COMPARISON BETWEEN THE EFFICIENCIES OF SURFACE PLASMON POLARITON EXCITATION BY THE METHODS OF RELIEF – PHASE DIFFRACTION GRATING AND ATTENUATED TOTAL REFLECTION PRISM

N.L. DMITRUK, A.V. KOROVIN, S.V. MAMYKIN, M.V. SOSNOVA, E.F. VENGER

V.E. Lashkarev Institute of Semiconductor Physics, Nat. Acad. of Sci. of Ukraine
(41, Nauky Ave., Kyiv 03028, Ukraine; e-mail: dmitruk@isp.kiev.ua)

UDC 535.016

The paper is devoted to the consecutive comparison of advantages and disadvantages of widely used methods of surface plasmon polariton excitation, namely attenuated total reflection and diffraction grating. The surface plasmon polariton efficiency and the influence of separated elements of the system on its sensitivity have been analyzed. The analytical expressions for the sensory system sensitivity with additional selective-sensitivity layer insertion are obtained for both types of sensor systems. It is established that the sensitivity of both types of sensor systems in a wide range of variation of the testing medium refractive index are different at different ranges of the refractive index. For a diffraction grating, the sensitivity maximum is achieved for low refractive indices, while, in the case of attenuated total reflection, the sensitivity is higher at a higher refractive index.

1. Introduction

Sensory systems based on the phenomenon of resonant excitation of surface plasmon polaritons (SPPs) [1, 2] have been intensively developed for almost two decades. As is known, surface polaritons are electromagnetic waves of the TM type which are localized at the interface between media, one of which must be necessarily surface-active, i.e. it must have a negative dielectric permittivity within a certain frequency range [3]. In the visible electromagnetic wave interval, this condition is satisfied by noble metals at frequencies lower than the plasma one (Au, Ag, Cu, Al, Pt). However, since the SPP velocity is much lower than that of light, it is impossible to excite such waves directly under ordinary conditions in the plane interface geometry. A necessary requirement is the equality between the SPP and light phase velocities, i.e. the condition of phase synchronism has to be satisfied.

The most widespread ways to provide the phase synchronism are given by two methods: the attenuated total reflection (ATR) method, which makes use of a prism, and the diffraction grating (DG) one. The ATR method is realized by depositing a thin continuous metal film onto the edge of a total internal reflection prism or onto a glass plate, which are put in optical contact with the prism by means of an immersion liquid. If the metal film is located between identical dielectric layers, this is the Sarid geometry [4]. In such a geometry, the long-range SSPs are generated, and the distance of their planar propagation is an order of magnitude longer (low dissipative losses) than that in the usual ATR geometry (Kretschmann, Otto). Another method is based on the creation of a relief-phase DG on the surface of a metal. In both cases, the projection of the light wave vector onto the interface is artificially increased up to its equality with the SPP wave vector. However, since the SPP wave is partially localized in the environment, its propagation parameters depend on the dielectric characteristics of this medium. This dependence is very strong just for surface waves, due to an enhancement of the local field in the vicinity of the metal. Therefore, the phenomenon of resonant SPP excitation is a powerful sensoric tool which is widely used in opto-chemical sensors and polaritonic photodetectors. The SPP excitation is accompanied by the resonance absorption of the field energy, which manifests itself as a minimum (maximum) in the spectral or angular dependence of the *p*-polarized electromagnetic wave reflectance (transmittance). Several approaches to register the SPP excitation are used in sensory systems: (i) measurements of the reflected optical wave intensity in the vicinity of the plasmon resonance, (ii) the determination of the resonance position variation in the angular or spectral dependences for the reflectance, transmittance, or a photocurrent through a special surface-barrier heterostructure, (iii) measurements of the phase variation of a reflected wave, and (iv) measurements of the SPP damping in planar geometry [1, 5–9].

The sensitivity of a sensory system is defined as a minimal value of the refractive index variation that is confidently registered by a device; it amounts to $\Delta n = 10^{-4} \div 10^{-7}$ [1]. It its turn, this quantity is determined by SPP parameters and a device design, whereas the selectivity by the presence of additional coverages that are selective to definite kinds of molecules. For the maximal sensitivity in the ATR method to be achieved, the so-called Kretschmann geometry with auxiliary or wave-guide layers (the Sarid geometry) is used, when long-range SPPs are excited. In such a geometry, the sensitivity to the refractive index variation $\Delta n = 2.5 \times 10^{-8}$ was obtained [10]. Alternatively, the wave phase variation is measured with the help of an interferometer [11] or an ellipsometer (in the mode of the so-called polaritonic ellipsometry) [12, 13].

To our knowledge, the theoretical calculations of the sensitivity of ATR- and DG-based sensory systems have been carried out taking no additional selectively sensitive layers into account [14]. In this work, the theoretical analysis of and a comparison between the sensitivities of sensory systems with and without immersion layers, have been done.

2. Sensitivity of Systems Without Immersion Layer

The sensitivity in the case of systems without an intermediate immersion layer can be found analytically, by applying the law of momentum conservation to the process of SPP excitation at the interface between two media. A typical thickness of a plasmon-carrying film which provides optimum conditions for SPP excitation amounts, e.g., to 45–50 nm for gold. For such thicknesses of a film, the finite plasmon-carrying layer can be replaced by a semiinfinite medium. In so doing, the influence of the connecting prism is made allowance for by considering the projection of the light wave vector in the prism onto the plane interface between two media; whereas the influence of the grating by introducing an additional inverse vector associated with the periodic surface structure.

In the general case, the sensitivity of a sensory system is determined as the partial derivative of a sensor resonance characteristic (the angle of incidence or the wavelength) with respect to a parameter that is responsible for variations in the test medium (the refractive index).

2.1. ATR Excitation of SPPs

The condition of SPP excitation in the ATR scheme, which follows from the momentum conservation law, can be presented in the form

$$\kappa_i = k_{\mathrm{spp}}(\lambda, n_{\mathrm{test}}), \qquad (1)$$

where $\kappa_i = (2\pi/\lambda) n_{\mathrm{prism}} \sin\phi_i$ is the projection of the incident wave vector onto the plane of incidence (in particular, this parameter is determined by a material that the prism is made of); ϕ_i is the angle of light incidence; $k_{\mathrm{spp}}(\lambda, n_{\mathrm{test}})$ is the SPP wave vector; and n_{test} and n_{prism} are the refractive indices of the test medium and the prism, respectively. Note that the refractive index of the prism must be higher than that of the test medium ($n_{\mathrm{test}} < n_{\mathrm{prism}}$). We assume that both the test medium and the connecting prism material are not absorptive.

The SPP wave vector for two media in contact (the test and the plasmon-carrying ones) is

$$k_{\mathrm{spp}}(\lambda, n_{\mathrm{test}}) = \frac{2\pi}{\lambda} n_{\mathrm{spp}}(\lambda, n_{\mathrm{test}}), \qquad (2)$$

where the notation

$$n_{\mathrm{spp}}(\lambda, n_{\mathrm{test}}) \equiv n_{\mathrm{test}} \mathrm{Re}\sqrt{\varepsilon(\lambda)/(n_{\mathrm{test}}^2 + \varepsilon(\lambda))}$$

was introduced (it can be interpreted as an effective coefficient of SPP refraction), and $\varepsilon(\lambda)$ is the complex dielectric permittivity of the plasmon-carrying medium which depends on the wavelength. Therefore, condition (1) looks like

$$n_{\mathrm{prism}} \sin(\phi_i) = n_{\mathrm{spp}}(\lambda, n_{\mathrm{test}}). \qquad (3)$$

2.1.1. Angular sensitivity of the ATR method

To determine the angular sensitivity, let us find – from condition (3) – an explicit expression for the resonance angle ϕ_i:

$$\phi_i = \arcsin\left(\frac{n_{\mathrm{test}}}{n_{\mathrm{prism}}} \mathrm{Re}\sqrt{\frac{\varepsilon(\lambda)}{n_{\mathrm{test}}^2 + \varepsilon(\lambda)}}\right). \qquad (4)$$

In this case, the angular sensitivity is found by a direct differentiation of resonance angle (4) with respect to the refractive index of the test medium:

$$\frac{\partial \phi_i}{\partial n_{\rm test}} = \frac{{\rm Re}\left[\left(\frac{\varepsilon(\lambda)}{n_{\rm test}^2+\varepsilon(\lambda)}\right)^{3/2}\right]}{\sqrt{n_{\rm prism}^2-\left(n_{\rm test}{\rm Re}\sqrt{\frac{\varepsilon(\lambda)}{n_{\rm test}^2+\varepsilon(\lambda)}}\right)^2}}, \quad (5)$$

Here, we used the identity $\partial{\rm Re}(f(z))/\partial z = {\rm Re}(\partial f(z)/\partial z)$.

2.1.2. Spectral sensitivity

To determine the spectral sensitivity, it is necessary to find the resonance wavelength λ. However, no explicit analytical expression can be obtained for the resonance wavelength from formula (3). Therefore, let us write down it as the implicit function

$$F(\lambda, n_{\rm test}) = n_{\rm prism}\sin(\phi_i) - n_{\rm test}{\rm Re}\sqrt{\frac{\varepsilon(\lambda)}{n_{\rm test}^2+\varepsilon(\lambda)}}. \quad (6)$$

Then, the spectral sensitivity – as a derivative of the resonance wavelength with respect to the refractive index of the test medium – looks like

$$\frac{\partial \lambda}{\partial n_{\rm test}} = -\frac{2{\rm Re}\left[\left(\frac{\varepsilon(\lambda)}{n_{\rm test}^2+\varepsilon(\lambda)}\right)^{3/2}\right]}{n_{\rm test}^3{\rm Re}\left[\frac{\partial\varepsilon(\lambda)/\partial\lambda}{\sqrt{\varepsilon(\lambda)}(n_{\rm test}^2+\varepsilon(\lambda))^{3/2}}\right]}. \quad (7)$$

2.2. DG excitation of SPPs

In the case of the diffraction grating method, the momentum conservation law for SPP excitation brings about the equation

$$\left|\kappa_i + \frac{2\pi}{\Lambda}m\right| = k_{\rm spp}(\lambda, n_{\rm test}), \quad (8)$$

where Λ is the grating period, and m is the diffraction order used to observe the SPP excitation. In contrast to the ATR method, the projection of the wave vector has to be presented in the form $\kappa_i = (2\pi/\lambda)n_{\rm test}\sin\phi_i$, since light falls onto the interface from the test medium side. Ultimately, condition (8) can be rewritten in the form

$$\left|n_{\rm test}\sin(\phi_i) + \frac{\lambda}{\Lambda}m\right| = n_{\rm spp}(\lambda, n_{\rm test}). \quad (9)$$

2.2.1. Angular sensitivity

Similarly to the case of the ATR scheme, the resonance angle for SPPs is determined from formula (9) in the explicit form:

$$\phi_i = \arcsin\left(\sigma{\rm Re}\sqrt{\frac{\varepsilon(\lambda)}{n_{\rm test}^2+\varepsilon(\lambda)}} - \frac{\lambda}{\Lambda}\frac{m}{n_{\rm test}}\right). \quad (10)$$

Here, the relation $\sigma = \pm 1$ takes the absolute value in formula (9) into account and is defined as the sign of m. Hence, the angular sensitivity looks like

$$\frac{\partial \phi_i}{\partial n_{\rm test}} = \frac{\frac{\lambda}{\Lambda}\frac{m}{n_{\rm test}^2} - \sigma{\rm Re}\left[\frac{n_{\rm test}\sqrt{\varepsilon(\lambda)}}{(n_{\rm test}^2+\varepsilon(\lambda))^{3/2}}\right]}{\sqrt{1-\left(\sigma{\rm Re}\sqrt{\frac{\varepsilon(\lambda)}{n_{\rm test}^2+\varepsilon(\lambda)}} - \frac{\lambda}{\Lambda}\frac{m}{n_{\rm test}}\right)^2}}. \quad (11)$$

2.2.2. Spectral sensitivity

Similarly to the case of the ATR scheme, the resonance wavelength is obtained from condition (9) as the implicit function

$$F(\lambda, n_{\rm test}) = \sin(\phi_i) + \frac{\lambda}{\Lambda}\frac{m}{n_{\rm test}} - \sigma{\rm Re}\sqrt{\frac{\varepsilon(\lambda)}{n_{\rm test}^2+\varepsilon(\lambda)}}. \quad (12)$$

Then, the spectral sensitivity is

$$\frac{\partial \lambda}{\partial n_{\rm test}} = \frac{\frac{\lambda}{\Lambda}\frac{m}{n_{\rm test}^2} - \sigma{\rm Re}\left[\frac{n_{\rm test}\sqrt{\varepsilon(\lambda)}}{(n_{\rm test}^2+\varepsilon(\lambda))^{3/2}}\right]}{\frac{1}{\Lambda}\frac{m}{n_{\rm test}} - \sigma{\rm Re}\left[\frac{n_{\rm test}^2\partial\varepsilon(\lambda)/\partial\lambda}{2\sqrt{\varepsilon(\lambda)}(n_{\rm test}^2+\varepsilon(\lambda))^{3/2}}\right]}. \quad (13)$$

3. Sensitivity of Systems with an Immersion Layer

The procedure of finding the sensitivity in the case of systems with an immersion layer is more complicated, because it is necessary to consider the problem of SPP excitation in a three-layer system, which, in contrast to the two-layer problem, has no straightforward analytical solution. The influence of the connecting prism and the diffraction grating is considered in the same manner, as it was in the case of systems without an immersion layer.

Now, the resonance angles and the wavelength are determined by finding the roots of the denominator of Fresnel factors, which – for a three-layer structure – looks like

$$\left(\frac{k_1^\perp}{\varepsilon_1} + \frac{k_2^\perp}{\varepsilon_2}\right)\left(\frac{k_2^\perp}{\varepsilon_2} + \frac{k_3^\perp}{\varepsilon_3}\right) +$$

$$+\left(\frac{k_1^\perp}{\varepsilon_1}-\frac{k_2^\perp}{\varepsilon_2}\right)\left(\frac{k_2^\perp}{\varepsilon_2}-\frac{k_3^\perp}{\varepsilon_3}\right)e^{ik_2^\perp d}. \quad (14)$$

Here, ε_i is the dielectric permittivity of the i-th medium ($i = 1,2,3$); $k_i^\perp = \sqrt{\varepsilon_i - (n\sin\phi_i)^2}$; n is the refractive index of the medium which light comes from; and d is the thickness of the second (immersion) layer. We suppose the first and the second medium to be insulators, and the third one plasmon-carrying, so that only ε_3 depends on the wavelength. In this case, the sensitivity is governed by changes in the immersion medium, i.e. not only by the variation of its refractive index, but also by its thickness [15, 16].

3.1. ATR excitation of SPPs

Let the first medium be air ($\varepsilon_1 = 1$), the second one an insulator which is used to detect changes in the medium, i.e. $\varepsilon_2 = n_{\text{test}}^2$, and the third one a plasmon-carrying medium. Then, the wavelength dependence can be considered only for $\varepsilon_3 = \varepsilon(\lambda)$. In addition, in this case, n is the refractive index of the prism. Hence, expression (14) can be rewritten as follows:

$$F(\lambda,\kappa,n_{\text{test}},d) = \left(\sqrt{1-\kappa^2}+\frac{\sqrt{n_{\text{test}}^2-\kappa^2}}{n_{\text{test}}^2}\right)\times$$

$$\times\left(\frac{\sqrt{n_{\text{test}}^2-\kappa^2}}{n_{\text{test}}^2}+\frac{\sqrt{\varepsilon(\lambda)-\kappa^2}}{\varepsilon(\lambda)}\right)+$$

$$+\left(\sqrt{1-\kappa^2}-\frac{\sqrt{n_{\text{test}}^2-\kappa^2}}{n_{\text{test}}^2}\right)\times$$

$$\times\left(\frac{\sqrt{n_{\text{test}}^2-\kappa^2}}{n_{\text{test}}^2}-\frac{\sqrt{\varepsilon(\lambda)-\kappa^2}}{\varepsilon(\lambda)}\right)e^{i\sqrt{n_{\text{test}}^2-\kappa^2}(2\pi/\lambda)d}, \quad (15)$$

where κ is the dimensionless planar component of the wave vector of incident light.

To determine the SPP dispersion, one has to solve the equation

$$F(\lambda,\kappa,n_{\text{test}},d) = 0. \quad (16)$$

Numerical methods are used to find $\kappa = n_{\text{spp}}(\lambda, n_{\text{test}}, d)$. Hence, the effective coefficient of SPP refraction depends now not only on the refractive index, but also on the immersion layer thickness.

3.1.1. Angular sensitivity of the ATR method

Condition (3) for the angular sensitivity in the case of SPPs with dispersion law (16) reads

$$\phi_i = \arcsin\left(\frac{n_{\text{spp}}(\lambda,n_{\text{test}},d)}{n_{\text{prism}}}\right). \quad (17)$$

After the partial differentiation of resonance angle (17) with respect to the refractive index or the thickness of the immersion medium layer, we obtain the expression for the sensitivity of the resonance angle variation to the variation of either the refractive index of the immersion layer with a fixed thickness,

$$\frac{\partial\phi_i}{\partial n_{\text{test}}} = \frac{\partial n_{\text{SPP}}(\lambda,n_{\text{test}},d)/\partial n_{\text{test}}}{\sqrt{n_{\text{prism}}^2 - n_{\text{SPP}}(\lambda,n_{\text{test}})^2}}, \quad (18)$$

or the immersion layer thickness at a fixed value of the refractive index

$$\frac{\partial\phi_i}{\partial d} = \frac{\partial n_{\text{SPP}}(\lambda,n_{\text{test}},d)/\partial d}{\sqrt{n_{\text{prism}}^2 - n_{\text{SPP}}(\lambda,n_{\text{test}})^2}}. \quad (19)$$

Here, we introduced

$$\frac{\partial n_{\text{SPP}}(\lambda,n_{\text{test}},d)}{\partial n_{\text{test}}} = -\left.\frac{\partial F(\lambda,\kappa,n_{\text{test}},d)/\partial n_{\text{test}}}{\partial F(\lambda,\kappa,n_{\text{test}},d)/\partial\kappa}\right|_{\kappa=n_{\text{SPP}}(\lambda,n_{\text{test}},d)},$$

$$\frac{\partial n_{\text{SPP}}(\lambda,n_{\text{test}},d)}{\partial d} = -\left.\frac{\partial F(\lambda,\kappa,n_{\text{test}},d)/\partial d}{\partial F(\lambda,\kappa,n_{\text{test}},d)/\partial\kappa}\right|_{\kappa=n_{\text{SPP}}(\lambda,n_{\text{test}},d)}.$$

3.1.2. Spectral sensitivity

The partial derivatives of the resonance wavelength given implicitly by Eq. (16) with respect to the refractive index and the thickness of the immersion medium layer give the spectral sensitivities

$$\frac{\partial\lambda}{\partial n_{\text{test}}} = -\left.\frac{\frac{F(\lambda,\kappa,n_{\text{test}},d)}{\partial n_{\text{test}}}}{\frac{\partial F(\lambda,\kappa,n_{\text{test}},d)}{\partial\lambda}}\right|_{\kappa=n_{\text{spp}}(\lambda,n_{\text{test}},d)} \quad (20)$$

and

$$\frac{\partial\lambda}{\partial d} = -\left.\frac{\frac{\partial F(\lambda,\kappa_i,n_{\text{test}},d)}{\partial d}}{\frac{\partial F(\lambda,\kappa,n_{\text{test}},d)}{\partial\lambda}}\right|_{\kappa=n_{\text{spp}}(\lambda,n_{\text{test}},d)}. \quad (21)$$

3.2. DG excitation of SPPs

Similarly to the ATR case, we assume that the first medium is air, the second an immersion layer, and the third a plasmon-carrying medium (metal). In this configuration, the dimensionless planar component of the wave vector of incident light is determined from formula (9), and the determination of the angular or spectral sensitivity leads to an implicit function in the form

$$F_{\text{grating}}(\lambda, n_{\text{test}}, d) = \left|\sin(\phi_i) + \frac{\lambda}{\Lambda}m\right| - n_{\text{SPP}}(\lambda, n_{\text{test}}, d). \tag{22}$$

3.2.1. Angular sensitivity

According to expression (22), the resonance angle is

$$\phi_i = \arcsin\left(\sigma n_{\text{SPP}}(\lambda, n_{\text{test}}, d) - \frac{\lambda}{\Lambda}m\right). \tag{23}$$

After the partial differentiation of this expression with respect to the refractive index and the thickness of the immersion medium layer, we obtain the angular sensitivities

$$\frac{\partial\phi_i}{\partial n_{\text{test}}} = \frac{\sigma\partial n_{\text{SPP}}(\lambda, n_{\text{test}}, d)/\partial n_{\text{test}}}{\sqrt{1-\left(\sigma n_{\text{SPP}}(\lambda, n_{\text{test}}, d) - \frac{\lambda}{\Lambda}m\right)^2}}, \tag{24}$$

and

$$\frac{\partial\phi_i}{\partial d} = \frac{\sigma\partial n_{\text{SPP}}(\lambda, n_{\text{test}}, d)/\partial d}{\sqrt{1-\left(\sigma n_{\text{SPP}}(\lambda, n_{\text{test}}, d) - \frac{\lambda}{\Lambda}m\right)^2}}. \tag{25}$$

3.2.2. Spectral sensitivity

The partial derivatives of the resonance wavelength given implicitly by expression (22) with respect to the refractive index and the thickness of the immersion medium layer give the spectral sensitivities

$$\frac{\partial\lambda}{\partial n_{\text{test}}} = -\frac{\frac{F_{\text{grating}}(\lambda, n_{\text{test}}, d)}{\partial n_{\text{test}}}}{\frac{F_{\text{grating}}(\lambda, n_{\text{test}}, d)}{\partial\lambda}}, \tag{26}$$

and

$$\frac{\partial\lambda}{\partial d} = -\frac{\frac{F_{\text{grating}}(\lambda, n_{\text{test}}, d)}{\partial d}}{\frac{F_{\text{grating}}(\lambda, n_{\text{test}}, d)}{\partial\lambda}}. \tag{27}$$

Here, the partial derivatives of function (16) given implicitly can be calculated analytically; but since the final expressions are cumbersome, they are omitted.

4. Results of Calculations

For calculations, the plasmon-carrying coating was simulated by a gold film with optical constants taken from work [17]. The refractive index of the prism substance was considered to be independent of the incident wavelength, and the value $n_{\text{prism}} = 1.5$ was accepted. The variation of the refractive index of the test medium was confined within the range $n_{\text{test}} = 1.0 \div 1.5$, which corresponds to its most typical values. For instance, the refractive indices of gaseous media vary from 1.0 to 1.1, whereas biochemical reactions run in aqueous solutions characterized by a refractive index varying within the limits $1.3 \div 1.4$.

In Fig. 1, the angular (*a*) and spectral (*b*) sensitivities of ATR-based sensory systems without an additional selectively sensitive layer (two-layer systems) are depicted. In the former case, the angular scanning is carried out for various wavelengths in the range from 600 to 800 nm. In the latter case, the wavelength scanning is carried out for various incidence angles in the range from 45 to 65°. Similar dependences for sensory systems on the basis of DG are presented in Fig. 2. The spectral dependences are calculated in this case for angles $0 \div 20°$, which is associated with geometrical features and conditions of SPP excitation in the system.

The dependences given for the angular sensitivity (Figs. 1,*a* and 2,*a*) illustrate that the sensory systems of two types have comparable sensitivities at small refractive indices of the test medium. If n_{test} approaches n_{prism}, the ATR scheme demonstrates a drastic increase of its sensitivity (Fig. 1,*a*), but the resonance angles tend to those characteristic of an almost grazing incidence, which complicates the signal registration. Moreover, in the ATR case, the n_{test}-values accessible to measurements are confined by a threshold value, beyond which SPPs cannot be excited, as it follows from excitation condition (2) (Fig. 1,*b*). For example, the threshold value is about 1.4 at a wavelength of 800 nm.

Unlike the ATR scheme, the DG one allows one to control the sensitivity by varying the geometrical parameters of the system. In particular, a reduction of the DG period from 1000 to 600 nm is accompanied by a relative – with respect to the ATR case – increase of the sensitivity by a factor of about 1.5 in the range of low refractive indices (~ 1).

The spectral dependences of the sensitivity for ATR-based sensor elements (Fig. 1,*b*) demonstrate their high characteristics with a drastic increase of this parameter in narrow intervals of the refractive index which are

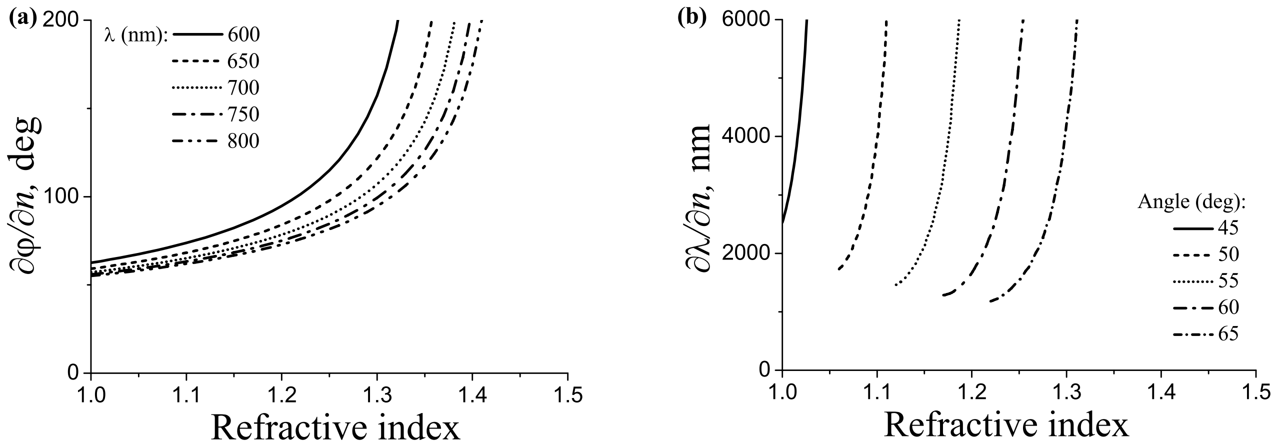

Fig. 1. Dependences of the Au/ATR-based sensory system sensitivity on the refractive index of the environment at scanning (*a*) over the angle for various incident wavelengths and (*b*) over the wavelength for various incidence angles. The refractive index of the prism $n_{\text{prism}} = 1.5$

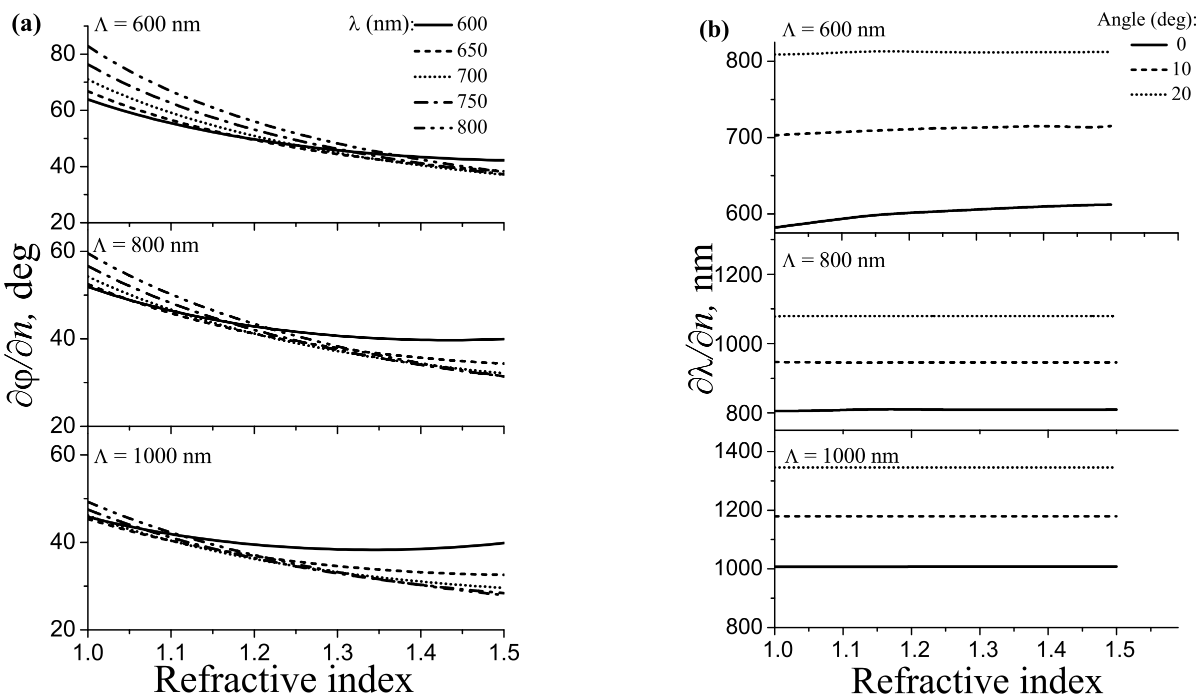

Fig. 2. Dependences of the sensitivity of Au/DG sensory systems with various grating periods Λ on the refractive index of the environment for the (−1)-th diffraction order at scanning (*a*) over the angle for various incident wavelengths and (*b*) over the wavelength for various incidence angles

determined by the incidence angle of the test beam. At the same time, the spectral sensitivity of the sensory scheme with DG does not depend on n_{test} (Fig. 2,*b*), being determined by the DG period, diffraction order, and incidence angle. As is seen from Fig. 2,*b*, the angular sensitivity of the DG-based system increases with the incidence angle. In this case, the resonance peak shifts to the infra-red range, and its intensity decreases, which imposes a restriction upon working incidence angles, when the optimum operating conditions for real sensory systems are selected.

In order to describe practically interesting selectively sensitive sensory systems, let us consider three-layer systems with an additional immersion layer. In the course of the simulation, let us assume that the system sensitivity is driven by changes that occur in this confined layer only.

In Fig. 3, the angular and spectral dependences of the sensitivity of an ATR-based sensory system on the variation of the refractive index of the immersion medium are depicted for fixed thicknesses of the immersion layer in the interval from 25 to 100 nm. Similar sensitivity dependences for the DG scheme for the two periods of 600 and 1000 nm are presented in Fig. 4.

Figure 3 demonstrates that the insertion of an immersion layer into the ATR scheme makes it possible to extend the operation range of the test medium refractive index in comparison with the similar case for a two-medium system. Moreover, the sensitivity becomes dependent on the immersion layer thickness and weakly dependent on the n_{test} variation range under increase in the wavelength of incident light.

The insertion of the immersion layer into the system with DG significantly changes the character of both the angular and spectral sensitivities. For example, the angular sensitivity (Fig. 4,*a,b*) increases with decrease in the wavelength of incident light and with increase in the DG period. In this case, on the contrary, the increase in the DG period decreases the spectral sensitivity (Fig. 4,*c,d*). In addition, increasing the incidence angle decreases the spectral sensitivity, as distinct from the case without an immersion layer (Fig. 2,*b*).

The comparison between the sensitivities of the systems of both types testifies to their comparability in a wide range of immersion layer refractive index variation. In the case of the ATR scheme, the spectral sensitivity is higher for any immersion layer thickness. In this case, the increase of the immersion layer thickness leads to an enhancement in the angular and spectral sensitivities in both cases under study. But, on the other hand, the capability to enhance the sensitivity by increasing the film thickness is restricted by the fact that the further increase of the thickness gives rise to a strong broadening of the polariton peak and complicates the experimental determination of resonance characteristics.

The obtained sensitivity values are much lower, as compared with the case of systems without immersion layer (except for the case with DG scheme, where the angular sensitivity can be greater) where the refractive index variations are registered in a semiconfined space, rather than in a thin film. However, in the case of a two-layer system, typical values of the refractive index variations are of the order of 10^{-4} (for instance, under the presence of ethanol vapor in air), whereas they are of about 10^{-1} in the immersion medium, so that the total shift of the resonance angle (or the wavelength) is comparable in both cases.

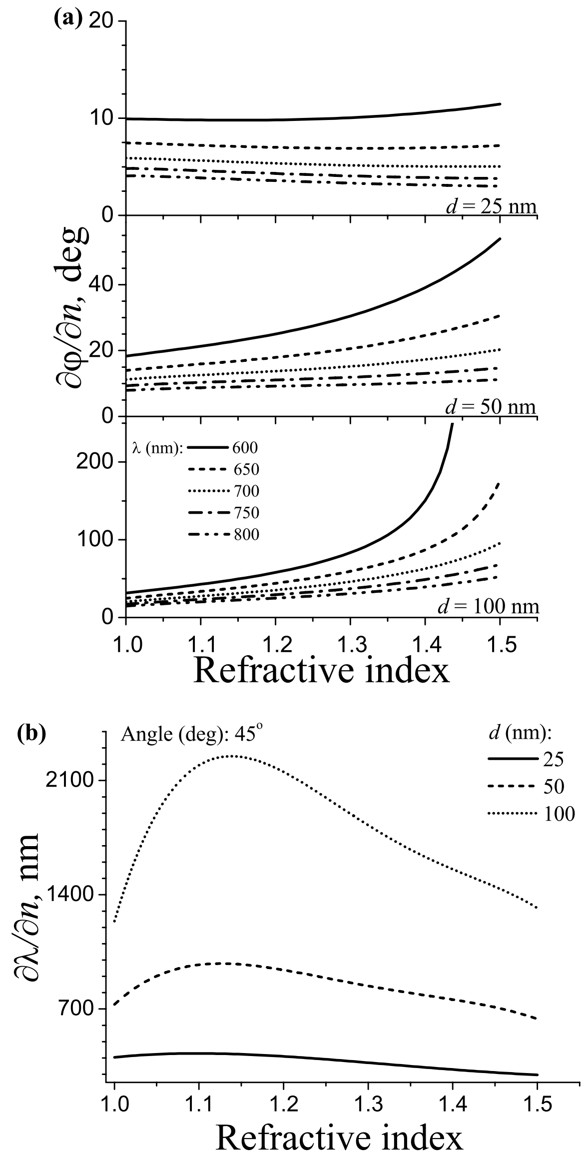

Fig. 3. Dependences of the Au/ATR-based sensory system sensitivity on the refractive index of the immersion medium at scanning (*a*) over the angle for various incident wavelengths and (*b*) over the wavelength for various incidence angles. The refractive index of the prism $n_{\text{prism}} = 1.5$

In Figs. 5 and 6, the dependences of the angular and spectral sensitivities of sensory systems of both types on the variation of the immersion layer thickness under the influence of the environment are depicted for a number

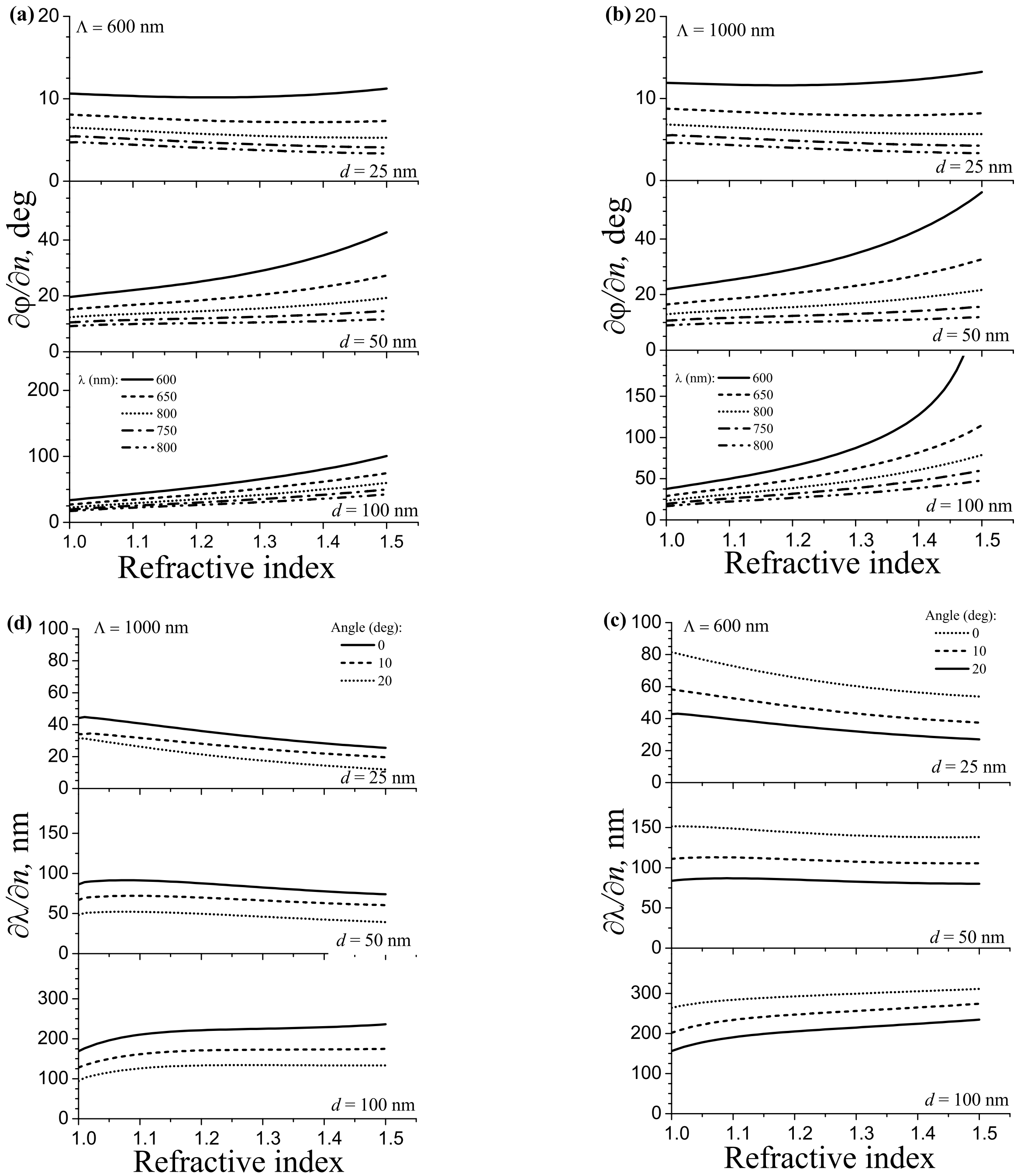

Fig. 4. Dependences of the Au/DG sensory system sensitivity on the refractive index of the immersion medium for the (-1)-th diffraction order at scanning (a and b) over the angle for various wavelengths and (c and d) over the wavelength for various incidence angles. The DG period is (a and c) 600 and (b and d) 1000 nm

of fixed refractive indices for this layer. A characteristic feature of the spectra is the presence of a maximum in the angular sensitivity which corresponds to the optimal thickness of the immersion layer (Figs. 5,a and 6,a). In the case of spectral dependences, this maximum is less pronounced and has a more complicated character of its dependence on both characteristics of selectively sensitive films (the thickness and the refractive index)

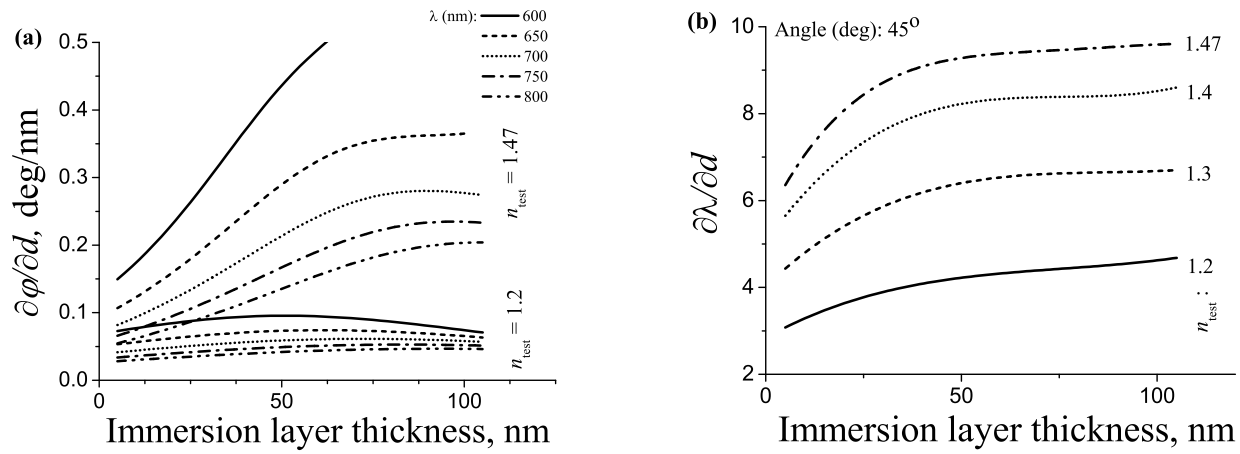

Fig. 5. Dependences of the Au/ATR-based sensory system sensitivity on the immersion layer thickness at scanning (a) over the angle for various incident wavelengths and (b) over the wavelength for various incidence angles. The refractive index of the prism $n_{\text{prism}} = 1.5$

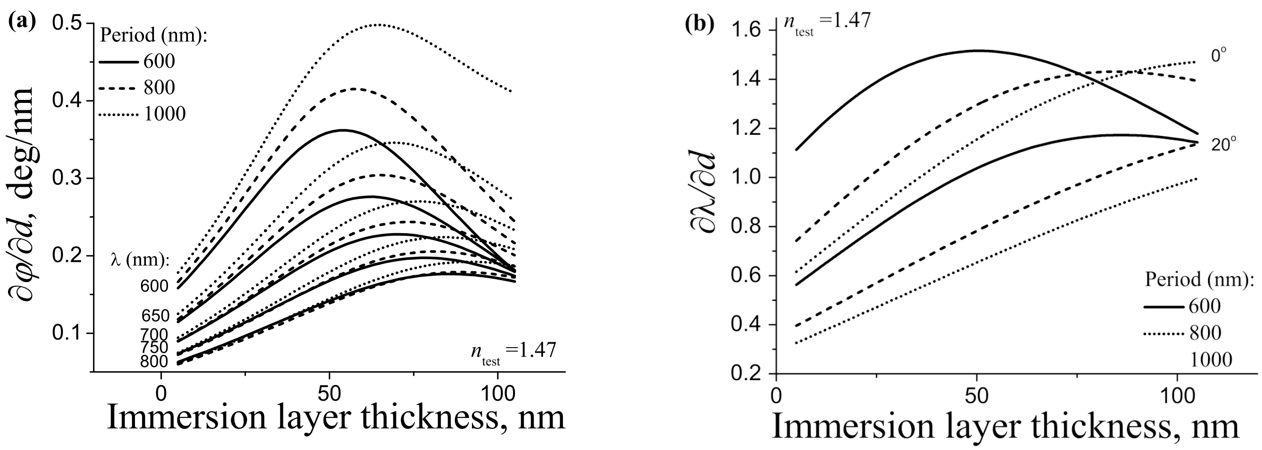

Fig. 6. Dependences of the Au/DG sensory system sensitivity on the immersion layer thickness for the (−1)-th diffraction order at scanning (a) over the angle for various incident wavelengths and (b) over the wavelength for various incidence angles

and the conditions of SPP excitation (the angle of incidence) (Figs. 5,b and 6,b). In the DG case, the position of this maximum is also affected by the geometrical parameters of the system (the DG period).

Our calculations showed that the growth of the immersion layer refractive index is accompanied by a substantial enhancement of the sensitivity of sensory systems of both types. But in reality, the refractive index of an immersion layer is influenced by many factors, such as the type of a selectively sensitive film, the methods of its deposition, the type of the substance (analyte), which the film is selective to, and even the very fact of analyte absorption [15, 16]. Therefore, an opportunity to vary its value in sufficiently wide limits is not always possible.

The changes of the immersion layer thickness, owing to the interaction with the analyte, also depend substantially on the immersion layer nature, as well as its initial thickness and absorption ability. If, according to the results of experiments dealing with the absorption of saturated benzene vapors by a calix[4]resorcinolarene film 20 monolayers in thickness [18], the layer thickness is assumed to be about 3.4 nm, the total shift of the resonance angle (or the wavelength) is about 0.61° (28.6 nm) in the case of the ATR scheme and about 0.62° (4.72 nm) in the case of the DG scheme with a period of 600 nm (the wavelength of incident light $\lambda = 650$ nm and the parameters of the immersion layer are as follows: the refractive index $n_{\text{test}} = 1.47$, the initial thickness $d = 22.4$ nm, and the final thickness $d = 25.8$ nm.

The sensory system sensitivity is also determined by the efficiency of light–SPP energy transformation η. This quantity is defined as a difference between the reflection

Efficiency of light transformation into a surface plasmon polariton for two excitation methods: DG and ATR

			ATR	DG		
				600-nm period	800-nm period	1000-nm period
Without an immersion layer	$\lambda = 650$ nm	η, %	94.0	87.4	80.8	80.1
		$\partial\phi/\partial n$, deg	59.2	66.7	52.5	45.4
($n_{\text{test}} = 1$)	$\lambda = 800$ nm	η, %	96.4	89.0	84.2	83.4
		$\partial\phi/\partial n$, deg	55.4	82.9	59.7	49.5
With an immersion layer	$\lambda = 650$ nm	η, %	94.0	53.5	35.7	37.3
		$\partial\phi/\partial n$, deg	7.1	7.24	7.6	8.1
($n_{\text{test}} = 1.47$, $d = 25.8$ nm)	$\lambda = 800$ nm	η, %	96.4	54.8	43.8	48.7
		$\partial\phi/\partial n$, deg	3.0	3.4	3.26	3.35

coefficients for light with s- and p-polarizations under the conditions of resonance SPP excitation. This allows separating the SPP contribution to the reflectance reduction from other losses of electromagnetic energy in a sensory system. The optimum thickness of a gold film (45 nm) was selected for calculations. In the DG case, the ratio between the grating depth and the period was selected to be 0.1, which corresponded to the highest efficiency of SPP excitation for sinusoidal gratings [6]. Table 1 exhibits the efficiencies of light–SPP transformation and the corresponding angular sensitivities for two ways of surface wave excitation considered above, without and with an immersion layer in the system and for two resonance wavelengths. It was found that the ATR scheme is more effective than the DG one, irrespective whether the immersion layer is present or not, and that the insertion of a selectively sensitive layer does not affect the efficiency. For the DG method, typical is the opposite dependence, namely, the efficiency of light–SPP transformation decreases, if an additional selectively sensitive layer is inserted into the system. Moreover, in the DG case, we have determined the dependences of the transformation efficiency on the exciting radiation wavelength and the grating period. We have also revealed that, contrary to the efficiency of light–SPP transformation, the sensitivity is greater for structures including a DG with optimized parameters in both cases without and with an immersion layer.

5. Conclusions

The sensitivity of polaritonic photodetectors and opto-chemical sensors has been shown to depend on both the excitation method of surface plasmon polaritons and the light transformation efficiency into a surface plasmon polariton, the latter being dependent on the optical and geometrical parameters of sensory systems. The ATR- and DG-based sensor elements were demonstrated to possess different sensitivities in various ranges of the test substance refractive index n_{test}. In the DG case, the maximal sensitivity is reached at low refractive indices, whereas, in the ATR case, the sensitivity is maximal at high n_{test}. Hence, DG-based sensor elements would be more suitable to analyze gas mixtures, where the refractive index is close to unity. At the same time, ATR sensory controls are more useful for the analysis of liquids and solutions. In addition, the sensor element on the basis of a surface barrier structure with a DG at the interface (e.g., Au/GaAs) essentially simplifies the device design, because the photodetector and the sensitive element are united. Such a configuration proposes more opportunities to optimize the sensitivity in the given spectral range by varying the geometrical parameters of the grating (the grating period, the depth and the shape of grooves). The analysis testifies that the insertion of additional intermediate layers (the Sarid geometry) is promising for both methods and improves SPP characteristics. In addition, the DG method with the measurement of the photocurrent through barrier structures on the basis of this grating has significant capabilities with respect to the sensitivity enhancement: the deposition of metal or semiconducting nanoparticles at the metal–semiconductor interface, the use of a special anticorrelated relief [19], and the interaction between SPP waves and local elementary excitations of nanoparticles.

1. J. Homola *et al.*, Sensors and Actuators B **54**, 3 (1999).
2. N.L. Dmitruk, O.I. Mayeva, and M.V. Sosnova, in *Encyclopedia of Sensors,* edited by C.A. Grimes, E.C. Dickey, and M.V. Pishko (ASP, New York, 2006), Vol. 8, p. 21.
3. N.L. Dmitruk, V.G. Litovchenko, and V.L. Strizhevskii, *Surface Polaritons in Semiconductors and Insulators* (Naukova Dumka, Kyiv, 1989) (in Russian).
4. D. Sarid, Phys. Rev. Lett **47**, 1927 (1981).
5. L.V. Belyakov, D.N. Goryachev, O.M. Sreseli, and I.D. Yaroshetskii, Pis'ma Zh. Tekh. Fiz. **11**, 1162 (1985).
6. A.A. Beloglazov, M.V. Valeyko, and P.I. Nikitin, Prib. Tekh. Eksp. **6**, 137 (1995).

7. O.V. Rengevich, Yu.M. Shirshov, Yu.V. Ushenin, and A.G. Beketov, Semicond. Phys. Quant. Electr. Optoelectr. **2**, 28 (1999).
8. Xia Liu *et al.*, Trends Analyt. Chem. **24**, 887 (2005).
9. G.N. Zhizhin, M.A. Moskaleva, V.G. Nazin, and V.A. Yakovlev, in *Surface Polaritons,* edited by V.M. Agranovich and D.L. Mills (North-Holland, Amsterdam, 1982).
10. R. Slavik and J. Homola, Sensors and Actuators B **123,** 10 (2008).
11. A.V. Kabashin and P.I. Nikitin, Opt. Commun. **150**, 5 (1998).
12. N.L. Dmitruk, O.I. Mayeva, S.V. Mamykin, O.B. Yastrubchak, and M.K. Klopfleisch. Sensors and Actuators A **88**, 52 (2001).
13. N.L. Dmitruk, O.V. Fursenko, O.S. Kondratenko, and V.R. Romanyuk, Semicond. Phys. Quant. Electr. Optoelectr. **6**, 349 (2003).
14. J. Homola, I. Koudela, and S.S. Yee, Sensors and Actuators B **54**, 16 (1999).
15. Y.M. Shirshov, V.Y. Khoruzhenko, K.V. Kostyukevych, R.V. Khristosenko, I.A. Samoylova, A.S. Pavluchenko, A.V. Samoylov, and Y.V. Ushenin, Sensors and Actuators B **122**, 427 (2007).
16. Y.M. Shirshov, S.A. Zynio, E.P. Matsas, G.V. Beketov, A.V. Prokhorovich, E.F. Venger, L.N. Markovskiy, V.I. Kalchenko, A.V. Soloviov, and R. Merker, Supramol. Sci. **4,** 491 (1997).
17. P.B. Johnson and R.W. Christy, Phys. Rev. B **6(12)**, 4370 (1972).
18. A.V. Nabok, N.V. Lavrik, Z.I. Kazantseva, B.A. Nesterenko, L.N. Markovskiy, V.I. Kalchenko, and A.N. Shivaniuk, Thin Solid Films **259**, 244 (1995).
19. N.L. Dmitruk and A.V. Korovin, Opt. Lett. **33**, 893 (2008).

Received 09.12.08.
Translated from Ukrainian by O.I. Voitenko

ПОРІВНЯННЯ ЕФЕКТИВНОСТІ ЗБУДЖЕННЯ ПОВЕРХНЕВИХ ПЛАЗМОННИХ ПОЛЯРИТОНІВ МЕТОДАМИ РЕЛЬЄФНО-ФАЗОВОЇ ДИФРАКЦІЙНОЇ ҐРАТКИ ТА ПРИЗМИ ОСЛАБЛЕНОГО ПОВНОГО ВІДБИТТЯ

М.Л. Дмитрук, О.В. Коровін, С.В. Мамикін, М.В. Соснова, Є.Ф. Венгер

Р е з ю м е

Роботу присвячено послідовному порівнянню переваг і недоліків двох найбільш уживаних методів збудження поверхневих плазмонних поляритонів – за допомогою призми ослабленого повного внутрішнього відбиття і дифракційної ґратки. Проаналізовано ефективність перетворення світла в поверхневий поляритон та вплив параметрів окремих елементів системи на її чутливість. Отримано аналітичні вирази для чутливості сенсорних систем двох типів при введенні додаткового селективно-чутливого шару. Встановлено, що в широкому діапазоні зміни показника заломлення тестованої речовини чутливість сенсорних елементів на базі таких методів збудження має різну величину у різних діапазонах зміни показника заломлення. У випадку дифракційної ґратки максимальна чутливість досягається в інтервалі малих показників заломлення, в той час як для призми ослабленого повного внутрішнього відбиття вища чутливість в діапазоні їх великих значень.