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Surface plasmon polariton characteristics and resonant coupling on thin Al, Ag and Au layers

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Herein we present surface plasmon polariton (SPP) main characteristics of Al, Au and Ag layers. SPP wavelength, propagation length, and penetration depths (into the dielectric and into the metal) are evaluated. The resonant coupling of two excited SPP on both metal/dielectric boundaries of a very thin metal layer is of great importance in the synthesis of new generation sensors and optoelectronic devices.

Keywords: Surface plasmon polariton, Thin metal layer, Al layer, Ag layer, Au layer

INTRODUCTION

Surface plasmon polariton (SPP) is an electromagnetic excitation that propagates along the interface between a metal and a dielectric medium and whose amplitude decays exponentially with increasing distance into each medium from the interface [1]. Surface plasmon polaritons are generated by resonant interaction between the surface charge oscillation and the electromagnetic field of light.

As early as 1950s Ritchie introduced the concept of SPP [1]. Recently the interest in them was renewed for various reasons [2]. The use of lasers in optical experiments also opens up new opportunities for researchers. Development of techniques for structuring surfaces with submicron resolution, allows production of high-quality devices, working in the visible spectrum. Various sensors based on SPP resonance were developed [3–6]. They are one of the possible ways for the development of nano-optics [7, 8]. The length of propagation of SPP in certain metals is sufficient to connect two optical devices in a chip. It is possible to make optical elements with very small losses, and hence to permit the propagation of SPP over several centimeters [9, 10].

The aim of this paper is to present an evaluation of SPP main charactericts of SPP with an emphasis on those aspects that underlie the recent research interest. Attention will be focused on the different length scales that are of practical interest: the SPP wavelength – λ_{SPP}, the SPP propagation length – δ_{SPP}, the penetration depth of the electromagnetic field associated with the SPP mode into the dielectric medium – δ_d, and the penetration depth of the field into the metal – δ_m. Although the approach we use here is based on some simplifying assumptions, the presented results clearly indicate the potential that SPPs offer for subwavelength optics.

THEORY

Optical excitation of SPP at a metal-dielectric interface requires matching of the momentum of the incident light and the SPP. The SPP is characterized by a complex wavevector k_{SPP}. Let us first consider a very thick metal layer and p-polarized (transverse magnetic or TM) wave, incident at the metal / dielectric interface.

For such wave the magnetic vector is perpendicular to the plane of incidence – the plane defined by the direction of propagation and the normal to the surface. Solving Maxwell's equations under the appropriate boundary conditions yields the SPP dispersion relation [7, 11]:

$$k_{SPP} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \qquad (1)$$

where ε_m and ε_d are the dielectric constants of the metal and dielectric layers.

When we consider an *s*-polarized (transverse electric or TE) wave, it is the electric vector that is

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perpendicular to the plane of incidence. Solving Maxwell's equations in this case, it becomes clear that surface plasmon polariton cannot exist for this light polarization [11]. Since the momentum of incident light in air is lower than that given by Eq. (1), a coupling device is needed. There are three main techniques by which the missing momentum can be provided. The first makes use of prism coupling to enhance the momentum of the incident light [12, 13]. The second involves scattering from a topological defect on the surface, such as a subwavelength protrusion or hole, which provides a convenient way to generate SPPs locally [14]. The third makes use of a periodic corrugation on the metal's surface [15].

Plasmon on the surface of a thin metal layer has properties that are not observed in SPP propagating on the interface of a semi-infinite dielectric media. If the metal is thin enough, then the surface plasmons of the two surfaces of the metal can interact and form a connected SPP mode. As we will show, the thickness of the metal layer must be of the order of 20 nm or less, in order to observe a significant binding.

The dispersion relation of SPP for the system: vacuum ($\varepsilon_1 = 1$)/metal layer (ε_m)/dielectric (ε_d) in direction parallel to the interface is given by Zayats *et al.* [11]:

$$\left[\frac{\varepsilon_m}{\varepsilon_1}\frac{k_z^1}{k_z^m}+1\right]\left[\frac{\varepsilon_m}{\varepsilon_d}\frac{k_z^d}{k_z^m}+1\right]= \left[\frac{\varepsilon_m}{\varepsilon_1}\frac{k_z^1}{k_z^m}-1\right]\left[\frac{\varepsilon_m}{\varepsilon_d}\frac{k_z^d}{k_z^m}-1\right]e^{-2k_z^m d} \tag{2}$$

Dispersion relations in the cases metal/vacuum and metal/dielectric are obtained as special cases of the equation for a thin layer, when the dielectric layer thickness $d \to \infty$.

There are two main approaches to find the dispersion equation of the SPP. One of them is to use Maxwell equations and boundary conditions, as described above. However, in case of complex systems, consisting of more than one thin layer, it is better to use a second method based on the Fresnel's formulas for reflection/transmission. This results in complex transcendental equations which can be solved only numerically.

Below we present a numerical analysis of the following key characteristics:

- the SPP wavelength – λ_{SPP},
- the SPP propagation length – δ_{SPP},
- the penetration depth of the SPP mode into the dielectric medium – δ_d, and
- the penetration depth of the field into the metal – δ_m.

Wavelength of SPP depends on the period of oscillation of the surface charges. The SPP wavelength and the SPP propagation length, may be found from the dispersion equation for two semi-infinite media, by using the real and imaginary part of the wave vector k'_{SPP} and k''_{SPP} [16]. When $\left|\varepsilon'_m\right| >> \left|\varepsilon_d\right|$, the real part of the wave vector of the SPP is:

$$k'_{SPP} = k_0\sqrt{\frac{\varepsilon_d\varepsilon'_m}{\varepsilon_d+\varepsilon'_m}} \tag{3}$$

Hence

$$\lambda_{SPP} = \lambda_0\sqrt{\frac{\varepsilon_d+\varepsilon'_m}{\varepsilon_d\varepsilon'_m}}\,. \tag{4}$$

The ratio between the wavelength of the plasmon and the wavelength in vacuum is:

$$\frac{\lambda_{SPP}}{\lambda_0} = \sqrt{\frac{\varepsilon_d+\varepsilon'_m}{\varepsilon_d\varepsilon'_m}}\,. \tag{5}$$

The SPP propagation length is another characteristic and it is calculated from the imaginary part of the wave vector of the plasmon. It is the distance in which the power or intensity of the mode is reduced to $1/e$ of its initial value. Taking into account that $\varepsilon''_m << \left|\varepsilon'_m\right|$, from the dispersion equation Eq. (1) follows that:

$$k''_{SPP} = k_0\frac{\varepsilon''_m}{2\left(\varepsilon'_m\right)^2}\left(\frac{\varepsilon'_m\varepsilon_d}{\varepsilon'_m+\varepsilon_d}\right)^{\frac{3}{2}} \tag{6}$$

The SPP propagation length δ_{SPP} is given by $\delta_{SPP} = 1/2k''_{SPP}$, and is:

$$\delta_{SPP} = \lambda_0\frac{\left(\varepsilon'_m\right)^2}{2\pi\varepsilon''_m}\left(\frac{\varepsilon'_m+\varepsilon_d}{\varepsilon'_m\varepsilon_d}\right)^{\frac{3}{2}}. \tag{7}$$

The penetration depths of the SPP mode into the dielectric medium δ_d, and into the metal δ_m are found similarly and they are:

$$\delta_d = \frac{1}{k_0}\left|\frac{\varepsilon_m' + \varepsilon_d}{\varepsilon_d^2}\right|^{\frac{1}{2}} \quad \text{and}$$

$$\delta_m = \frac{1}{k_0}\left|\frac{\varepsilon_m' + \varepsilon_d}{\varepsilon_m'^2}\right|^{\frac{1}{2}} \tag{8}$$

RESULTS AND DISCUSION

The first basic characteristic of SPP is the ratio between the wavelength of the plasmon λ_{SPP} and the wavelength in vacuum λ_0. We can calculate it from Eq. (5) for metal layer (in this case silver) bordering either with air or with polycarbonate as used in [16-18]. Results in the range 400–1200 nm (VIS and NIR) are shown in Fig. 1.

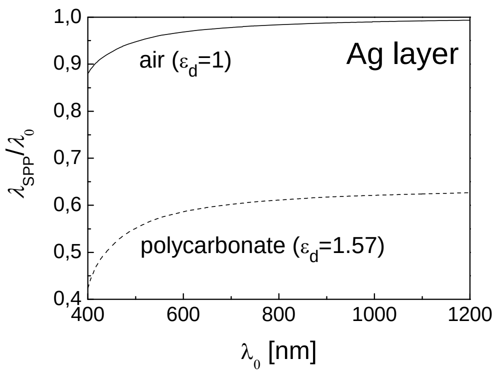

Fig.1. Dependence of the SPP wavelength on the wavelength in vacuum. The dielectric is air (solid line) or polycarbonate (dashed line).

In the case when the dielectric media is air with $\varepsilon_d = 1$ (solid line in Fig. 1), the wavelength of the plasmon is very close, but always smaller than the wavelength in vacuum. When $\varepsilon_d \neq 1$ (Fig. 1, dashed line), the wavelength of the plasmon is always less, but approaches the wavelength in the corresponding dielectric. The important conclusion from these data is that if we want to control the SPP by a periodic structure, then its characteristic length should be of the order of the SPP wavelength.

The next characteristic important for the practical applications of the surface plasmons is the SPP propagation length δ_{SPP}. As mentioned in the theoretical section, this characteristic can be determined by Eq. (7).

In Fig. 2 the dependences of the SPP propagation length on the wavelength in vacuum

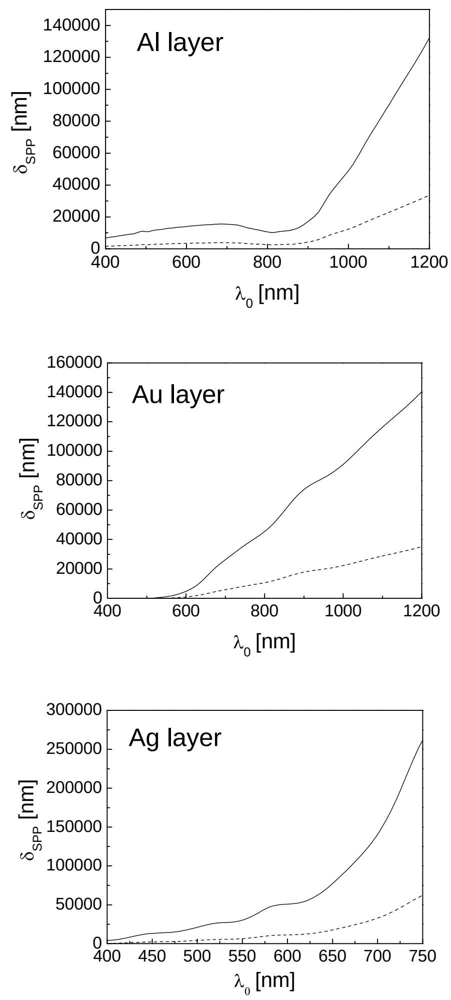

Fig. 2. Dependence of the SPP propagation length on the wavelength for Al, Au and Ag. The dielectric is air (solid line) or polycarbonate (dashed line).

for three metals: aluminum, gold and silver (Al, Au and Ag) are shown.

The SPP propagation length sets an upper limit on the size of the structures that can be used. One way to increase δ_{SPP} is by using coupled modes that are present in the thin metal layers. The SPP propagation length is significantly greater (about $10^2 \div 10^3$ times) than the wavelength of the plasmon. Hence, diffraction gratings with period on the order of the SPP wavelength can be used to control the plasmon propagation, provided that interaction with the SPP over several periods of the structure is ensured.

Other basic characteristics are the penetration depths of the plasmon in the metal and in the dielectric. Their dependences on the wavelength are shown in Fig. 3 and Fig. 4. They are very important, in order to determine whether coupling

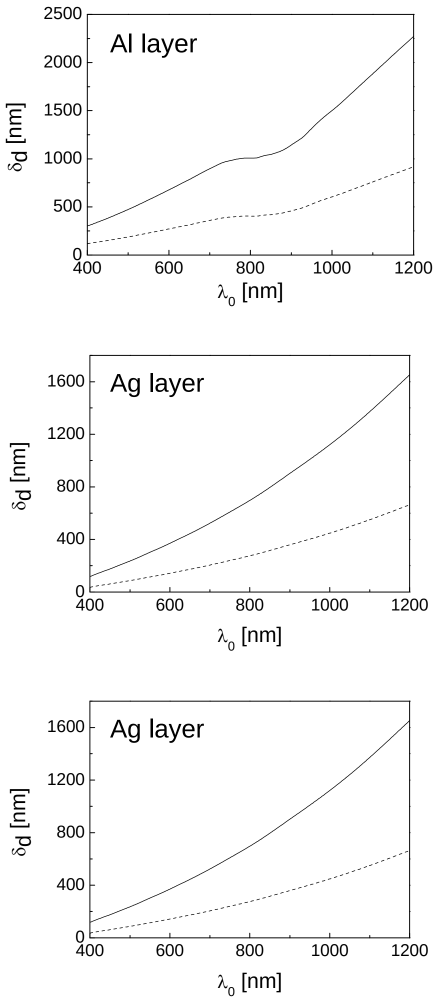

Fig. 3. Dependence of the SPP penetration depth in the dielectric on the wavelength for Al, Au and Ag layer. The dielectric is air (solid line) or polycarbonate (dashed line).

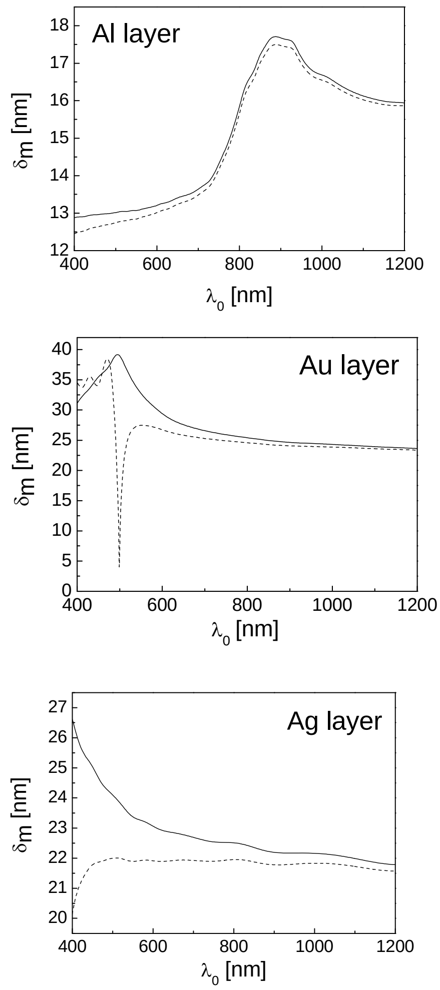

Fig. 4. Dependence of the SPP penetration depth in the metal on the wavelength for Al, Au and Ag layer. The dielectric is air (solid line) or polycarbonate (dashed line).

of plasmons from both sides of the metal layer is possible. They are calculated using Eq. (8).

The SPP penetration depth into the dielectric is a measure of the distance at which the SPP mode is sensitive to changes in the refractive index of the dielectric layer.

As seen in Fig. 4, penetration of the SPP into the aluminum layer on the two boundaries is approximately 16 nm (the value obtained for the longer wavelengths is used), i.e. coupling between the plasmons on both sides of the thin layer may be expected for thickness less than 32 nm. In the case of gold and for wavelengths above 600 nm coupling of the plasmons can be expected in films with thickness below 48 nm.

Note that for the combination gold/polycarbonate, there is a sharp dip in the penetration depth around 500 nm, i.e. the SPPs remain localized. At this wavelength the numerator in Eq. (8) becomes close to zero, due to the value of the dielectric constant of polycarbonate. Penetration on the two boundaries for silver is approximately 22 nm and coupling of the plasmons is possible for thickness less than 44 nm.

CONCLUSION

We have numerically solved equations that give some SPP main characteristics. We have shown that for large wavelengths, i.e. in the NIR region of the spectrum, δ_m asymptotically approaches a different limit for each metal. In our case, the penetration depth is smallest for aluminum and highest for the noble metals especially for gold, which is also confirmed in the literature. Knowledge of the basic characteristics of the SPP is important and necessary for a deeper understanding of resonance processes in the studied structures. In this manner, one can optimize the individual elements in the realization of the various sensing devices.

REFERENCES

1. R. H. Ritchie, *Phys. Rev.*, **106**, 874 (1957).
2. J. Homola, *Anal. Bioanal. Chem.*, **377**, 528 (2003).
3. B. N. Feltis, B. A. Sexton, F. L. Glenn, M. J. Best, M. Wilkins, T. J. Davis, *Biosensors and Bioelectronics*, **23**, 1131 (2008).
4. D. Nazarova, B. Mednikarov, P. Sharlandjiev, *Appl. Opt.*, **46**, 8250 (2007).
5. B. K. Singh, A. C. Hillier, *Anal. Chem.*, **80**, 3803 (2008).
6. K. Welford, *Opt. Quantum Electron.*, **23**, 1 (1991).
7. W. L. Barnes, A. Dereux, T. W. Ebbesen, *Nature*, **424**, 824 (2003).
8. W. L. Barnes, *Nature*, **3**, 588 (2004).
9. P. Berini, R. Charbonneau, N. Lahoud, G. Mattiussi, *J. Appl. Phys*, **98**, 043109 (2005).
10. P. Berini, *Phys. Rev. B*, **61**, 10484 (2000).
11. A. V. Zayats , I. I. Smolyaninov, A. A. Maradudin, *Phys. Rep.*, **408**, 131 (2005).
12. E. Kretschmann, H. Raether, *Z. Naturforsch. A*, **23**, 2135 (1968).
13. A. Otto, *Z. Phys.*, **216**, 398 (1968).
14. H. Ditlbacher, J. R. Krenn, N. Felidj, B. Lamprecht, G. Schider, M. Salerno, A. Leitner, F. R. Aussenegg, *Appl. Phys. Lett.*, **80**, 404 (2002).
15. R. H. Ritchie, E. T. Arakawa, J. J. Cowan, R. N. Hamm, *Phys. Rev. Lett.*, **21**, 1530 (1968).
16. W. L. Barnes, *J. Opt. A: Pure Appl. Opt.*, **8**, S87 (2006).
17. B. K. Singh, A. C. Hillier, *Anal. Chem.*, **80**, 3803 (2008).
18. W. H. Yeh, J. W. Petefish, A. C. Hillier, *Anal. Chem.*, **83**, 6047 (2011).

ПОВЪРХНОСТНИ ПЛАЗМОН-ПОЛАРИТОННИ РЕЗОНАНСИ ПРИ ТЪНКИ Al, Ag И Au СЛОЕВЕ

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(Резюме)

В тази статия разглеждаме основните характеристики на повърхностните плазмон-поларитони (ППП) за слоеве от Al, Au и Ag. Дължината на вълната на ППП, дължината на разпространение и дълбочините на проникване в метала и в диелектрика. Взаимодействието на два ППП от двете граници на много тънък слой е от голямо значение за синтезирането на ново поколение сензори и оптоелектронни устройства.