Surface plasmon resonance sensor with silicon-based prism coupling

Sergiy Patskovsky[*], Andrei V. Kabashin, Michel Meunier

Laser Processing Laboratory, Department of Engineering Physics, Ecole Polytechnique de Montreal, Case Postale 6079, Succ. Centre-ville, Montreal, Quebec, Canada, H3C 3A7

John H.T. Luong

Biotechnology Research Institute, National Research Council Canada, Montreal, Quebec, Canada, H4P 2R2

ABSTRACT

We study possibilities of implementation of Surface Plasmon Resonance (SPR) sensors on purely silicon platform, in which SPR-supporting Au film is used with a silicon prism in the Kretschmann-Raether geometry. Based on theoretical and experimental analyses we have determined the conditions and parameters of SPR excitations on such a platform in the infrared light for configurations of bio- and gas sensing. The approach enables one to apply well-developed silicon microfabrication and integration methods for SPR technique, opening up the possibilities to miniaturize SPR bio- and chemical sensors.

Keywords: surface plasmon resonance, silicon, dispersion, infrared.

1. INTRODUCTION

In recent years, the miniaturization of biochemical and physical sensor devices and their integration onto a single microchip have become a dominant goal of sensor research and development. Advances in the microfabrication methods make possible the fabrication of low-cost sensors and sensor arrays having high degree of reliability.

Among modern sensing techniques, surface plasmon resonance is known by its high sensitivity and a possibility of real-time and label free recording of biological or chemical events. This technique has a wide spectrum of applications in medical and environmental analyses[1,2,3]. SPR sensor relies on the physical principle that the energy carried by photons of light can be transferred to electrons on a metal surface[4]. Resulting surface plasmon propagates over the metal/dielectric interface and generates an electrical field over a certain distance above the metal surface. The wave number of surface plasmons k_{SP} can be represented by the dispersion relation for two homogeneous semi-infinite media:

$$k_{SP} \approx \frac{\omega}{c}\left(\frac{\varepsilon_m(\omega)\varepsilon_s(\omega)}{\varepsilon_m(\omega)+\varepsilon_s(\omega)} \right)^{1/2} \quad (1)$$

where ε_m and ε_s, are dielectric constants of the metal and dielectric media, ω is the wave frequency, and c is the velocity of light. SPR is generally produced in the Kretschmann-Raether prism arrangement scheme[5], in which p-polarized visible light is directed through a prism with a relatively high refractive index n_p and then reflected from the gold film deposited on the prism surface (Fig.1). If one deposits a thin chemical or biological layer on the gold, any change in its thickness within range of the plasmon field causes a change in the incident angle or wavelength of light that resonates

[*] psv@canada.com; phone 1-(514)340-4711 ext. 2995, Ecole Polytechnique de Montréal, Laser Processing Laboratory, Département de Génie Physique, Case Postale 6079, succ. Centre-ville, Montréal (Québec), Canada, H3C 3A7

with the plasmon. Thus, by measuring such changes, one obtains a sensitive real-time analytical tool for detection of binding or recognition bio- (chemical) events on the gold surface.

Further improvements of SPR technique could be achieved through the miniaturization and integration of SPR sensors, which should make them portable and inexpensive. However, conventional glass-based sensor technology imposes certain limitations on the possibilities of such miniaturization. In this paper, we consider basic conditions of SPR production with a silicon platform, which is believed to be more flexible from the point of view of potential sensor miniaturization and integration due to the existence of well-developed Si-based microfabrication methods.
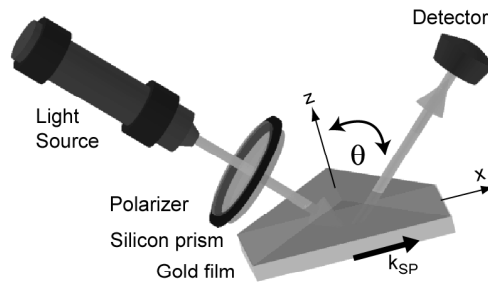

Figure 1: Schematic of the SPR system with a silicon sensing prism used in the experiment.

2. RESULTS AND DISCUSSION

Within the theoretical framework, we have developed software based on the model of surface plasmon excitation in multi-layer system (detailed description of the model will be given elsewhere.[6]) and have taken into account dispersion characteristics of all materials (including the sensing prism material), which can play a crucial role in the formation of SPR characteristics. In this study, we consider air and water as two typical testing media. The dispersion relation for water was taken from Harvey et al.[7], with a correction factor due to weak water absorption taken from the data of Kou et al.[8]. Dispersion properties of gold in visible and IR light were taken from the data of Innes and Sambles[9] and Johansen et al.[10]. The gold film thickness was optimized using equations from Kurihara and Suzuki[11]. The optical constants for silicon were obtained from the approximation of experimental dependencies reported by Herzinger et al.[12]

In addition, we carried out a series of experiments in the Kretschmann-Raether prism arrangement consisting of a silicon prism and a gold film, as shown in Fig. 1. The gold film was deposited on the prism or, in some cases, on a 1-mm thick glass slide or a 0.5-mm thick silicon wafer, which was then placed in intimate contact with the silicon prism. Two silicon prisms (FZ, p-type, R>20 Ω·cm, Almaz Optics, West Berlin, NJ) with a base angle of $\alpha = 16.6°$ and $\alpha = 22.4°$, respectively, were custom made for our study. Such prisms allowed for the attainment of the incidence of the laser beam onto the silicon/gold interface at angles close to resonance (θ_{SPR}) obtained from theoretical calculations. The gold layer thickness (40 nm) was selected to provide relatively low reflected light intensity with SPR sensing in the range of 1100-1700 nm. The gold film was in contact with a flow cell (empty or filled with deionized water, depending on whether the sensing medium is air or liquid). The SPR coupling system was placed onto a rotary block of a variable angle spectroscopic ellipsometer (Woollam VASE® ellipsometer, J.A. Woollam, Lincoln, NE) to allow for a very fine variation of the angular prism position with respect to the optical path of the ellipsometer. The system was illuminated by monochromatic p-polarized light with variable wavelengths, obtained by passing a white light source through a monochromator. The light reflected from the coupling system was analyzed by a detector, whose characteristics determined the dynamic range of the spectral measurement from 193-1700 nm. The experiments were performed in a configuration of a fixed wavelength or incident angle. The precision of angular and spectral measurements was 0.005° and 0.1 nm, respectively.

The calculation and experimental values revealed that the SPR effect can indeed be produced with the silicon prism if the pumping wavelength is above 1100 nm. Fig. 2 presents typical angular reflectivity curves from the theory (broken

line) and experimental data (solid line) for the gaseous (a) and aqueous (b) testing media. As presented by the experimental curves, the angles were related to the prism/gold interface, while a slight light refraction at the entrance to the prism was taken into account as a correction coefficient. Essentially, the main trend of the theory was well confirmed by the experimental data. The calculated and measured positions of reflectivity minimum were almost identical for the silicon prism.
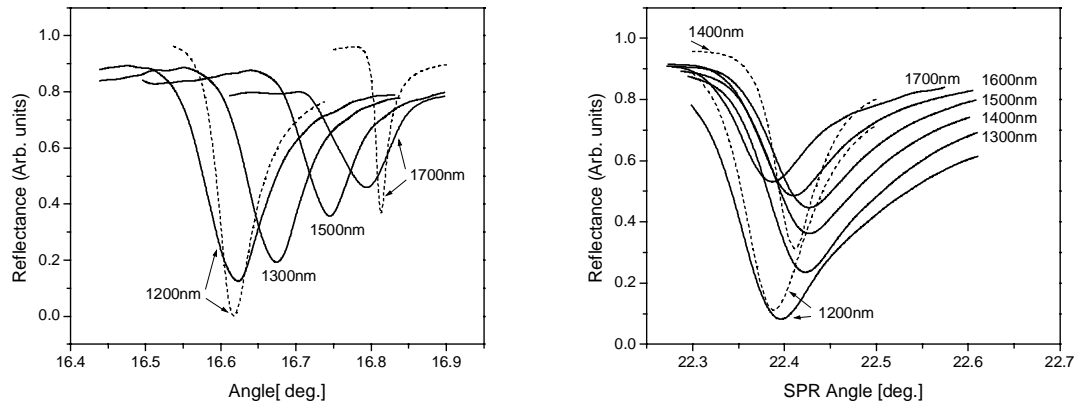

Figure 2: Typical angular reflectivity curves for the silicon prism in the configuration of gaseous (a) and aqueous (b) sensing medium. The broken and solid lines present the calculated and experimental data, respectively.

The SPR effect on the silicon prism was achieved in the gaseous medium at the θ_{SPR} value about 16.5-16.8° while those of the aqueous medium were 22-25° (Fig. 2a,b). It is noteworthy that the experimental reflectivity curves were slightly broader in comparison to the theoretical ones. For the experiment performed at λ=1200 nm in the gaseous and aqueous medium, the value of full width at half maximum (FWHM) was about 0.12° and 0.18° compared to the calculated values of 0.066° and 0.16°, respectively. The relative broadness of these curves was apparently explained by a certain non-ideality of the experimental setup due to the convergence of the light beam from the ellipsometer. The (FWHM) of the reflectivity curve decreased with an increase of the prism refractive index. For silicon, it was about two-fold smaller the value obtained using the glass prism. The position of the reflectivity minimum for each prism material was strongly dependent on the wavelength of pumping light (Fig. 2a,b). For each wavelength, an appropriate angle of incidence could be selected to provide resonant conditions.

Similar minimum values were observed in the spectral dependence of the reflectivity when the angle of incidence was kept constant (Fig. 3). In this case, the position of the spectral minimum was very sensitive to the angle of incidence. As an example, in the gaseous medium (Fig. 3a), only a slight decrease of the incident angle from 16.8° to 16.5° led to a considerable shift of the reflectivity minimum to shorter wavelengths (1100-1700 nm). A discrepancy between experimental and theoretical results in the aqueous media (Fig. 3b) could be minimized by further optimization of experimental conditions, mainly the gold layer thickness and more precise angle setting.

The data for the SPR minimum position collected from the angular and spectral reflectivity curves are summarized in Fig. 4, which described the resonant conditions for a simultaneous variation in the wavelength and the angle of incidence. The theoretical SPR minimum angle and wavelength could be generated from these plots by taking a cut parallel to the Y or X-axis. As illustrated in this figure, in the air sensing medium, the increase of wavelength was accompanied by an increase in the resonant angle. This behavior was completely opposite to the common case of the glass prism used for SPR sensors in the visible and NIR[13]. In aqueous milieu, the behavior of SPR dispersion curves became even more complicated and intriguing (Fig. 4). The resonant angle initially increased with an increase in the wavelength and reached a maximum value at λ = 1400 nm and then decreased with a further increase in λ. For a resonant angle below 22.4°, there were two dips in the IR range (Fig. 3b). Such behavior of SPR dispersion curves for in the gaseous and aqueous medium could be explained by considering the refractive index dispersion in IR for silicon and water.
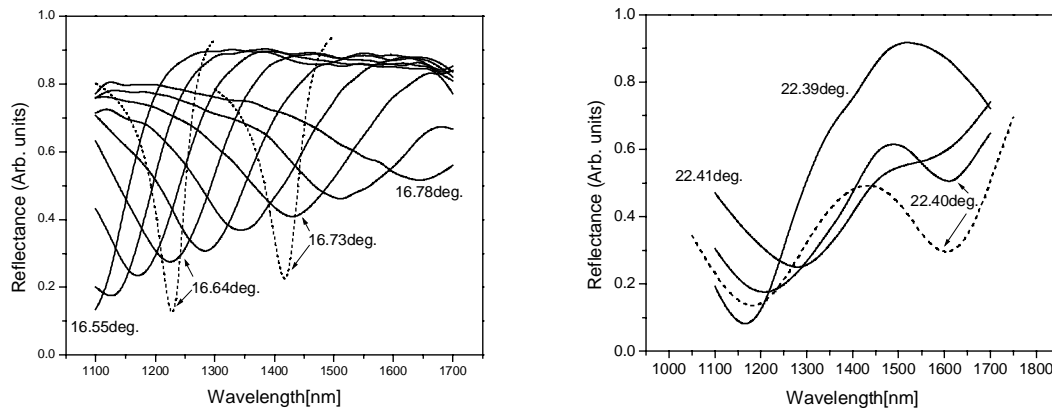
Figure 3: Typical spectral reflectivity curves for the silicon prism in the configuration of gaseous (a) and aqueous (b) sensing medium. The broken and solid lines present the calculated and experimental data, respectively.

SPR schemes on silicon with IR light could be more efficient for remote sensing applications. From our perspective, this phenomenon might be used to monitor the sensing event far from the gold surface and/or to detect interactions of large objects with a their receptors immobilized on the gold surface. Deadly viruses and bacteria are two important examples of such bio-objects, which cannot be detected by current visible-based SPR schemes.
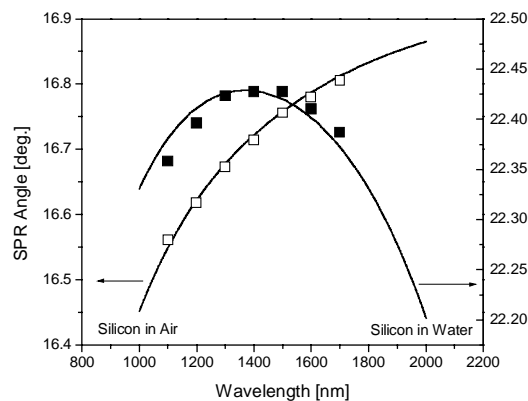
Figure 4: SPR dispersion curves for the silicon prism in the configuration of gaseous and aqueous sensing medium. The symbols present the experimental data, while the curves depict to the results of calculations.

The design of sensing on a silicon platform is especially appealing with respect to the ease of miniaturization of SPR systems, a key requirement for realization of μTAS. Of course, the expectation is based on the fact that methods for microfabrication and circuit integration are well developed for silicon materials. Undoubtedly, the integration of the SPR-based transducer on a Si-based processing chip will contribute to the development of novel compact biosensors and microarrays.

2. CONCLUSIONS

We have established schemes and conditions for SPR excitation in the Kretschmann-Raether geometry with a silicon prism in the IR range. It was demonstrated that the qualitative behavior of SPR dependencies in the IR range was

strongly influenced by the dispersion properties of the involved materials. Finally, we consider the possibility of sensor implementation on a purely silicon platform to provide novel opportunities for the miniaturization and integration of SPR biosensors, a key requirement for development of effective micro multi-analysis systems.

ACKNOWLEDGEMENTS

REFERENCES

1   P. Schuck, "Use of surface plasmon resonance to probe the equilibrium and dynamic aspects of interactions between biological macromolecules," Annu. Rev. Biophys. Biomol. Struct. 26 (1997) 541-566.
2   P.B. Garland, "Optical evanescent wave methods for the study of biomolecular interactions," Q. Rev. Biophys. 29 (1996) 91-117.
3   S. Lofas, "Dextran modified self-assembled monolayer surfaces for use in biointeraction analysis with surface plasmon resonance," Pure Appl. Chem. 67, 829-834 (1995).
4   E. Kretschmann, H. Raether, "Radiative decay of non radiative surface plasmons excited by light," Z. *Naturforschung* A 23 (1968)2135-2136.
5   E. Kretschmann, "The determination of the optical constants of metals by excitation of surface plasmons," Zeitschrift fur Physik A 241/4(1971)313-324.
6   S. Patskovsky, A. V. Kabashin, M. Meunier, J. H. T. Luong, Submitted to J. Opt. Soc. Am. A.
7   A.H. Harvey, J.S. Gallagher, J.M.H. Levelt-Sengers, "Revised Formulation for the Refractive Index of Water and Steam as a Function of Wavelength, Temperature and Density," J. Phys. Chem. Ref. Data 27(1968)761-774.
8   L. Kou, D. Labrie, P. Chylek, "Refractive indices of water and ice in the 0.65-2.5 mm spectral range," Appl. Opt. 32 (1993)3531-3540.
9   R.A. Innes, J. R. Sambles, "Optical characterisation of gold using surface plasmon- polaritons," J. Physics F 17(1987)277-287.
10 K. Johansen, , H. Arwin, I. Lundström, B. Liedberg, "Imaging surface plasmon resonance sensor based on multiple wavelengths: sensitivity considerations," Rev. Sci. Instrum. 71(2000)3530-3538.
11 K. Kurihara, K. Suzuki, "Theoretical Understanding of an Absorption-Based Surface Plasmon Resonance Sensor Based on Kretchmann's Theory "Anal. Chem. 74, 696-671 (2002).
12 C.M. Herzinger, B. Johs, W.A. McGahan, J.A.Woollam, W. Paulson, "Ellipsometric determination of optical constants for silicon and thermally grown silicon dioxide via a multi-sample, multi-wavelength, multi-angle investigation," J. Appl. Phys. 83 (1998) 3323-3336.
13 B.P. Nelson, A.G. Frutos, J.M. Brockman, R.M. Corn, "Near-infrared surface plasmon resonance measurements of ultrathin films. 1. Angle shift and SPR imaging experiments," Anal. Chem. 71(1999)3928-3934.