Terahertz plasmonics with semiconductor surfaces and antennas

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***Abstract*— Semiconductors have a Drude-like behavior at terahertz (THz) frequencies similar to metals at optical frequencies. Narrow band gap semiconductors have a dielectric constant with a negative real component and a relatively small imaginary component. This permittivity is characteristic of noble metals in the visible. Therefore, similar to metals at optical frequencies, semiconductors sustain surface plasmon polaritons (SPPs) or collective oscillations of free charge carriers at the interface with a dielectric. We present here a description of the characteristic lengths of SPPs on semiconductor surfaces. We also consider localized surface plasmon polaritons (LSPPs) in small semiconductor particles or plasmonic antennas. These LSPPs lead to resonances that can be tuned by varying the carrier concentration.**

***Index Terms*— Surface plasmon polaritons, Localized surface plasmon resonances, Terahertz, Semiconductors.**

I. Introduction

Methods for confining and guiding electromagnetic radiation into the smallest possible volume have been pursued since the first studies of electromagnetism. A very compact approach for guiding electromagnetic waves is to couple them to the collective oscillation of free electrons at the interface between a conductor and a dielectric, forming so-called surface plasmon polaritons (SPPs) [1]. SPPs propagate along this interface, decaying evanescently into both media. If this interface is not spatially extended but instead the conductor forms a particle, SPPs generate resonances known as localized surface plasmon polaritons (LSPPs) or particle plasmons [3]. These resonances can lead to very large local field enhancements in the vicinity of the particles.

Most of the work on plasmonics has focused on optical frequencies. The reason for this focus lies on the strength of coupling between the radiation and the free electrons, which is determined by the permittivity of the conductor. This coupling is optimum, and the confinement of SPPs to the surface maximum, when the absolute value of the permittivity is small, i.e., at optical frequencies for noble metals such as gold and silver. Metals at THz frequencies have very large permittivities, which leads to a weak confinement of SPPs to the surface.

Two major approaches can be taken to increase the confinement of THz SPPs: Either electromagnetic waves bound to metal surfaces that mimic SPPs (referred to as spoof SPPs) are obtained by perforating a flat metal surface periodically with holes and grooves [4]-[8]; or SPPs are excited in semiconductor surfaces instead of metals [9]. In this manuscript we focus on the second approach, namely, on the excitation of strongly confined SPPs on semiconductors. As we will see next, semiconductors have a much lower permittivity that metals at THz frequencies, mainly due to their much lower free carrier concentration. This permittivity allows for a strong coupling of the THz field to free charges at the interface and a good confinement of the surface mode to the interface. Another crucial difference between metals and semiconductors is that semiconductors are much more versatile materials since their free carrier concentration, hence the properties of SPPs, are remarkably tunable. Consequently semiconductors are promising candidates for active plasmonic devices at THz frequencies.

In this article we describe the characteristics lengths at THz frequencies of surface plasmon polaritons on extended, flat interfaces and compare these lengths for gold and InSb surfaces. We also discuss LSPPs in InSb particles and the tunability of the localized resonance by varying the carrier concentration.

II. Characteristic Lengths of Surface Plasmon Polaritons

The characteristic lengths of surface plasmon polaritons, namely the the SPPs wavelength ($\lambda_{\rm spp}$), propagation length ($L_{\rm spp}$) and confinement to the surface ($L_{\rm z}$) can be derived from the SPPs complex wavenumber, which is given by

$$k_{\rm spp} = \frac{\omega}{c}\sqrt{\frac{\epsilon_{\rm c}\epsilon_{\rm d}}{\epsilon_{\rm c}+\epsilon_{\rm d}}}\ , \tag{1}$$

where ω is the angular frequecy, c the speed of light in vacuum, and $\epsilon_{\rm c}$ and $\epsilon_{\rm d}$ are the relative permittivities of the conductor and the dielectric respectively. For simplicity, we will consider vacuum as the dielectric with $\epsilon_{\rm d} = 1$. The relative permittivity of the conductor is a complex quantity, $\epsilon_{\rm c} = \Re(\epsilon_{\rm c}) + \imath\Im(\epsilon_{\rm c})$, which can be approximated by a Drude model for free charge carriers [10]

$$\epsilon_{\rm c} = \epsilon_\infty\left(1 - \frac{\omega_{\rm p}^2}{\omega^2 + \imath\gamma\omega}\right)\ , \tag{2}$$

where ϵ_∞ is the high-frequency permittivity, γ is the average collision rate of the charge carriers and $\omega_{\rm p} = \sqrt{Ne^2/\epsilon_\infty\epsilon_0 m^*}$ is the plasma frequency. The semiconductor charge carrier

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concentration is given by N, while e is the fundamental charge, ϵ_0 the vacuum permittivity and m^* the charge effective mass.

Figure 1(a) displays $-\Re(\epsilon_c)$ and $\Im(\epsilon_c)$ for gold as a function of frequency. The free carrier concentration of gold is $N \simeq 6 \times 10^{22}$ cm^{-3} and the plasma frequency $\omega_{\rm p}/2\pi \simeq 2 \times 10^3$ THz [11]. At high frequencies, i.e., in the visible, the real and imaginary components of the permittivity of gold of have a small value. As the frequency decreases the permittivity increases due to the ω^{-2} dependence in Eq. 2. At THz frequencies the permittivity has large absolute values. In contrast to metals, the permittivity of some semiconductors can be low at THz frequencies. Figure 1(b) displays the permittivity of intrinsic InSb at room temperature at THz frequencies. InSb is a semiconductor with a small energy gap of 0.17 eV and a very large electronic mobility. The effective electron mass is $0.013m_0$. The density of thermally excited carriers at room temperature is $N \simeq 2 \times 10^{16}$ cm^{-3} and the electronic mobility $\mu = 7.7$ m^2 V^{-1} s^{-1}. At this temperature the corresponding plasma frequency lies around 3 THz. The hole mobility is almost two orders of magnitude smaller than the electron mobility, thus making the metallic character of InSb with the same hole and electron density (undoped) be mainly determined by the electrons. The much lower values of this permittivity compared to gold is caused by the lower $\omega_{\rm p}$, due to the much lower carrier concentration of free charge carriers. This carrier concentration can be easily controlled in semiconductors by adding dopants, or by thermal or optical excitation of carriers from the valence to the conduction band [12]-[15].

The dispersion relation of SPPs is defined by the frequency dependence of the real component of the complex wave number $\Re(k_{\rm spp})$. From this dispersion relation, the SPP wavelength is given by

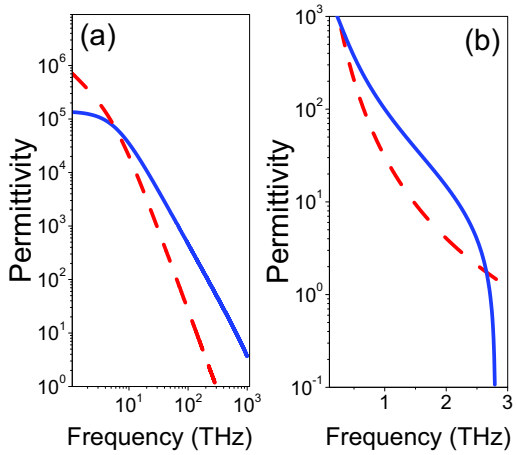

Fig. 1. Complex permittivity $\epsilon_{\rm c}$ of gold (a) and InSb (b) as a function of frequency. The solid lines represent $-\Re(\epsilon_{\rm c})$, while the dashed line is $\Im(\epsilon_{\rm c})$. Note that (a) spans from THz to visible frequencies, while (b) is plotted only at THz frequencies.

$$\lambda_{\rm spp} = \frac{2\pi}{\Re(k_{\rm spp})} \ . \tag{3}$$

The imaginary component of the SPP wave number defines its propagation length along the surface

$$L_{\rm spp} = \frac{1}{2\Im(k_{\rm spp})} \ . \tag{4}$$

The decay length of the mode from the interface into the conductor or the air is defined from the complex wavenumber along the direction perpendicular to the surface

$$L_{\rm z_j} = \frac{1}{2\Re(k_{\rm z_j})} \tag{5}$$

where j=1 corresponds to air and j=2 to the conductor and

$$k_{\rm z_j} = \sqrt{k_{\rm spp}^2 - \epsilon_{\rm j}\omega^2/c^2} \tag{6}$$

Table I displays the characteristic lengths of SPPs at 1 THz for an Au-air and InSb-air interface. For completeness we also list the values of carrier concentration, the plasma frequency and the complex permittivity of Au and InSb. The large carrier concentration of gold leads to very large values of the permittivity (both real and imaginary components). These values of the permittivity give rise to a large impedance mismatch at the surface and a weak coupling of the electromagnetic field to the electrons in the metal, i.e., a short penetration of the field in the conductor, $L_{\rm z_2}$. Therefore, the field extends over distances, $L_{\rm z_1}$, of several centimeters into the dielectric. Note that in spite of the large value of the imaginary component of the permittivity of gold, the surface wave can propagate a long distance, $L_{\rm spp}$, of several meters along the surface. This long propagation length is a direct consequence of the weak coupling of the field with the charges and the small penetration of this field in the metal. In contrast to gold, InSb have a much lower permittivity at THz frequencies. The penetration of the SPP in InSb is thus larger, leading to a stronger coupling of the electric field to the charge carriers. As a consequence of the larger penetration of the field in the lossy medium, the propagation length of SPPs is reduced to several centimeters. The decay length of the SPP from the interface to air is on the order of one wavelength in InSb, in contrast to few centimeters in Au. This good confinement of the electromagnetic field of SPPs to the interface of semiconductors underlines the relevance of these materials for compact waveguiding and sensitive sensors at THz frequencies.

III. LOCALIZED SURFACE PLASMON RESONANCES

The discussion of the previous section was limited to surface plasmon polaritons on extended, flat surfaces. It is also possible to excite localized surface plasmon resonances (LSPRs) in small particles, which are also known as particle plasmons. By properly choosing the dimensions of the particles, the localized plasmon frequency can be tuned. This tuning has lead to the term of plasmonic antennas in reference to metallic

TABLE I

CARRIER DENSITY AND PLASMA FREQUENCY OF AU AND INSB. ALSO LISTED ARE THE REAL AND IMAGINARY COMPONENTS OF THE PERMITTIVITY AT 1 THZ AND THE CHARACTERISTIC LENGTHS OF SPPS IN THESE MATERIALS.

material	N (cm^{-3})	$\omega_p/2\pi$ (THz)	$\Re(\epsilon)$	$\Im(\epsilon)$	λ_{spp} (m)	L_{spp} (m)	L_{z_1} (m)	L_{z_2} (m)
gold	5.9×10^{22}	2.2×10^3	-8.6×10^4	6.2×10^5	3.0×10^{-4}	3.0×10^1	2.5×10^{-2}	4.0×10^{-8}
InSb	2×10^{16}	2.8	-9.9×10^1	3.0×10^1	2.9×10^{-4}	1.5×10^{-2}	2.4×10^{-4}	2.3×10^{-6}

(typically Au or Ag) nanoparticles supporting LSPRs at optical frequencies. In analogy to metallic plasmonic nanoantennas, it is possible to excite localized surface plasmon resonances in semiconductor plasmonic antennas at THz frequencies. An example of these resonances is shown in Fig. 2, where finite difference in time domain calculations, done with a commercial code (Lumerical, Inc.), of the extinction cross section of a 2D dimer InSb antenna are presented. The dimer antenna is represented schematically in Fig. 2(a) in cross sectional view, and consists of two arms, each of length L and height h, separated by a gap of size Δ. The incident THz radiation is polarized along L. To save computation time, the calculations have been performed in a 2D system, i.e., the arms of the antenna extend to infinity in the direction perpendicular to L and h. It has been recently demonstrated that 2D calculation of the nanoantenna cross sections describe properly 3D structures [16].

The calculations of Fig. 2(b) have been done for different values of the carrier concentration to illustrate the tunability of the LSPRs in semiconductor plasmonic antennas.

IV. CONCLUSION

We have presented a comparison of the characteristic lengths of surface plasmon polaritons (SPPs) on metals (Au) and semiconductors (InSb) at THz frequencies. The large permittivity of metals at these frequencies leads to a weak confinement SPPs to the surface. In contrast to metals, semiconductors confine much better SPPs to the surface, at the expense of a reduced propagation length. Semiconductor particles exhibit pronounced localized surface plasmon resonances, which can be tuned by varying the carrier concentration.

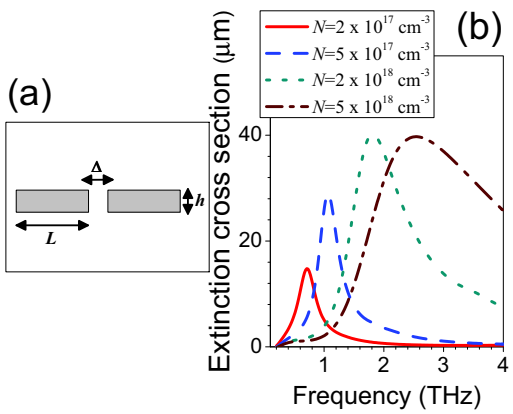

Fig. 2. (a) Schematic representation of the cross section of a dimer antenna. (b) FDTD calculation of the extinction cross section of a 2D InSb dimer antenna with a length (L) of 10 μm, a width (h) of 0.5 μm and a gap (Δ) of 0.1 μm. The calculations have been done for different values of the InSb carrier concentration.

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