electric field direction.

By using the NiFe layer and the conductive Si substrate as the top and the bottom electrodes, respectively, we applied different potentials across the ZnO layer and then measured the magnetic hysteresis loops of the NiFe films simultaneously. Figures 4(a) and

FIG. 4. The hysteresis loops, coercivity distribution, and initial curves of the Kerr signal of ZnO/NiFe bilayers under different bias voltages. (a), (c) and (e) were for \( t=10 \) nm. (b), (d) and (f) were for \( t=50 \) nm.
showed a series of the hysteresis loops of the NiFe films with t= 10 nm and t= 50 nm, respectively, under different potential ranged from 0 V to 10 V. The Hc versus potential were plotted in Figs. 4(c) and 4(d) for the thickness, t, equal to 10 nm and 50 nm, respectively. We observed that a monotonic reduction of the Hc and Kerr signal of the NiFe films no matter what polarity of the electric field was. The starting voltage for the reduction of coercivity is 2.2V and 5.1V for t= 10 and 50nm, respectively. The reduction ratio of the Hc and the Kerr signal were 64% and 0.5mV (/43% and 0.4mV) for t= 10nm (/50nm) sample after applying 10V across the ZnO layer.

From the EDS spectrum (not shown here) and the XRD (inset of Fig. 1), we got that the permalloy film possessed an atomic ratio of Ni and Fe equals to 1:1 and a (111) orientation mainly. The (111) peak of the 50-nm-thick NiFe was slightly intense due to the thickness effect. The bulk value of λ111 of Ni50Fe50 is around 3×10−5. Through the magnetostrictive effect, such a lattice strain possibly alters the magnetic behaviors of the NiFe film. From the above observations, comparing with the 10-nm-thick sample, the 50nm one was less sensitive to the same applied potential. In general, a thicker film needed a larger stress to result in a significant lattice strain. A larger starting voltage and less reduction ratios of the Hc and the Kerr signal implied that the magnetic behavior of the NiFe film was dominated by the lattice strain imposed by the ZnO under layer.

Furthermore, Figs. 4(c) and 4(d) were the initial Kerr curves of the samples under different bias voltage for t= 10nm and 50nm, respectively. For the 10nm sample, the field required to saturate the magnetization was lower for higher bias voltages. For the 50nm sample, a sharp jump was observed for bias voltage higher than 7V. As reported by M. J. Sablik et al., for a magnetic sample under compressive stress, the initial curve of magnetization reaches saturation state at a relatively lower field.

Figures 5(a) and 5(b) showed the peak-to-peak Kerr intensity under different bias voltages for t= 10nm and 50nm, respectively. A monotonic decrease of the peak-to-peak Kerr intensity was observed for both samples. In the voltage modulation experiments, a 10 V step function with a period of 30 s was applied across the ZnO layer and the Kerr signal of the NiFe films was monitored. Figures 5(c) and 5(d) sketched the applied potential across the ZnO layer and the corresponding variations of the Kerr single for t= 10nm and 50nm, respectively. A larger change in Kerr intensity was observed in the 10-nm-thick sample due to a larger strain field as mentioned above. For the potential higher than 11 V, nonlinear behavior of the Kerr signal can be observed and the reversible modulation of the Kerr signal cannot be achieved.

A repeatable modulation of the Kerr signal under a 10 V potential can also be explained by the reversible lattice strain of the ZnO layers. From the out-of-plane X-ray diffraction, Fig. 1, the lattice parameter along the c-axis of the ZnO crystal was calculated to be 5.40 Å. If we assume that the volume of the ZnO hexagonal unit cell equal to the bulk one, that is 47.57 Å3, the in-plane lattice parameter of the hexagonal unit cell will be 3.19Å. If we applied 10 V across the ZnO film, the lattice parameter of the c- (i.e.) domain will be enlarge (shrinkage) by 50 pm, that corresponded to a 9.3% change in dimension, along the c-axis. Under an assumption of constant volume, the in-plane lattice parameter of the ZnO film will change 5.0% under a potential of 10 V.

Considering the formation energy of dislocations and the strain energy stored in the film, for the lattice distortion larger than 11%, the dislocations will form inside a film and the recovery of the lattice cannot be achieved. In our case, under the application of 10 V, the lattice parameter of the c-axis of the ZnO layer changed 9.3%. It is quite close to the 11% upper limit of the reversible distortion. We
estimated that the highest potential for the reversible modulation of the Kerr signal will be 11.9 V that corresponds to an 11% lattice distortion along the c-axis of the ZnO layer.

In the previous reports, in addition to the lattice strain induced change of magnetic properties, the leakage current inside the oxide layer increased film temperature will also affect the magnetic behaviors. In our case, the leakage current versus bias voltage of the ZnO(0001) film was sketched in Fig. 2(d). A resistance switch can be observed for the application of voltage around 14.9 V and the leakage current was quite low for the applied voltage lower than 8 V. We cannot exclude the influence of the thermal effect especially for the applied voltage higher than 8 V. But for the ZnO/NiFe bilayers studied here, the starting voltage of the change in $H_c$ was 2.2 V and 5.1 V for $t=10$ and 50 nm, respectively. Therefore, we concluded that the strain effect played an important role under low applied voltages.

**IV. CONCLUSION**

The manipulations of the $H_c$ and Kerr signal of the Ni$_{50}$Fe$_{50}$ layers through the strain effect asserted by the ZnO underlayer were achieved at a 0-10 V bias voltage region. The coercive values and Kerr signals of the NiFe films decreased monotonically as increasing the bias voltage. The starting voltage for the reduction of coercivity is 2.2 V and 5.1 V for $t=10$ and 50 nm, respectively. The reduction ratio of the $H_c$ and the Kerr signal were 64% and 0.5 mV (43% and 0.4 mV) for $t=10$ nm (50 nm) sample after applying 10 V across the ZnO layer. The thermal effect resulted from the leakage current of the ZnO layer cannot be avoided as the bias voltage larger than 8 V.

**ACKNOWLEDGMENTS**

The authors are grateful for the long-term support by the Ministry of Science and Technology, Taiwan, R.O.C.

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