SURFACE PLASMON RESONANCE SENSOR WITH MAGNETO-OPTICAL THIN FILM

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ABSTRACT

Thanks to resonant excitation of surface plasmons, SPR sensors including ferromagnetic thin films allow the enhancement of the magneto-optical response. MO-SPR structures with Au/Co/Au sandwiches are theoretically analyzed in transverse configuration. The influence of sandwich film thicknesses and layer order is discussed. The optimized geometry and corresponding feedback are specified.

Keywords: *surface plasmon resonance, magneto-optics*

1. INTRODUCTION

The surface plasmons are collective oscillations of noble metal electron gas propagating at the boundary of a metal and a dielectric. The excitation condition of the surface plasmon resonance (SPR) is strongly sensitive to the change of refractive index (the order of 10^{-5}) of dielectric medium [1]. This physical principle has been applied in SPR sensors for physicists, chemists, material scientists and biologists. Several approaches have been described to improve the sensitivity of SPR (sensors with angular-, wavelength-, intensity-, phase-, and polarization modulation) [2]. The relatively new access is the combination of magneto-optical activity (MO) of the magnetic materials and SPR. The magneto-optic effects in surface plasmon polaritons propagating in thin metallic layers are analyzed in [3]. The increasing in the detection limit by a factor of 3 in refractive index changes for MO-SPR sensor compared with standard SPR sensors is presented in [1]. The authors in [4] show that the best optimization not only depends on the orientation of the magnetic field but also on the magneto-optical coefficients. The accurate control of MO-SPR film thickness is critical to achieve a remarkable increase in MO activity [5]. The large enhancement of Faraday effect by localized surface plasmon resonance in gold nanoparticles embedded in magnetic garnet film is described in [6]. In this paper we study the film thickness influence of Au/Co/Au sandwiches for MO-SPR sensors in the Kretschmann configuration to increase sensor sensitivity.

2. THEORY

As regards the quadratic contribution to the relative permittivity is generally small the modelling has been focused on linear magneto-optical properties. For transverse geometry at linear approximation the permittivity tensor is in that case defined by [7]

$$\hat{\varepsilon}_{r\tau} = \begin{bmatrix} \varepsilon_0 & 0 & 0 \\ 0 & \varepsilon_0 & -i\,\varepsilon_{1\tau} \\ 0 & i\,\varepsilon_{1\tau} & \varepsilon_0 \end{bmatrix}, \tag{1}$$

where

$$Q_\tau = \frac{\varepsilon_{1\tau}}{\varepsilon_0} \tag{2}$$

is known as Voigt´s parameter.

The chosen Cartesian system supposed that *xy* plane is parallel to planar system (*x*-axis is normal to the incidence plane); *z*-axis is normal to the structure.

The matrix formalism 4x4 is an extremely useful form of the steady-state solution to Maxwell’s equations subject to the boundary conditions imposed by isotropic and anisotropic multilayer stacks [8].

Electromagnetic field on each boundary (in our experimental set-up: prism$^{(P)}$ x Au$^{(0)}$ -film, Au$^{(0)}$ -film x Co$^{(1)}$ -film,…, Au$^{(N-1)}$ -film x halfspace$^{(N)}$) is obtained using the following partial products

$$M^{(P,0)} = (D^{(P)})^{-1}D^{(0)}\,(C^{(0)}),\; M^{(0,1)} = (C^{(0)})^{-1}\,(D^{(0)})^{-1}D^{(1)}\,(C^{(1)}),$$

$$M^{(N-1,N)} = (C^{(N-1)})^{-1}\,(D^{(N-1)})^{-1}D^{(N)}. \tag{3}$$

$D^{(i)}$ denote the dynamic matrices. The total 4 x 4 (overall transfer) matrix M describing the global reflection and transmission properties of system can be expressed as

$$M = (D^{(P)})^{-1}D^{(0)}P^{(0)}(D^{(0)})^{-1}D^{(1)}P^{(1)}(D^{(1)})^{-1\cdots}D^{(N-1)}P^{(N-1)}.$$

$$(D^{(N-1)})^{-1}\,D^{(N)} =$$

$$= (D^{(P)})^{-1}S^{(0)}S^{(1)}\ldots S^{(N-1)}\,D^{(N)}, \tag{4}$$

where

$$S^{(0)} = D^{(0)}P^{(0)}(D^{(0)})^{-1},\; S^{(1)} = D^{(1)}P^{(1)}(D^{(1)})^{-1},\;\ldots \tag{5}$$

$$S^{(N-1)} = D^{(N-1)}P^{(N-1)}(\,D^{(N-1)})^{-1}.$$

$S^{(0)}$, $S^{(1)}$, …, $S^{(N-1)}$ are in our experimental arrangement the characteristic matrices of Au or Co films and $P^{(k)}$ is matrix determinating the propagation of plane waves between boundaries for the k-th medium. For the transverse geometry the relatively easy elements of characteristics matrices provide a valuable insight into the magnetic and optical behavior of system. The characteristic matrices are block-diagonalized for transverse geometry in the case of the effects linear in magnetization. In this special arrangement the mode conversion is not observed and waves are going through planar structure without polarization conversion.

The relations between the amplitudes of the incident, transmitted and reflected waves and the interaction of the plane electromagnetic wave with the structure are determined in terms of the M_{ij} (i, j = 1,…,4) elements of overall matrix M.

At transverse magnetization ("T" - the magnetization lies in the plane of sample and is normal to plane of incidence):

$$r_{ssT} = M_{21T}/M_{11T}, \quad r_{ppt} = M_{43T}/M_{33T}$$

$$t_{ssT} = 1/M_{11T}, \; t_{ppT} = 1/M_{33T} \tag{6}$$

$$r_{spT} = r_{psT} = t_{spT} = t_{psT} = 0$$

To find out how much energy is reflected from the boundary, we need to consider a reflectance:

$$R_{pp} = |r_{pp}|^2. \tag{7}$$

For the situation without magnetization we suppose isotropic media and the reflection and transmission can be expressed by familiar relations.

3. NUMERICAL SIMULATION

The MO effect produces at tranverse configuration (linear approximation only) a relative change of the reflectance R_{pp} of the p-polarized light:

$$\Delta R_{pp}/R_{pp} = [\, R_{pp}(M) - R_{pp}(0)] \,/\, R_{pp}(0) \tag{8}$$

$R_{pp}(M)$ and $R_{pp}(0)$ denote reflectances with and without magnetization, respectively. We analyze the magneto-optical effects in the structures created by Au and Co thin films with the aim to maximize the value of $\Delta R_{pp}/R_{pp}$. In our modelling we assume a Kretschmann experimental arrangement [9] with BK-7 prism (ε_p = 2.310) and a water as dielectric medium (ε_w = 1.775). The value of dielectric constant for Co has been chosen as ε_{xxCo} = -12.5040 + i18.4639 [10], the Voigt´s parameter of this ferromagnetic material is Q = 0.03273 + i0.01092. Applied size of Au dielectric constant is ε_{Au} = -11.2376 + i1.2834 [11]. All listed optical parameters are related to 632.8 nm wavelength. During mathematical simulation the thicknesses of Co layers have been fixed to 2.7 nm.

The attention has been concentrated on SPR configuration with Au/Co/Au sandwiches. In the first case the thickness of gold layer fixed directly to prism base has constant value of 29.4 nm (to have a comparison with [1]). Fig. 1 demonstrates the omission of the gold underlying thin film originally contacted with inspected medium. We observe the explicit enhancement of $\Delta R_{pp}/R_{pp}$ parameter for setup without this noble metal layer. The question is the application of this structure, where ferromagnetic Co film is not protected. The optimization MO-SPR sandwich is specified in Fig. 2. The relative small change of the protected gold film thickness creates ultra amplitude shift of maximum.

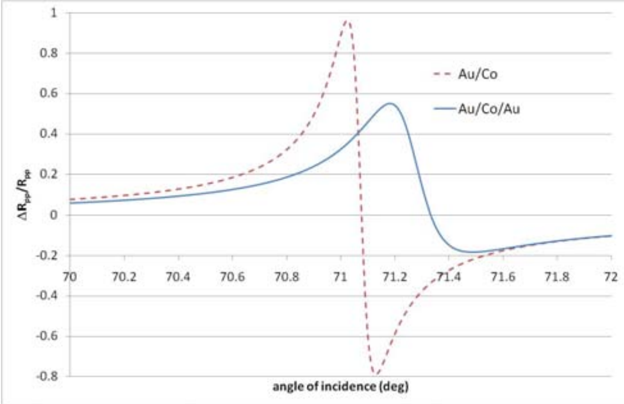

Fig. 1 SPR Au/Co/Au sandwich – the influence of the gold underlying thin film (Au/Co: Au-29.4 nm/Co-2.7 nm, Au/Co/Au: Au-29.4 nm/Co-2.7 nm/Au-2 nm)

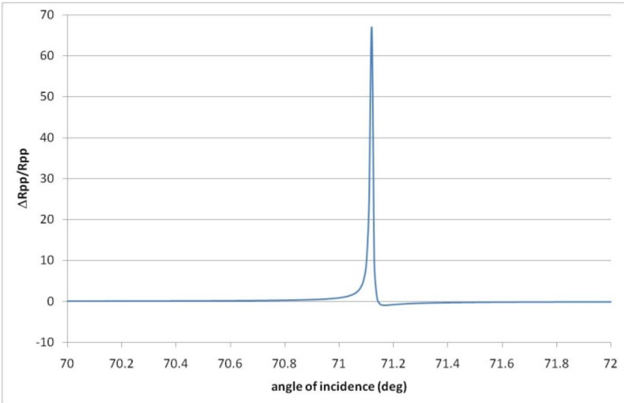

Fig. 2 SPR Au/Co/Au sandwich – optimized geometry (Au-29.4 nm/Co-2.7 nm/Au-0.5 nm)

The question is the influence of thin films sequence on prism base. The following figure demonstrates this effect ($BK7/Au/Co/H_2O$ versus $BK7/Co/Au/H_2O$) with inalterable other parameters. The situation with Co thin film on prism base causes the important reduction of MO-SPR sensor sensitivity (see Fig. 3 and Fig. 1).

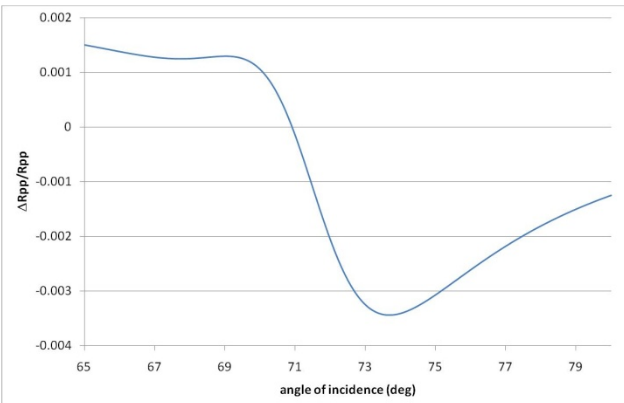

Fig. 3 The response of structure with Co film deposited directly on prism base ($BK7/Co$-2.7 nm/Au-29.4 nm/H_2O)

We have presented theoretical analysis of MO-SPR sensor wit Au/Co/Au sandwiches. The results demonstrate the eminent role of thin film thicknesses and layer order. The geometrical optimization of sandwich components enables hundredfold response enhancement.

4. CONCLUSIONS

For the transverse orientation (in linear approximation), optimization is achieved with high-quality surface plasmons (no rotation of polarization occurs). The application of Au/Co/Au sandwiches for MO-SPR sensors enables importantly change a sensing unit response. The optimized state of sandwich layer thicknesses (Au-29.4 nm/Co-2.7 nm/Au-0.5 nm) brings the explicit enhancement of $\Delta R_{pp}/R_{pp}$ parameter. The gold thin film thickness alteration of the layer originally contacted with inspected medium from 2 nm to 0.5 nm amplifies discussed parameter in the frame of two orders.

ACKNOWLEDGMENTS

This work has been partially supported by the Ministry of Education, Youth and Sport of the Czech Republic (#MSM 6198910016).

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Received March 19, 2010, accepted July 9, 2010

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