Arrays of doped and un-doped semiconductors for sensor applications

Thierry Taliercio*, Vilianne Ntsame Guilengui, and Eric Tournié

Institut d’Electronique du Sud, CNRS-INSIS-UMR 5214, Université Montpellier 2,
34095 MONTPELLIER cedex 05 (France)
*corresponding author, E-mail: thierry.taliercio@univ-montp2.fr

Abstract

This numerical investigation proposes to use a lamellar grating of doped semiconductors as the active region of a nanoplasmonic biosensing device. Working with highly doped semiconductors instead of a metal allows controlling the value of the plasma frequency. It is possible to reach the plasma frequency close to the range of detection of the sensor to improve its sensitivity. A red-shift of the plasmonic resonance of 10.2 nm for a 10^{-2} refractive index unit (RIU) increase can be achieved.

1. Introduction

Surface Plasmon Resonance (SPR) [1] sensing is a leading technology for biosensing [2]. The principle is to detect small changes in the optical refractive index using the high sensitivity of the frequency of SPR. Until now, the SPR biosensor technology is mainly based on the use of metal on glass substrate which is not well suited for integration and limited to the visible or near infrared ranges. Midinfrared (MIR) surface plasmon resonance has been recently investigated and showed a real potential [3] although based only on surface electromagnetic waves propagating at the metal-dielectric interface. To work at MIR wavelengths ZnS prisms replace glass prisms.

Nanoplasmonic offers the possibility of high integration without degrading the sensitivity of the device. Several works exploit the unique optical properties of nanoplasmonic structures on Si substrates, allowing proposing new architectures for biosensing [4, 5]. These new designs are based on gold or silver for the sensitive layer. Unfortunately both metals have drawbacks: Au is forbidden in microelectronic environment because it generate deep level in the band gap [6,7], and Ag is highly reactive in aqueous media. It is thus interesting to investigate new materials to bypass these limitations while maintaining high sensitivity. In the present work we propose to use a lamellar grating of doped semiconductors as active region for biosensing applications. The period of the grating is chosen to be largely sub-wavelength compared to the plasma wavelength of the doped semiconductor and of the wavelength of detection. This allows exciting mainly localized surface plasmon (LSP) modes propagating vertically into the slits [8].

2. The metamaterial as sensing media

We used two approaches to model the optical properties of the lamellar structure: i) an analytical model recently developed [9] which allows to save considerable time to roughly depict the adapted structure, ii) a finite difference time domain (FDTD) software [10] to valid the selected structure. Indeed, the analytic model does not take into account the surface plasmon polaritons (SPP) propagating at the surface of the lamellar structure while in some cases it is necessary to consider them. Figure 1 represents a scheme of the structure. It consists of a highly anisotropic plasmonic media (yellow).

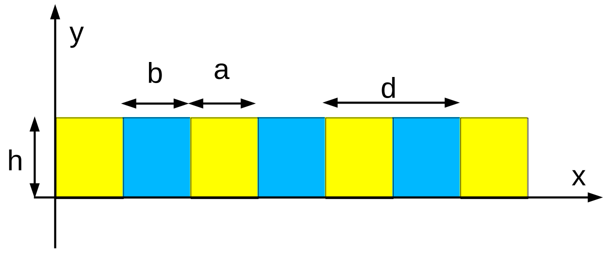

Figure 1: Schema of the lamellar grating of the doped semiconductors (yellow) and the dielectric or liquid (blue). The thickness of the lamellar grating is h, the period is d. a and b are respectively the width of the doped semiconductor and of the studied liquid.

The structure consists in a grating with a 520 nm period and a thickness of 1 µm. The widths of the slit and of the doped semiconductor are equal to 260 nm. The dielectric or liquid to analysis will be sitting into the slit. The wavelength corresponding to the plasma frequency of the semiconductor is chosen close to 6 µm which is a reasonable value to reach [11]. In these conditions, we have recently demonstrated that the lamellar grating can be viewed as an ionic crystal characterized by an oscillator wavelength λ_r under a transvers magnetic (TM) field and as a metal characterized by a pseudo-volume plasmon wavelength λ_t under a transverse electric (TE) field [9]. We look at the transmission of this metamaterial and try to evaluate its sensitivity to index variation of the dielectric material. It is also possible to investigate the metamaterial in reflectance which gives us equivalent sensitivity to the index variation. We focus ourselves on the experimental configuration proposed in ref. 5. They proposed a setup based on orthogonal linearly light polarization of a laser beam. This particular optical configuration leads to a sensitivity improvement and noise reduction.

3. Results and discussion

Before investigating a particular structure we compare both models used in this study. Figure 2 shows calculated transmittance of the previously-defined lamellar grating using the analytic model and the FDTD method. We can see a good agreement between both methods. The differences are due to the approximation of the analytic model that supposes that we are in the long wavelength limit. However, the essential results are similar: resonances, amplitudes… The real advantage of the analytic model is saving much time (several orders of magnitude) that allows to quickly identify the best structure. However, because of the imperfection of the analytical model, it is necessary to use FDTD simulation to refine the design of the structure and to obtain accurate value of the sensitivity. In the following of the article we just present FDTD results except when it will be specified.

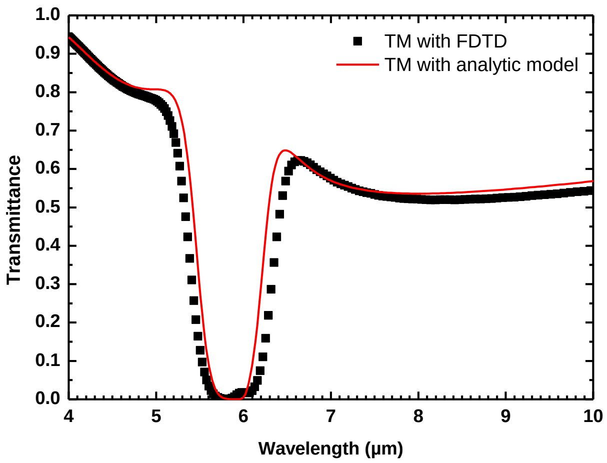

Figure 2: Calculated transmittance in normal incidence of the lamellar grating with a = b = 260 nm, d = 520 nm, h = 1 μm, using the FDTD method (dark symbols) or analytic model (red curve). The index of the dielectric part is taken equal to 1.5. The polarization is TM.

We now study the lamellar structure to identify the more sensitive wavelength range. Figure 3 shows the calculated transmittance in normal incidence of the lamellar grating with a = b = 260 nm, d = 520 nm, h = 1 μm, in TM polarization (black squares and red curve) or in TE polarization (green squares and blue curve). The vertical black arrows show respectively the wavelength associated to the plasma wavelength of the doped semiconductor λ_p, of λ_t and of λ_r. To demonstrate the sensing concept, the index of the studied material is taken equal to 1.5 (solid symbols) or 1.51 (solid lines). We can see that λ_t is associated to the small shoulder at 5.95 μm TM polarization (dark symbols). In the same time, λ_r corresponds exactly to the pseudo volume plasma wavelength in TE polarization (green symbol). Both wavelengths are degenerate due to identical value of a and b (see ref. 9 for more details).

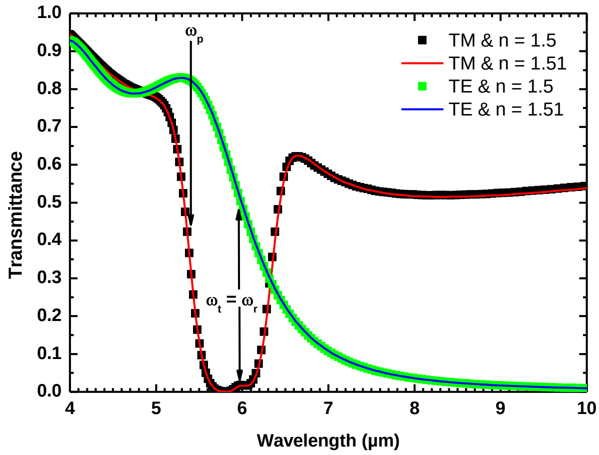

Figure 3: Calculated transmittance in normal incidence of the lamellar grating with a = b = 260 nm, d = 520 nm, h = 1 μm, in TM polarization (black symbols and red curve) or in TE polarization (green symbols and blue curve). The index of the liquid is taken equal to 1.5 (symbols) or 1.51 (lines). Vertical arrows show the frequency associated to λ_p, to λ_t and λ_r.

The modulation of the transmitted signal at wavelengths larger than λ_p is due to interference effects in the metamaterial layer which selects some LSP modes. To identify the best working area it is interesting to draw the transmittance modification, ΔT, for an index variation of the dielectric media from 1.50 to 1.51, that is Δn = 0.01. Results are represented in figure 4. ΔT are drawn for TM (dark) and TE polarization (red). The blue curve corresponds to the summation of the absolute value of ΔT of both polarizations.

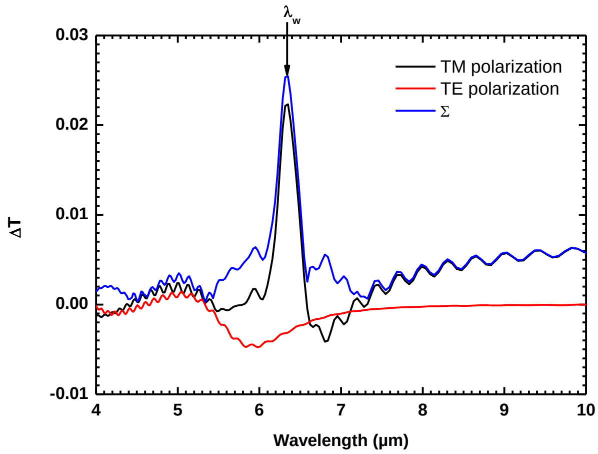

Figure 4: Transmission variation ΔT for an index modification of Δn = 0.01, under TM polarization (dark curve) or TE polarization (red curve). The summation of the absolute value of ΔT for both polarizations is the

curve Σ (blue).

The small amplitude interferences observed for each spectrum are due to numerical artifacts arising from the step size in time and in space of FDTD techniques. They have no physical meaning. The zone of interest is obtained for the maximum amplitude of Σ. Indeed, this corresponds to the maximum sensitivity of the metamaterial. We obtain an amplitude modulation of 2.5 % for a wavelength of 6.32 µm corresponding to λ_W. This is exactly the spectral range where spectra in both polarizations cross (see Fig. 4).

Figure 5 demonstrates the impact of the index variation on the calculated transmittance spectra in TE and TM polarization. Figure 5 corresponds to a zoom of the Figure 3 for a wavelength around λ_W. The red arrow shows the red-shift of the LSP resonance, 10.2 nm, due to a 10^{-2} refractive index unit (RIU) modification. This corresponds to a sensitivity of 1.02 10^3 nm/RIU. This is comparable to values obtained with conventional SPR biosensor [3] in the same range of wavelength, but smaller than which is achieved in visible range [12]. Biosensor based on localized surface plasmon resonator (Pillar [13], Split Ring Resonator [14] in the near infrared range) which are comparable to structures of this study, gave smaller values of sensitivity.

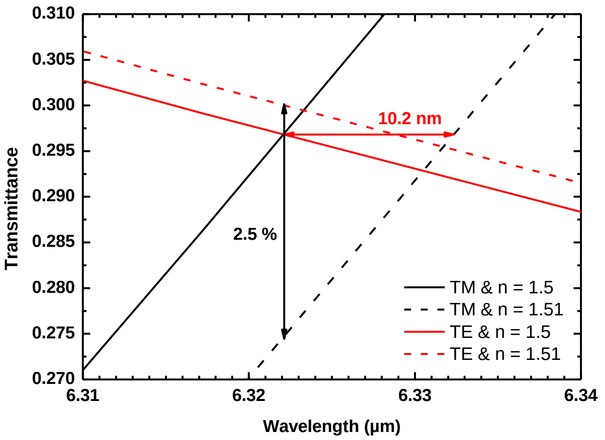

Figure 5: Zoom of the intersection between both spectra in TM and TE polarization of the Fig.2. The dark and red arrows are respectively the amplitude modification between both polarization and the red-shift of the spectra in TM polarization due to index variation.

The nanoplasmonic sensors are generally based on the measurement of the wavelength of the localized plasmons. It is also possible to propose intensity plasmonic sensing. In this configuration the wavelength is fixed (for example at λ_W) and the amplitude variation is measured for both polarizations by a detector behind the metamaterial [5]. In our case, an index variation of $\Delta n = 0.01$ at a wavelength of λ_W provokes an amplitude modification of 2.5 %. This is in the same order of magnitude than in ref. 5.

It is necessary to integrate this metamaterial into a complete device and evaluate its sensitivity in the MIR range.

4. Device proposition

We propose to study a device equivalent to that adopted in ref. 5. Figure 6 represents a scheme of the structure. It consists on a highly anisotropic plasmonic media (yellow) deposited onto a MIR detector (grey). A linearly polarized light is injected backward the y direction. The light to be detected should be a laser polarized along x (TM polarized), or z axes (TE polarized). The MIR detector should be a quantum well infrared photodetector (QWIP) [15], a quantum dot infrared photodetector (QDIP) [16] or a superlattice infrared photodetector (SLIP) [17].

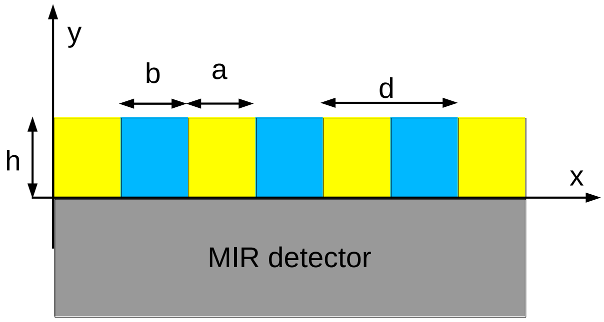

Figure 6: Schema of nanoplasmonic sensing. The lamellar grating of doped semiconductors (yellow) deposited onto a MIR detector (grey). The blue parts correspond to the liquid that will be analyzed.

Simulations of the complete structure are shown in Figure 8. Spectra are somewhat modified by the presence of the detector layer behind the metamaterial. This is mainly due to the refractive index difference between both faces of the metamaterial ($n_{det} = 3.6$). The resonance associated to LSP is not deeply modified. As we can see we conserve a good agreement between the FDTD simulation and the analytic model (red dash line) around 6 µm.

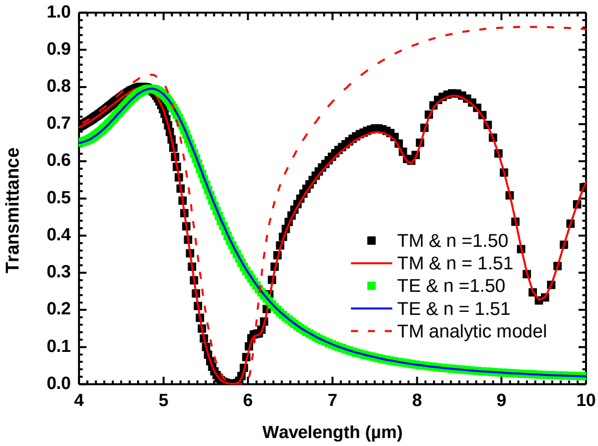

Figure 7: Calculated transmittance in normal incidence of the lamellar grating deposited on a detector modeled by a dielectric with an index of refraction $n_{det} = 3.6$, in TE polarization (dark curves) or in TM polarization (red curves). The index of the liquid is taken equal to 1.5 (solid lines) or 1.51 (dashed lines).

On the other hand, at longer wavelengths we can see two resonances at 8 µm and 9.3 µm associated to SPP propagating at both interfaces of the metamaterial. We do not detail much more this point and focus ourselves on the LSP resonance. The LSP resonance modifies a little bit their shape and wavelength as compared to the lamellar grating alone. This provokes a small blue-shift until 6.24 µm. This demonstrates that the LSP is essentially sensitive to what is happening into the metamaterial.

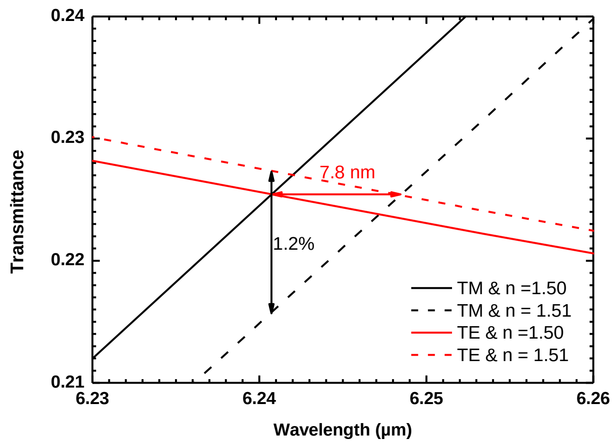

Figure 8: Zoom of the intersection between both spectra in TM and TE polarization of the Fig.6. The dark and red arrows are respectively the amplitude modification between both polarizations and the red-shift of the spectra in TM polarization due to index variation.

Figure 8 shows a zoom of the transmittance spectra in TM (dark) and TE (red) polarizations for different indexes of liquid (n = 1.50 for solid line curves and n = 1.51 for dashed line curves). The sensitivity of the device is slightly degraded. We obtain a sensitivity of 7.8 10^{-2} nm/RIU.

The sensitivity of our devices should be comparable to this recently proposed [5]. To increase the sensitivity of the metamaterial we can adjust the size of the slit, a, compare to the ribbon width, b. Indeed, decreasing the ratio a/b increases the sensitivity because the reflectance spectra for both polarization cross in range of very high reflectance signal variation. Of course it is necessary to keep a period of the array smaller than λ_p and larger than 200 nm, i) first because propagative modes appear in the range of wavelength of interest reducing the sensitivity of the structure, ii) second because the analytic model fails due, the homogenization is not possible at all, iii) and third because of the technological limit (limit of resolution, large aspect ratio h/a). It is also quite easy to extend the validity of our metamaterial to longer wavelength by modifying the doping level [11] of the semiconductor or the geometry of the system [9].

5. Conclusions

Lamellar gratings of doped semiconductors are very interesting for the fabrication of integrated biosensors operating in the IR wavelength range. We have demonstrated that a sensitivity of 10^{-3} nm/RIU can be reached. The analytical model has allowed us to easily identify the good structure and using the FDTD simulation we have obtained an accurate design of the structure and of the expected performance. Experimental validation of this concept in the IR range is now needed. The use of doped semiconductors allows easy integration into silicon technology while maintaining high sensitivity. By simply adjusting the geometry or the doping level it is possible to control efficiently the resonance position of the LSP. This allows finely defining the kind of biological material to be detected to be much more selective. It is also possible to extend the use of doped semiconductors to experimental techniques such as surface enhanced infrared absorption spectroscopy (SEIRA) by adapting the geometry of the metamaterial.

References

[1] H. Reather, "Surface plasmons on smooth and Rough surfaces and on gratings," Springer-Verlag Tracts Mod. Phys. **111** (Spring-Verlag, 1988).

[2] [B. Liedberg, C. Nylander, and I. Lundström, "Biosensing with surface plasmon resonance-how it all started," Biosens. Bioelectron. **10**(8), i-ix (1995).

[3] M. Golosovsky, V. Lirtsman, V. Yashunsky, D. Davidov, and B. Aroeti, "Midinfrared surface-plasmon resonance: A novel biophysical tool for studying living cells," Journal Appl. Phys. **105**, 102036, 2009.

[4] Y. Wang, X. Su, Y. Zhu, Q. Wang, D. Zhu, J. Zhao, S. Chen, W. Huang, and S. Wu, "Photocurrent in Ag-Si photodiodes modulated by plasmonic nanopatterns," Appl. Phys. Lett. **95**, 241106, 2009.

[5] L. Guyot, A-P Blanchard-Dionne, S. Patskovsky, and M. Meunier, "Integrated silicon-based nanoplasmonic sensor," Optics Exp. **19**, 9962, 2011.

[6] J. D. Struthers, J. Appl. Phys. **27**, 1560, 1956.

[7] H. Feichtinger, In "Electronic Structure and Properties of Semiconductors," W. Schröter, Volume Ed., Materials Science and Technology, VCH: Weinheim, Vol. **4**, pp 143-195, 1991.

[8] J. A. Porto, F. J. Garcia-Vidal, and J. B. Pendry, "Transmission Resonances on metallic gratings with very narrow slits," Phys. Rev. Lett. **83**, 2845, 1999.

[9] J. Léon and T. Taliercio, "Large tunable photonic band gaps in nanostructured doped semiconductors," Phys. Rev B **82**, 195301, 2010.

[10] FDTD SOLUTIONS 8.0, Lumercial Solution Inc., Canada.

[11] Y.B. Li, R. A. Stradling, T. Knight, J. R. Birch, R. H. Thomas, C. C. Philips and I. T. Ferguson, "Infrared reflection and transmission of undoped and Si-doped InAs grown on GaAs by molecular beam epitaxy," Semicond. Sci. Technol. **8**, 101, 1993.

[12] J. Homola, S. S. Yee and G. Gauglitz, "Surface plasmon resonance sensors: review," Sensor and Actuators B **54**, 3, 1999.

[13] C.-C. Liang, M.-Y. Liao, W.-Y. Chen, T.-C. Cheng, W.-H. Chang, and C.-H. Lin, "Plasmonic metallic nanostructures by direct nanoimprinting of gold nanoparticles," Optics Express **19**, 4768, 2011.
[14] Y.T. Chang, Y.-C. Lai, C.-T. Li, C.-K. Chen and T.-J. Yen, "A multi-functional plasmonic biosensor," Optics Express **18**, 9561, 2010.
[15] J. Y. Andersson and L. Lundqvist, "Near-unity quantum efficiency of AlGaAs/GaAs quantum well infrared detectors using a waveguide with a doubly periodic grating coupler", Appl. Phys. Lett **59**, 857, 1991.
[16] K. W. Berryman, S. A. Lyon, and M. Segev, "Mid-infrared photoconductivity in self-organized InAs quantum dots," Appl. Phys. Lett. **70**, 1861, 1997.
[17] J. B. Rodriguez, C. Cervera, and P. Christol, "A type-II superlattice period with a modified InAs to GaSb thickness ratio for midwavelength infrared photodiode performance improvement," Appl. Phys. Lett. **97**, 251113, 2010.