**Nanostructured arrays of doped semiconductors for IR nanophotonics**

**Thierry TALIERCIO**, Vilianne N'TSAME GULENGUI
*Institut d'Electronique du Sud, CNRS-INSIS-UMR 5214, Université Montpellier 2, 34095 MONTPELLIER cedex 05 (France)*

Jérôme LEON
*Laboratoire Charles Coulomb, CNRS-UM2 UMR 5221, Département Physique Théorique, CC 070 Université Montpellier 2, 34095 MONTPELLIER cedex 05 (France)*

Thierry.taliercio@univ-montp2.fr

Recent developments of plasmonic have opened new prospects in the control of light-matter interactions. The surface plasmons (SP), at the origin of this new topic, result from the coupling of the electromagnetic wave with the collective oscillation of the electrons supported by the metal/dielectric interface. SP have unique physical properties based on enhanced nanolocalized optical fields. Engineering of surface plasmons using nanostructured materials (nanoparticle, nanostructured film, fishnet etc) made it possible to develop a new range of materials with remarkable properties like, e.g., extraordinary optical transmission (EOT) [1]. A lot of theoretical investigations have been made in the case of one dimensional periodic arrays of slits [2,3]. All these studies focus on the low energy part of the plasmon polariton dispersion, that is, below the plasma frequency. In a recent work [4], we have proposed a model which describes the optical properties of an infinitely periodical nanostructure in a large range of frequencies around the plasma frequency $\omega_p$. The elementary period of the structure, quite similar to a slit, is composed of two layers: a metal, or doped semiconductor, and a dielectric or un-doped semiconductor, considered in its dielectric range (Figure 1). The index of the periodic structure is defined as (1):

$$n^2(z,\omega)=\begin{cases} \varepsilon_1 \quad for \quad z\in[-b,0] \\ \varepsilon\left[1-\dfrac{1}{\omega(\omega+i\gamma)}\right] \quad for \quad z\in[0,a] \end{cases} \quad (1)$$

where a Drude dielectric function is used to model the behavior of the doped semiconductor. In this work all frequencies are normalized to the plasma frequency $\omega_p$, the wave numbers to $k_p = \omega_p /c$, the lengths to $k_p^{-1}$ (including spatial variables), and time to $\omega_p^{-1}$. In the range of validity of the long wavelength limit, that is, typically a and b < 0.1 $\lambda_p$, we prove that under transverse magnetic wave (TM) irradiation, the structure can be modeled by means of the following single effective dielectric function of a ionic-crystal type

$$\varepsilon_{eff}=\tilde{\varepsilon}\frac{\omega(\omega+i\gamma)-1}{\omega(\omega+i\gamma)-\omega_r} \qquad (2)$$
$$where \quad \tilde{\varepsilon}=\frac{(a+b)\varepsilon_1\varepsilon}{a\varepsilon_1+b\varepsilon}, \quad \omega_r^2=\frac{b\varepsilon}{a\varepsilon_1+b\varepsilon}$$

where $\gamma$ is the damping due to losses. In the case of transverse electric (TE) illumination the nanostructure behaves like a metal but with a new plasma frequency, $\omega_t$, which depend on a, b, $\varepsilon$ and $\varepsilon_1$, see ref. [4] for more details.

This work presents original optical properties of the nanostructure for different geometrical or physical parameters. Indeed, by modifying the thickness of both layers and the plasma frequency through electrons density, it is possible to highlight a strong coupling between the incident light and the free electrons of the doped semiconductor. This strong coupling results in a broad photonic band gap ($\Delta\omega = 1-\omega_t$) near the plasma frequency. Figures 2 and 3 show respectively the reflectance in TE and TM polarization in normal incidence for different values of a and b. The sizes vary from 0.1 to 0.3 µm. $\omega_p$ is defined at a value of 54 THz (corresponding to 6 µm) and $\gamma = 0.03\ \omega_p$. These values are realistic in the case of a layer of InAs doped by silicon atoms at $10^{20}$ $cm^{-3}$. We can see on figure 3 that increasing the ratio between a and b increases considerably the stop band since $\Delta\omega$ (green line) reaches an incredible value of 55 % of $\omega_p$. In the same time, figure 2 shows an increase of $\omega_t$ which approaches $\omega_p$. Both behavior are awaited. Indeed a reduction of b versus a corresponds to an increase of the metallic part with respect to the dielectric one. In the extreme case, that is b = 0 µm, pure metallic regime is reached. In this case the plasma frequency just depends of the electron density ($\omega_t = \omega_p$) and $\omega_r$ reaches 0, we are dealing with a free electron gas. On the contrary, if a/b decreases, $\omega_t$ and $\omega_r$ tend respectively towards 0 and $\omega_p$. In the same time $\Delta\omega$ (red line on figure 3) decreases denoting a reduction of the light-matter coupling, that is, the equivalent "oscillator strength". For a ~ 0 µm, the nanostructure gives an optical response similar to that of a dielectric containing oscillators of frequency $\omega_p$.

The interesting aspect of this simple nanostructure is the possibility offered to control the light matter coupling just by adjusting the geometry of the nanostructure or its electrons density. We obtain a metamaterial equivalent to an ensemble of oscillators of which we can control the optical properties, that is, oscillator strength, frequency, broadening, etc. The polaritonic nature of the surface plasmon is at the origin of this specific behavior.

**References**
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[2] J.A. Porto, F.J. Garcia-Vidal, and J.B. Pendry, Phys. Rev. Lett. **83** (1999) 2 845.
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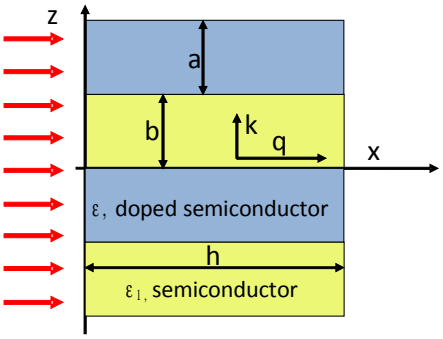
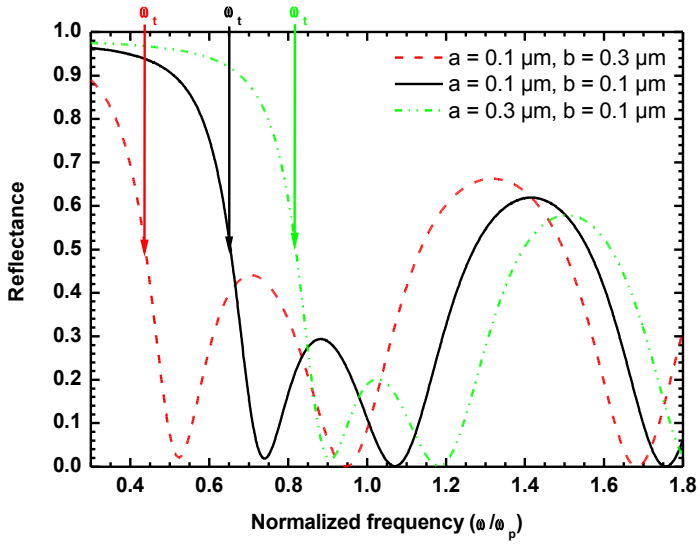
**Figure 1:**



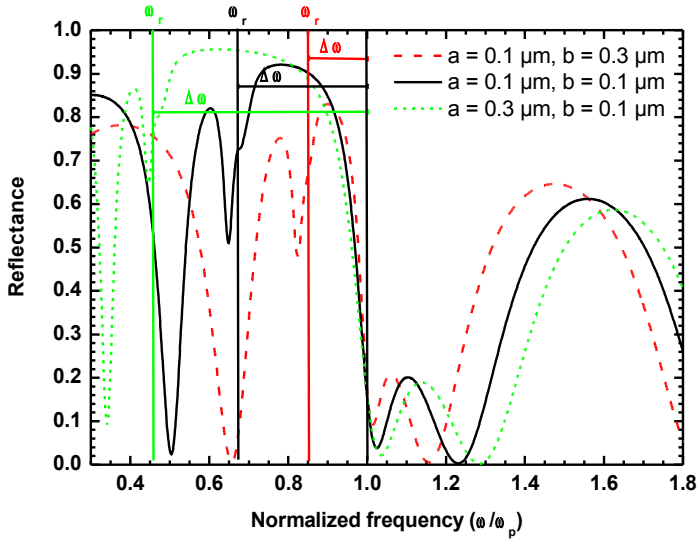

Caption: Scheme of the nanostructure, infinitely periodic in direction z and infinite in direction y.

**Figure 2:**




*Caption: Calculated reflectance spectra in normal incidence and TE polarization for different size of doped (a) and undoped (b) semiconductor layers. The characteristic plasma frequency ($w_t$) of the different layers are indicated by the vertical arrows.*

**Figure 3:**




*Caption: Calculated reflectance spectra in normal incidence and TM polarization for different size of doped (a) and undoped (b) semiconductor layers. The characteristic frequency ($\omega_t$) and stop band ($\Delta\omega$) of the different layers are respectively indicated by the vertical and horizontal barres.*