УДК 536.51.083.6/621.373.826+620.179.142.6

NONDESTRUCTIVE MAGNETO-OPTICAL LASER THERMOMETRY

Maksymykhin M.Ye.
University of Maine, France,
National Technical University of Ukraine
«Kyiv Polytechnic Institute»
Parpiiev T.A.
University of Maine, France

The research of nanomaterial samples by magneto-optical methods is performed. One set of the samples has little coercive force and it is not possible for us to change it with weak external magnetic field. In another set of samples coercivity is larger so after heating such sample with laser it is possible to observe the change of hysteresis loop under heating. Very interesting observation was made, such as for thin layer of nonmagnetic material (40 nm of gold) with light penetration of 15 nm we could still observe magneto-optical signal of next deposited magnetic layer. Application of this technique allows controlling quality and homogeneity of the ferromagnetic samples with nanometer depth resolution without applying complicated femtosecond technique. We did not observe decreasing of magnetic signal with heating by continuous laser of high (up to 1.5 W) power but we saw the change of coercivity.

Keywords: laser, thermometry, magnet, loop heterosis, signal.

Introduction. Sustained interest in nanostructures due to the possibility of significant modifications and fundamental changes in the qualities of materials known in the transition to the nanocrystalline state. Created through nanotechnology new nanoscale magnetic materials exhibit a number of unusual properties: giant magnetic resistance (GMR), giant magnetic impedance (GMI), the anomalous Hall effect (AHE), strong magneto-optical (MO) response and anomalous optical effects. The subject of intense experimental and theoretical researches is the question of the mutual influence of composition and microstructure on the magnetic, magneto-optical and magnetictransport properties of nanoheterostructures. Despite the large number of works there is still no clarity in understanding of the processes that accompany the restructuring of the material.At nanoscale there are following significant parameters that are responsible for material properties: interactions among nanoparticles and with substrate, as well as influence of the size and surface effects.

In this connection are relevant experimental methods to gain an understanding of the internal structure of such materials and features of the magnetic interaction in them. Optical and magneto-optical methods are the most simple, efficient and informative in the study of nanostructures. MO methods have several advantages, the main of which consists in the fact that, unlike optical, they are susceptible to spin. MO methods sensitive to the presence of magnetic nonhomogeneities, changesof the shape and the particle size, their volume distribution and the appearance of new magnetic phases.

In the last ten years the field of femtosecond magnetism has attracted huge attention which is confirmed by a large number of researches in this area. It poses fundamental questions as well as possible applications such as ultrafast magnetization switching. Under influence of femtosecond laser pulses ferromagnetic films exhibit an ultrafast demagnetization. Usually for investigating the underlying microscopic processes responsible for the observed demagnetization the magnetic solid picoseconds laser pulses are used. Observed reduction in the coercivity with increasing pump power is attributed to a heat-assisted magnetization switching process taking place on the millisecond timescale. We show that such type of experiment could be formed with continues laser irradiation and propose an experimental setup that would allow this experiment to be done.

Coercivity is a structurally sensitive characteristic, so it can be used for the analysis of structural and phase transformations in magnetic materials for the study of lattice defects formed under various influences on the metal (plastic deformation, irradiation). Through this work we will widely use this property of magnetic material.

1.1. Samplesand experimental setup

The samples under investigation are cobalt thin films (with thickness 30nm), grown quasi-epitaxially on a sapphire substrate by means of electron beam evaporation, covered by gold layer thus we had multilayer samples.

Sample set:
- 20 nm Au/30 Co/Sapphire
- 40 nm Au/30 Co/Sapphire
- 50 nm Au/30 Co/Sapphire
- 70 nm Au/30 nm Co/Sapphire
- 100 nm Au/30 Co/Sapphire
- 130 nm Au/30 nm Co/Sapphire
- 160 nm Au/30 nm Co/Sapphire

The detailed experimental setup for measurements is described with help of fig. 1. Briefly, a two-color pump-probe experiment is used, where pump laser is operating at a central wavelength of 532 nm in continues mode. For probe He-Ne laser is using with wavelength of 632 nm. A high signal to noise ratio (SNR) is accomplished by means of balanced optical bridge detection with subsequent lock-in filtering. Experiments are performed at room temperature in the transversal Kerr configuration. In our case the external field is applied perpendicular to the multilayer gold/cobalt/sapphire sample.

Generally in TR-MOKE record full hysteresis loops is not recorded, but the difference in the Kerr signals (positive and negative) for two external fields that are large enough to magnetically saturate the sample. For observing dynamic behavior of both magnetic saturations and coercivity we record complete hysteresis loops without any time delays. It allows as to control quality of alignment and check if irreversible sample damage occurs.

Beam splitter cube is put on for split a beam of light emitted by a probe laser in two. It is necessary for generating a reference beam which is in turn used to balance the photodetector thus allows to increase SNR. Another beam which passes the splitter is focusing on the sample and then, after reflection, it falls on the detector. Laser characteristics are listed below:

Probe laser:

- wavelength – 632 nm;
- intensity – 1 mW.

Pump laser:

- wavelength – 532 nm;
- intensity (max) – 5 W.

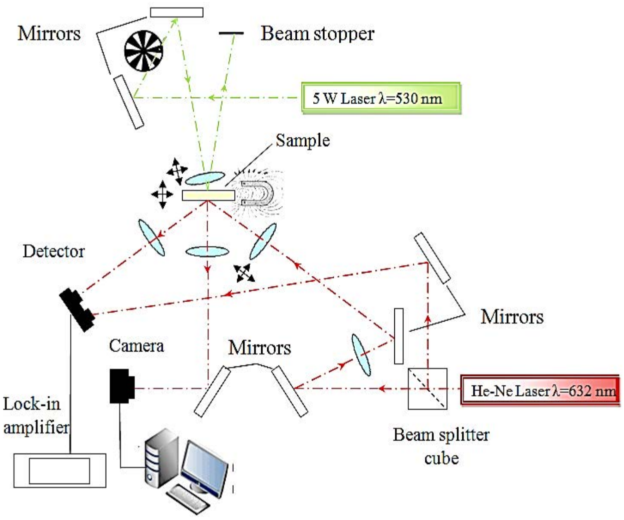

Fig. 1. Schema of the setup

1.2. Hysteresis loop detecting

Dynamic method of measuring TR MOKE is detecting small changes in the intensity of the reflected light when the sample magnetization reversal of an alternating magnetic field. Computer program for hysteresis loop detecting was developed by using MatLab and LabView. The main idea of developed program isfollowing: first of all we detect two signals (sine wave magnetic field signal and magneto-optical signal), further using DAQ Card and PC these two signals are processedafter preliminary Lock-in treatment. Then program build several graphics including hysteresis loop of testingsample. A change of its form can be observed as a result of heating the sample [1]. The scheme of data acquiring is shown on fig. 2.

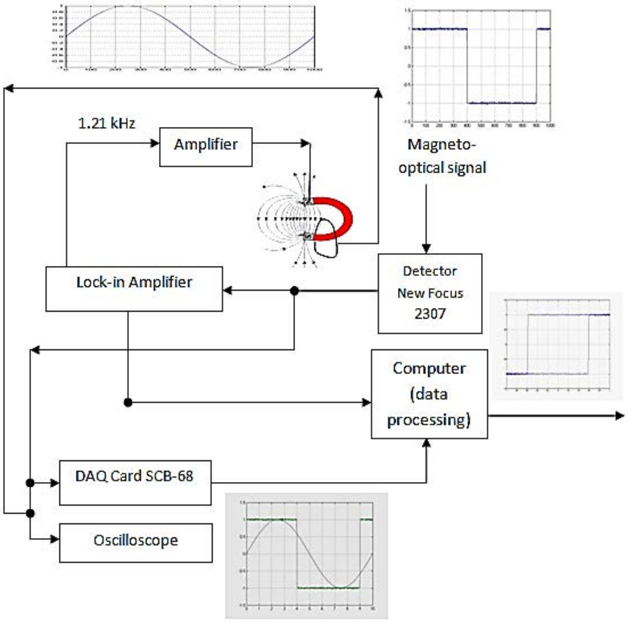

Fig. 2. Data detecting and processing diagram

To observe two signals in real time mode we were using two-channel oscilloscope.

For detection of the magneto-optical signal was usedLarge Area Balanced Photoreceiver (400-1070 nm, 1 MHz). New Focus 2307 with maximum transimpedance gain for several gain positions equal to **$2*10^3$, 10^5, $2*10^6$ V/A**. We worked with low gain.

DAQ Card SCB-68 National Instruments was used in our setup for convert physical values into digital form for further processing. Data acquisition is the process of sampling signals that measure real world physical conditions and converting the resulting samples into digital numeric values that can be manipulated by a computer. Data acquisition systems (abbreviated with the acronym DAS or DAQ) typically convert analog waveforms into digital values for processing. The components of data acquisition systems include: sensors that convert physical parameters to electrical signals; signal conditioning circuitry to convert sensor signals into a form that can be converted to digital values; analog-to-digital converters, which convert conditioned sensor signals to digital values. Data acquisition applications are controlled by software programs developed using various general purpose programming languages [2].

Due to the fact that magneto optical signal is relatively low we got to use a lock-in amplifier. We used a lock-in amplifier from Stanford Research Systems. They are also known as phase-sensitive detectors. This is a type of amplifier that can extract a signal with a known carrier wave from an extremely noisy environment. Depending on the dynamic reserve of the instrument, signals up to 1 million times smaller than noise components, potentially fairly close by in frequency, can still be reliably detected. Recovering signals at low signal-to-noise ratios requires a strong, clean reference signal the same frequency as the received signal. This is not the case in many experiments, so the instrument can recover signals buried in the noise only in a limited set of circumstances. Lock-in measurements require a frequency reference. Typically, an experiment is excited at a fixed frequency (from an oscillator or function generator), and the lock-in detects the response from the experiment at the reference frequency. Lock-in amplifiers generate their own internal reference signal usually by a phase-locked-loop locked to the external reference. We used this possibility for generate internal reference signal by 1.21 kHz to create electromagnetic field.

A skin-layer deep for material is calculated using following expression:

$$h = \frac{\lambda}{4\pi k},$$

where λ – is wavelength, k – is absorption rate of the material.

Table 1

Co optical parameters

CCo	λ=0.5 μm			λ=5.0 μm		
	n (reflection index)	k (absorption rate)	R (reflectivity), %	n (reflection index)	k (absorption rate)	R (reflectivity), %
	1.56	3.43	65.9	4.3	14.6	92.9

Consequently, for probing Co with λ=0.632 μm

$$h = \frac{\lambda}{4\pi k} = \frac{632 * 10^{-9}}{4 * \pi * 3.5} = 14.37\ (nm)$$

For Au we obtained:

$$h = \frac{\lambda}{4\pi k} = \frac{632 * 10^{-9}}{4 * \pi * 3.27} = 15\ (nm)$$

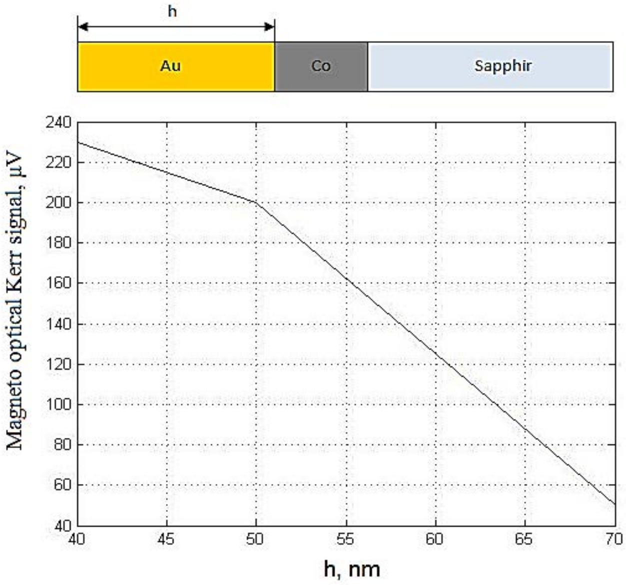

Fig. 3. Depends of the magneto optical signal as a function of depth h

1.3. Measurement errors

Source of measurement errors, which affect the value of the magneto-optical effects, but do not affect on the spectral curves (systematic errors) consist of errors associated with the accuracy class of devices, with the inaccuracy of their setting, with noise and pickups in the measuring system, the influence of scattered light on radiation detectors and other systematic errors may also include errors associated with inaccuracy of the position of the angle of incidence of light on the sample, etc. Some of this interference can be taken into account and eliminated some minimized. In particular, the least-controlled noise and crosstalk are minimized by appropriate positioning devices, lead wires, their shielding and grounding. Therefore it is necessary to carefully darken the optical part of the setup. It is difficult to estimate theoretically the contribution of individual random errors in the accuracy of magneto-optical effects; they can vary from measurement to measurement. In each case, they can be determined experimentally by studying the distribution of the measured value. Numerous inspection and evaluation show that they do not exceed 10%.Influence of random errors is minimized by multiple repetitions of measurements, as well as a thorough stabilization of power supply of photodetector and radiation sources. In this case, random errors are minimal in the areas of highest sensitivity setting and constitute 2-3%.

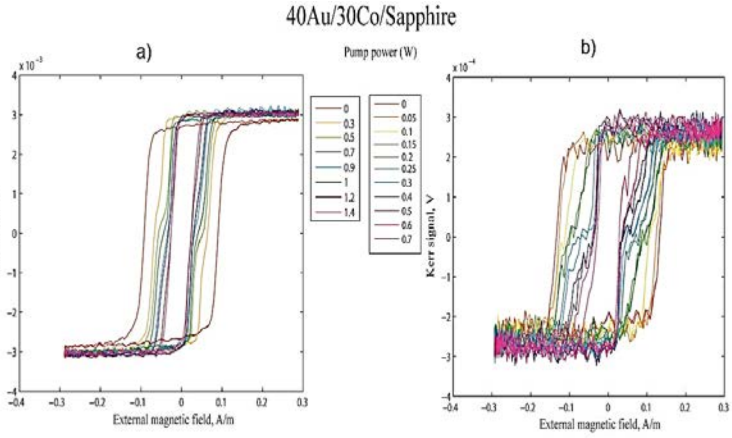

Fig. 4. Hysteresis loops for 40Au/30Co/Sapphire sample from a) cobalt side and b) gold side

Results and discussion. Figures 2-6 presents a series of hysteresis loops recorded for samples with various goldthicknesses and with different pump laser powers. All measurements except one are made from substrate side. All presented curves are reversible. We observed sample destruction after about 1.5…1.6W powers.

For *40Au/30Co/Sapphire* sample (fig. 4) we were able to record hysteresis loops from both sides (substrate and gold). As was found earlier, skin layer for cobalt for wavelength of 632 nm is about 14 nm and for gold it is 15 nm. That is why, in principle we should not see any magnetic signal from gold side but we observe almost the same tendency for hysteresis loop but with amplitude of magnetic signal which is 10 times smaller. Such observation proves that all measurements made from substrate side are clean and could be trusted.

Through all the data we clearly observe a monotonically decreasing coercive field with increasing of pump power. Similar trend of magnetic coercivity of cobalt was observed in [3].

For some samples *(20Au/30Co/Sapphire, 50Au/30Co/Sapphire, 70Au/30 Co/sapphire)* we did not observe so large change of the coercivity and of magneto-optical signal (fig. 9) even after increasing of magnetic field in 3 times. We suppose that samples with initiallow coercive field (magnetically hard) are less sensitive to temperature fluctuations. And from another side all remaining samples could be defined as magnetically soft and are good for investigation of heating.

It was considered that behavior of magnetic coercivity of ferromagnetic material under temperature influence could be observed without using complicated ultrafast pump-probe techniques. Unfortunately we could not get temperature of ferromagnetic material under investigation during heating them from our experiments because of relatively high Curie temperature of Cobalt (≈1400K) and relatively weak magnetic fields (200 mT). Observed unusual growth of signal amplitude could be due to some alloy of gold and cobalt.

From fig. 9 it can be seen that amplitude of magneto-optical signal grows linearly with increasing of pump power.

Coercivity field is linearly decreasing at higher pump powers as it shown on fig. 10.

To calibrate our results we use the reflectivity measurements. For gold, it was found that *n*is increasing with temperature and*k*is slightly decreasing for wavelengths *500 nm, 670 nm, 830 nm* [4]. It means that the signal reflected from heated surface should be of higher amplitude than that from non-heated.

By solving the Fresnel equations in the Matlabfor *s* and *p* polarized light we can get the reflectivity ratio as a function of angle of incidence (fig. 11).

After adding temperature term in these equations and solving them we can get the dependence of reflectivity from temperature as it shown below:

$$\frac{\left|R_p(n_0 + ik_0 + \frac{dn}{dT}\Delta T + \frac{dk}{dT}\Delta T)\right|^2 - \left|R_p(n_0)\right|^2}{\left|R_p(n_0)\right|^2} = \frac{\Delta R}{R}$$

Where $R_p(n_0)$ is reflectivity for p-polarized light for a particular wavelength.

We are interested only in this component of light because of our set-up configuration.

For gold at wavelength 632 nm the behavior of reflectivity versus temperature is shown on fig. 12. As it was supposed, reflectivity is higher for heated gold.

The result of fitting is presented on fig. 13, where red stars are experimental data and blue line is fit. Initially, we suppose that the starting point of fitted curve is equal to ambient temperature T=300K. And the only fit parameter that we use is the upper bound temperature.

This fit gives the heating equal to 125K. Destruction of the sample on this relatively low temperatures could be explained by inaccuracies in pump and probe lasers focusing. Parameters that were used for fitting:

$$n_0 = 0.19715$$
$$k_0 = 3.0899i$$
$$\frac{dn}{dT} = 2.7 * 10^{-4}$$
$$\frac{dk}{dT} = 1.1 * 10^{-4}$$

n_0, k_0 – refractive index (real part of complex index of refraction), extinction coefficient (imaginary part of complex index of refraction) $\frac{dn}{dT}$, $\frac{dk}{dT}$ derivatives with temperature for wavelength $\lambda = 632\ nm$ [4]. And temperature gradient ΔT.

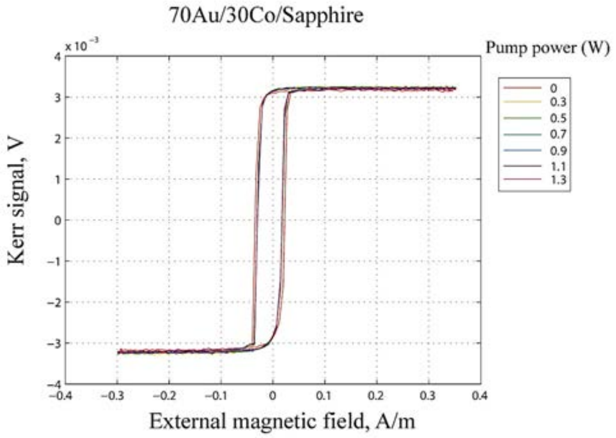

Fig. 5. Hysteresis loops for 70Au/30Co/Sapphire sample from Sapphire side

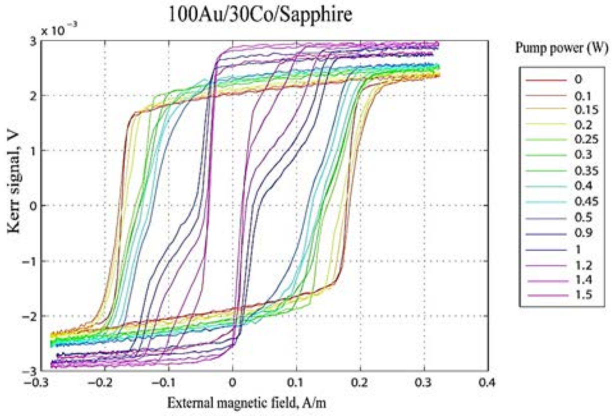

Fig. 6. Hysteresis loops for 100Au/30Co/Sapphire sample from Sapphire side

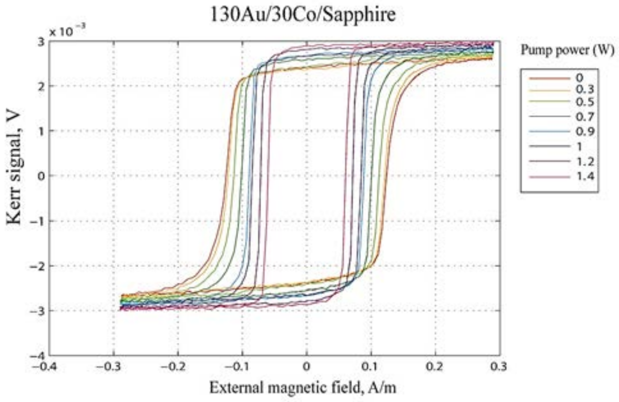

Fig. 7. Hysteresis loops for 130Au/30Co/Sapphire sample from Sapphire side

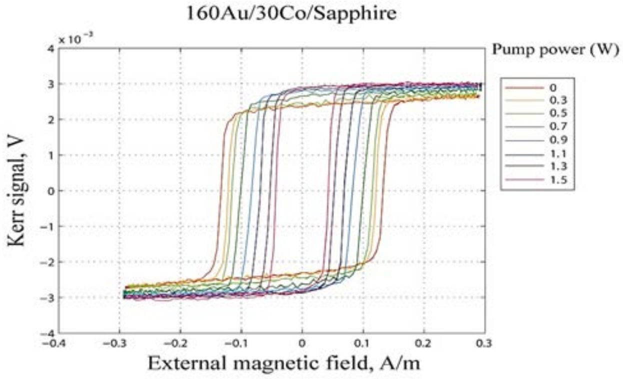

Fig. 8. Hysteresis loops for 160Au/30Co/Sapphire sample from Sapphire side

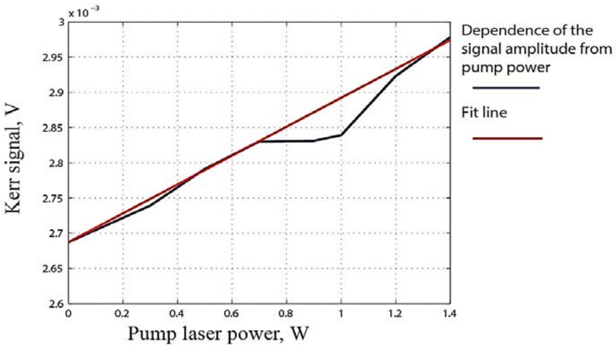

Fig. 9.Dependence of the signal amplitude from pump power

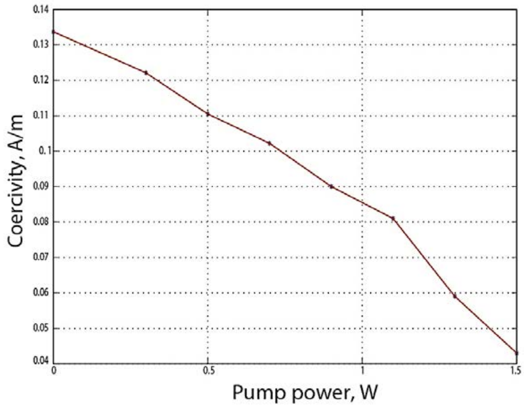

Fig. 10. Coercivity change as a function of pump laser power

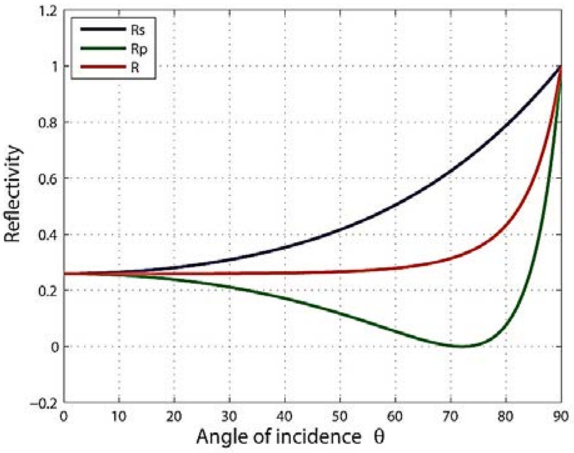

Fig. 11. Dependence of reflectivity of gold from angle of incidence

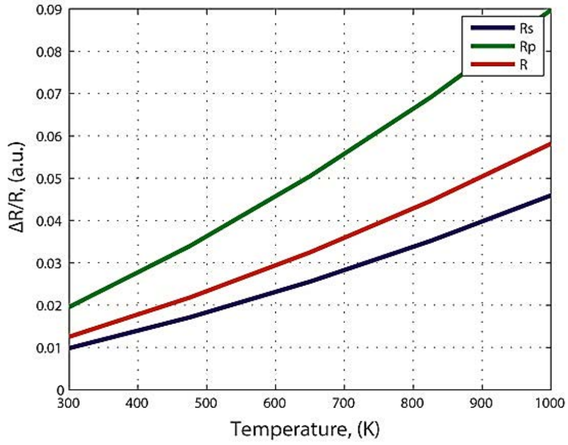

Fig. 12. Dependence of reflectivity of gold from temperature

Conclusion. Asa result of this work experimental set-up for TR MOKE measurements was build. Also automatic hysteresis loops recording program in LabView was designed. Several samples sets were investigated. One set of the samples has little coercive force and it is not possible for us to change it with weak external magnetic field. In another set of samples coercivity is larger so after heating such sample with laserit is possible to observe the change of hysteresis loop under heating.

Very interesting observation was made, such as for thin layer of nonmagnetic material (40 nm of gold) with light penetration of 15 nm we could still observe magneto-optical signal of next deposited magnetic layer.

Application of this technique allows control quality and homogeneity of the ferromagnetic samples with nanometer depth resolution without applying complicated femtosecond technique. We did not observe decreasing of magnetic signal with heating by continuous laser of high (up to 1.5 W) power but we saw the change of coercivity.

Also a technique for measurements of temperature via reflectivity changes was proposed. It was estimated that heat up by continuous laser is equal to 125K. To evaluate adequacy of such technique we propose to make the same experiment but instead of continuous laser to use special heating device with controlled temperature.

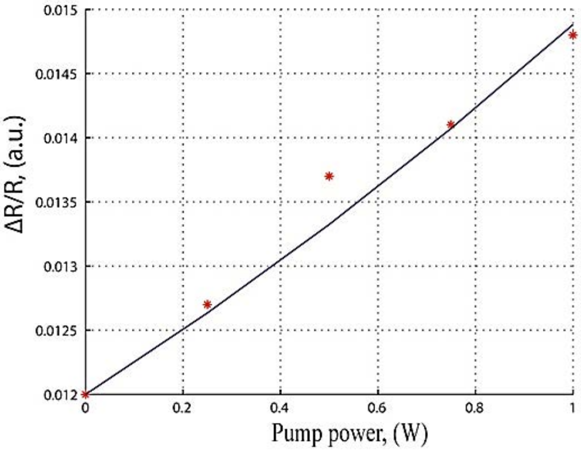

Fig. 13. Normalized reflectivity as a function pump laser power

It is possible to create magneto-optical thermometer if Curie temperature will be adjusted to the desired value (lower than existing). It is possible to do by varying the cobalt thickness. The optimal cobalt thickness lies between one and two atomic layers.

References:

1. Temvov V., Armelles G., Woggon U., Guzatov D., Cebollada A., Garcia-Martin A., Garcia-Martin J.M., Thomay T., Leitenstorfer A. and Bratschitsch R. «Active magneto-plasmonics in hybrid metal-ferromagnet structures», 2010, Nature Photonics, Vol. 4, 107-111 p.
2. SCB-68 User Manualfor Advanced Functions, 2007, National Instruments, 64 p.
3. Roth T., Steil D., Hoffmann D., Bauer M., Cinchetti M. and Aeschlimann M. «Dynamics of the coercivity in ultrafast pump-probe experiments», 2008, J. Phys. D: Appl. Phys. 41, 164001, 5 pp.
4. Moreira C.S., Lima A.M.N., Neff H., C. Thirstup, «Temperature-dependent sensivity of surface Plasmon resonance sensors at the gold-water interface», Sensors and Actuators B 134, 2008, 854-862 pp.

Максимихін М.Є.
Університет міста Ман, Франція,
Національний технічний університет України
«Київський політехнічний інститут»
Парпієв Т.А.
Університета міста Ман, Франція

НЕРУЙНІВНА МАНІТО-ОПТИЧНА ЛАЗЕРНА ТЕРМОМЕТРІЯ

Анотація
Виконане дослідження зразків наноматеріалів за допомогою магнітооптичних методів.Один комплект зразків має невелику коерцитивну силу й не можливо змінити його за допомогою слабкого зовнішнього магнітного поля.В іншому наборі зразків коерцитивна сила більше, тому після прогріву такого зразка за допомогою лазера можна спостерігати зміну петлі гістерезису при нагріванні. Дуже цікаве спостереження було зроблено, для тонкого шару немагнітного матеріалу (40 нм золота) із проникнення світла 15 нм можна було спостерігати магнітооптичний сигнал наступній вкладці магнітного шару. Застосування даної методики дозволяє контролювати якість і однорідність феромагнітних зразків з нанометровим дозволом по глибині без застосування складної фемтосекундної техніки. Ми не спостерігали зменшення магнітного сигналу з нагріванням за допомогою безперервного лазера високої (до 1,5 Вт) потужності, але спостерігалась зміна коерцитивної сили.
Ключові слова: лазер, термометрія, магніт, петля гістерезису, сигнал.

Максимихин Н.Е.
Университет города Ман, Франция,
Нацианальный технического университета Украины
«Киевский политехнический институт»
Парпиев Т.А.
Университета города Ман, Франция

НЕРАЗРУШАЮЩАЯ МАГНИТО-ОПТИЧЕСКАЯ ЛАЗЕРНАЯ ТЕРМОМЕТРИЯ

Аннотация
Выполнено исследование образцов наноматериалов с помощью магнитооптических методов.Один комплект образцов имеет небольшую коэрцитивную силу и не возможно изменить его с помощью слабого внешнего магнитного поля.В другой наборе образцов коэрцитивная сила больше, поэтому после прогрева такого образца с помощью лазера можно наблюдать изменение петли гистерезиса при нагревании. Очень интересное наблюдение было сделано, для тонкого слоя немагнитного материала (40 нм золота) с проникновения света 15 нм можно было наблюдать магнитооптический сигнал следующей вкладки магнитного слоя. Применение данной методики позволяет контролировать качество и однородность ферромагнитных образцов с нанометровым разрешением по глубине без применения сложной фемтосекундной техники. Мы не наблюдали уменьшения магнитного сигнала с нагреванием с помощью непрерывного лазера высокой (до 1,5 Вт) мощности, но наблюдлось изменение коэрцитивной силы.
Ключевые слова: лазер, термометрия, магнит, петля гистерезиса, сигнал.

УДК 539.1.01

СТАТИЧНЫЙ АТОМ

Попенко В.И.
Научно-производственная корпорация
«Киевский институт автоматики»

Анализ взаимодействия электрона и протона показывает, что на определённых расстояниях взаимное притяжение между ними сменяется отталкиванием, что позволяет предположить, что в атоме водорода и других атомах электроны и ядро связаны статично. В статье рассмотрены возможные варианты устройства статичных атомов.
Ключевые слова: атом, электрон, протон, ядро, Кулоновское взаимодействие, слабые взаимодействия.

Согласно исследованиям Резерфорда атомы состоят из центрального положительно заряженного ядра, окруженного отрицательно, заряженными электронами. Простейшая атомная система – атом водорода состоит из протона и одного электрона, разделённых расстоянием предположительно равным $0{,}53 \cdot 10^{-8}$ см, называемым первым Боровским радиусом.

Предполагается, что для сохранения устойчивости атома, электрон должен находиться в непрерывном движении по замкнутой орбите вокруг ядра, напоминающем движение планет вокруг Солнца. В противном случае сила притяжения заставит их сблизиться, и они столкнутся через доли микросекунды.

Действительно ли неизбежно это событие, в свете последующих со времени появления этой гипотезы познаний о природе частиц электрона и протона. Этот вопрос и представляет основной интерес