Investigation of the Possibility to Use Ge p-i-n Photodiodes in Infrared SPR Sensors

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ABSTRACT

Considered in this work are the possibility and advantages of applying a Ge photodiode to measure the surface plasmon resonance (SPR) in the near infrared range (IR). The investigations were performed using the prototype of IR SPR refractometer that operates with two fixed wavelengths (1310 and 1552 nm) for excitation of surface plasmons in a thin gold film in the Kretschmann optical scheme. The obtained results of experiments enabled us to draw the conclusion that application of the Ge photodiode in the SPR sensor at the wavelength 1.5 µm allows increasing the sensitivity and response magnitude as well as widening the dynamic range of this sensor device.

Keywords: Ge photodiode, near infrared range, surface plasmon resonance.

I. INTRODUCTION

It is known that plasmonics is now the field of extraordinary active investigations [1]. Majority of the available SPR devices is designed using the Kretschmann optical scheme with the fixed wavelength of p-polarized light in the configuration for scanning the angle, which is necessary to visualize the phenomenon of total internal reflection at the boundary “dielectric-studied medium”. In this case, SPR devices can operate with various wavelengths taken, for example, from the very promising IR range [2]. The obvious advantage of SPR-sensors operating in this range is the possibility to study biological objects [3]. Besides, in particular cases, it can be expected increasing the sensitivity of bio-detectors based on the SPR phenomenon when transferring from resonances observed in the visible range to those in the IR range [4, 5]. It is possible owing to the following factors:

1. Majority of bio-molecules possesses specific peaks of absorption in the IR range. Therefore, when carrying out investigations for various wavelengths in this range and juxtaposing the results with the known absorption spectra of bio-molecules, it becomes possible to make selective research of molecules in the studied substances.

2. In the first approximation, the plasmon path length is proportional to the wavelength of light incident onto the prism. According to it, the path length for plasmons excited with the IR light becomes longer, which can provide an additional positive effect on the sensitivity of bio-detectors.

3. To provide a high sorption capability, the gold coatings are prepared to be relatively “thick” (their thickness often exceeds 50 nm) as compared with the effective depth of surface plasmon penetration into the studied substance [6]. It results not only in decreasing the electric field at the surface of this coating but in widening the resonance characteristics of reflection as well as enhancing the intensity of reflected light near the resonance angle, which influences on the SPR-sensor response amplitude and increases the error in determining the position of resonance angle. When using the IR range, the optimum thickness of the gold film can be decreased approximately to 30 nm [7].

The above advantages need to be experimentally checked accordingly to the specific wavelength and chosen photodetector.

It is known that the wavelength 1.5 µm is promising for application in SPR sensors [8], [9]. Operation of the device
at this wavelength provides additional constructive possibilities, for instance, using the optical fibers [10], [11].

To perform studying the SPR features at the wavelength 1.5 µm, we used a Ge fast-response p-i-n photodiode designed at the V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine [12], also we compared it with the serial Ge photodiode, and both were tested for operation at the wavelengths 1310 and 1552 nm.

The aim of this work was to study the possibility to apply the developed photodiode for SPR investigations within the near infrared range as well as advantages of the SPR sensor based on it in comparison with sensors operating in the visible range.

II. MATERIALS AND METHODS

The measurements were performed using the prototype of IR SPR refractometer operating at the fixed wavelength for excitation of surface plasmons in a thin gold film used in the Kretschmann optical scheme (Fig. 1) with angle modulation.

The main constructive optical elements of this scheme were as follows: the source of monochromatic p-polarized light – semiconductor laser 1, connective prism 2 from glass Ф1, which provides total internal reflection, thin gold film 3 of the optimal thickness (37 nm) that was deposited using thermal evaporation in vacuum onto the operation face of connective prism and was carrying the surface plasmons excited by laser radiation. The photodiode 4 was used for measuring the intensity of light reflected from the gold film. That enabled to plot the photometric characteristics (reflection curves). Changing the angle of laser beam incidence onto the gold film from the side of connective prism was provided by simultaneous rotation of the laser source and photodetector. Applied in these measurements were two lasers with different wavelengths 1310 and 1552 nm. The rated optical power of these lasers was the same – 10 mW. The measurements were performed with two diodes, namely: serial Ge p-n diode FD 6G as well as the developed Ge p-i-n diode FDG-2 with an additional silicon filter (Table 1).

The photodetectors chosen for researches were used in the photodiode regime with the constant backward bias equal to 0.13·Umax. For the photodiode FDG-2, this value was equal to 2.6 V, while for FD-6G – 1.3 V. The voltage drop on the measuring resistor connected in series with the photodiode was inputted to ADC module Arduino NANO and then to the computer via the USB port.

| TABLE I: THE ARRANGEMENT OF CHANNELS |
|---------------------------------------|
| Photodiode | Central wavelength, µm | Operation range, µm | Reverse voltage, V | Dark current, µA | Time constant, µs | Sensitivity, µA/lux |
|------------|------------------------|---------------------|------------------|-----------------|-----------------|------------------|
| FDG-2      | 1.5                    | 1.15...1.7          | 20               | 1               | 0.004           | 40               |
| FD-6G      | 1.5                    | 0.4...1.8           | 10               | 13              | 5               | 7                |

III. RESULTS AND DISCUSSION

The measured with the prototype of IR SPR refractometer reflection characteristics inherent to distilled water are shown in Fig. 2. These plots show that both studied photodiodes with p-n and p-i-n structures provide typical narrowing the reflection curves as well as the shift of their minima to the side of lower angles when increasing the wavelength of radiation exciting surface plasmons.

The substitution kinetics for changing the distilled water with the water solution of sodium chloride (9 mg/mL) in the measuring cuvette of refractometer prototype are adduced in Fig. 3 and 4. When using the longer wavelength 1552 nm, instead of 1310 nm, it was observed not only increasing the sensitivity of sensor but decreasing the temperature drift of base line, too.

Fig. 2. Reflection curves measured with the Ge photodetectors FD-6G and FDG-2 for two wavelengths of light exciting surface plasmons: 1310 (a) and 1552 nm (b).

Fig. 3. The substitution kinetics for changing the distilled water with the water solution of sodium chloride (9 mg/mL) in the measuring cuvette of refractometer prototype are adduced.
The summarized data of investigations are adduced in Tables II and III.

### Table II: Measured Parameters of SPR Sensors for Two Wavelengths

| Wavelength, nm | Photodiode | Angle of the SPR curve, mV | Sensor response, mV | Dynamic range, % | Operation range, mV | Drift velocity, mV/min |
|---------------|------------|---------------------------|---------------------|------------------|---------------------|------------------------|
| 1310          | FDG-2      | 25.7                      | 107                 | 626              | 3.938               | -2.1                   |
|               | FD-6G      | 25.7                      | 107                 | 626              | 3.938               | -2.1                   |
| 1552          | FDG-2      | 25.7                      | 107                 | 626              | 3.938               | -2.1                   |
|               | FD-6D      | 25.7                      | 107                 | 626              | 3.938               | -2.1                   |

### Table III: Change in the SPR Sensor Parameters When Transferring from the Wavelength 1310 up to 1552 nm

| Photodiode | Sensor response, times | Operation range, % | Drift velocity, times | Dynamic range, times |
|------------|------------------------|--------------------|-----------------------|----------------------|
| FDG-2      | 2                      | 28                 | 1.4                   | 1.95                 |
| FD-6G      | 2                      | 28                 | 1.4                   | 1.95                 |

In addition, we performed determination of the sensitivity inherent to the SPR sensor equipped with the photodetector FDG-2 to glucose at the wavelength 1310 nm. As objects of investigations, we chose water solutions of glucose with the concentration dependence of the SPR sensor response are shown in Figure 5 as well as parameters of laser operation regimes and the values of SPR resonance angles – in Table IV.

### Table IV: Parameters of Laser and Photodiode Operation Regimes as well as the Values of SPR Resonance Angles

| No | Laser regime | Photodiode regime | Resonance angles, ang. deg. | θSP | Δθ |
|----|--------------|-------------------|-----------------------------|-----|----|
| 1  | 1.015 12.338 | 2.4676            | 0.2239                      | 56  | 0.723                      |
| 2  | 1.060 24.047 | 4.8074            | 0.2239                      | 56  | 0.723                      |
| 3  | 1.127 41.454 | 8.2908            | 0.9016                      | 368 | 0.674                      |
|    | 1.160 50.000 | 10.0000           | 1.1420                      | 500 |                |

The chosen regimes of laser operation were provided by changing the applied voltage \( U_L \) not exceeding the maximum allowed values (see the fourth line in Table IV). Also adduced in this Table are the operation parameters of photodetector FDG-2: reverse current and voltage, as well as the scattered power that was two-fold lower than the maximum allowed one (\( 500 \mu W \)). Changing the power had no essential effect on the value of resonance angle \( \theta_{SP} \) but changed the dynamic range of measuring \( \Delta \theta \) practically two-fold. When using the power 8.3 mW, the sensitivity was 1.7 times higher than that for the power 2.5 mW due to the steeper left slope of the resonance curve. Therefore, measurements were performed just in this regime. The calculated sensitivity for the chosen regime of measurements was 72 mV·mg\(^{-1}\)·mL, while for the minimum power of laser radiation it was 41 mV·mg\(^{-1}\)·mL. But the deficiency of operation under this relatively high power was a temperature effect on the analyte, which caused some drift of the base line.
The measured kinetic made it possible to determine the magnitude of hash (3 mV) as well as the lower limit of detecting the concentration of glucose in water (0.05 mg/mL).

It was experimentally ascertained that the increase in laser radiation power from 2.5 up to 8.3 mW enhances both the sensitivity to glucose by 1.7 times (from 41 mV·mg⁻¹·mL to 72 mV·mg⁻¹·mL) and dynamic range of measurements at the left slope of resonance curve by 1.45 times (from 0.56 up to 0.81 ang. deg.). The lower limit of detecting the concentration of glucose in water is 0.05 mg/mL for the power of laser radiation 8.3 mW, and the magnitude of hash (in kinetic curve) is only 3 mV. At high laser radiation powers, there observed was an essential temperature effect on the analyte, which caused the temperature drift of the base line (1.8 mV/min). Therefore, when performing specific investigations, it is always necessary to optimize the regimes of investigations, in particular, the voltage applied to the laser, the bias voltage on photodiode and resistance of the measuring resistor to minimize the temperature effect and provide the maximum sensitivity and sufficient dynamic range for measurements with this SPR sensor.

IV. CONCLUSION

Thus, the obtained results enable to draw the following conclusions about advantages of using the wavelength from the infrared range and application of the designed photodetector FDG-2:

1. Diminishing expenses on gold – for the wavelengths of the visible spectral range (e.g., 650 nm) the optimum thickness of the gold film is 49 nm, while for the wavelength 1310 nm it is 37 nm, and for 1552 nm – only 34 nm.
2. The higher sensitivity, owing to a higher steepness of the SPR reflection curve slope than that for the wavelengths from the visible range.
3. The wider dynamic range, due to a new developed photodetector FDG-2. For instance, when transferring from the wavelength 1310 to 1552 nm the dynamic range increases by 15% larger than for the serial photodetector FD-6G.
4. The higher sensor response, which is provided by using the photodetector FDG-2. E.g., when transferring from the wavelength 1310 to 1552 nm, the SPR sensor response increases by 80% higher than in the case of commercial photodetector FD-6G. Besides, using the photodetector FDG-2 provides a higher noise immunity.

REFERENCES

[1] M.L. Dmitruk, S.Z. Malinich, “Surface plasmon resonances and their manifestation in optical properties of noble metal nanostructures,” Ukrainski fizichnyi zhurnal, vol. 9(1), pp. 3-37, 2014 (in Ukrainian).
[2] S. Franzen, M. Losego, M. Kang, E. Sachet, J.-P. Maria, “Infrared Surface Plasmon Resonance,” Introduction to Plasmonics, pp. 143-167, 2015, doi:10.1201/18229-7.
[3] R. Ziblat, V. Lirtsman, D. Davidov, B. Aroeti, “Infrared Surface Plasmon Resonance: A Novel Tool for Real Time Sensing of Variations in Living Cells,” Biophysical Journal, vol. 90, pp. 2592-2599, April 2006.
[4] M. Golosovsky, V. Lirtsman, V. Yashunsky, D. Davidov, B. Aroeti, “Midinfrared surface-plasmon resonance—A novel biophysical tool for studying living cell,” Journal of Applied Physics, vol. 105, pp. 102036, 2009.
[5] V. Lirtsman, M. Golosovsky, and D. Davidov, “Infrared surface plasmon resonance technique for biological studies,” Journal of Applied Physics, vol. 103, pp. 014702, 2008.

[6] Zh. Zhe, L. Qan, Qi Zhimei “Study of Au-Ag alloy film based surface plasmon resonance sensor with wavelength interrogation in the near infrared region.” 2012.

[7] J. Guske, J. Brown, A. Welsh, S. Franzen, “Infrared surface plasmon resonance of AZO-Ag-AZO sandwich thin films,” OPTICS EXPRESS, vol. 20(21), pp. 23215-23226, October 2012.

[8] Yi Xu, Lin Wu, Kee Ang Lay, “MoS2-based Highly Sensitive Near-infrared Surface Plasmon Resonance Refractive Index Sensor,” IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, vol. 25(2), pp. 4600307, March/April 2019.

[9] S. Patskovsky, A. Kabashin, M. Meunier, J. Luong, “Near-infrared surface plasmon resonance sensing on a silicon platform,” Sensors and Actuators B, vol. 97, pp. 409 –414, 2004.

[10] H. Rahul, A. Sanjida, M. Rahman, “Design of a surface plasmon resonance refractive index sensor with high sensitivity,” Optical Engineering, vol. 56(8), pp. 087101, 2017.

[11] Ch. Liu, L. Yang, X. Lu, Q. Liu, F. Wang, J. Lv, T Sun, H Mu, P. Chu “Mid-infrared surface plasmon resonance sensor based on photonic crystal fibers,” OPTICS EXPRESS, vol. 25(13), pp. 14227-14237, June, 2017.

[12] V.P. Maslov, A.V. Sukach, V.V. Tetyorkin, et al. “Particularities in manufacturing, electrical and photoelectrical properties of diffusion Ge p-i-n photo diodes,” Optoelektronika i poluprovodnikovaya tekhnika, vol. 53, pp. 188 – 198, 2018 (in Ukrainian).

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