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Enhancement of the surface plasmon-polariton excitation in nanometer metal films

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Abstract. This study is aimed to the numerical modeling of the surface plasmon-polariton excitation by a layer of active (electrically pumped) quantum dots embedded in a semiconductor, covered with a metal. It is shown that this excitation becomes much more efficient if the metal has a form of a thin (with thickness of several nanometers) film. The cause of this enhancement in comparison with a thick covering metal film is the partial surface plasmon-polariton localized at the metal-semiconductor interface penetration into air. In result the real part of the metal+air half-space effective dielectric function becomes closer (in absolute value) to the real part of the semiconductor dielectric function than in the case of a thick covering metal film. This leads to approaching the point of the surface plasmon-polariton resonance (where absolute values of these parts coincide) and, therefore, the enhancement of the surface plasmon-polariton excitation. The calculations were made for a particular example of InAs quantum dot layer embedded in GaAs matrix covered with an Au film. Its results indicate that for the 10 nm Au film the rate of this excitation becomes by 2.5 times, and for the 5 nm Au film – by 6-7 times larger than in the case of a thick (40 nm or more) Au film.

Keywords: surface plasmon-polaritons; nanometer metal films; quantum dots

1. Introduction

Surface plasmon-polaritons are self-consistent oscillations of polarization and electromagnetic field, localized at a boundary of two media with different signs of real parts of their dielectric functions (Maier 2007). The surface plasmon-polaritons dimensions along all the three coordinates can be significantly smaller than the electromagnetic field frequency-related wavelengths both in vacuum and in either medium taken apart. This allows to coincide small dimensions of micro- and nanoelectronic schemes with relatively large frequency-related wavelengths of electromagnetic field of the infrared and optical frequency range in homogeneous media. In results it becomes possible to use the radiation of this source-rich frequency domain in optoelectronics,

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nanophotonics, bio-detection schemes and other applications.

One of the main problems while practically utilizing the surface plasmon-polaritons is their quick extinction with passed distanced caused by strong ohmic dissipation of their electromagnetic field in a medium with a negative real part of dielectric function (which is, as a rule, a metal). In result special waveguides with amplifying media compensating for their absorption were created for their transportation (please see the corresponding calculations and references to experimental works in Fedyanin *et al*. 2012). Unfortunately, owing to relatively large frequency-related wavelengths of infrared and optical radiation in homogeneous media, the efficiency of its coupling to these small-aperture devices is rather low.

In result the researchers' attention was attracted by an idea of a surface plasmon-polariton laser (a so called spaser, Bergmann and Stockman 2003) in which an amplifying medium, placed in a micro- or even nanoresonator, could itself generate surface plasmon-polaritons. Several years ago the first reports on the creation of such devices appeared (Hill *et al*. 2009, Oulton *et al*. 2009, Noginov *et al* 2009). Unfortunately, their parameters are still far from desired for applications.

The aim of the present work is the search for optimal conditions for the surface plasmon-polariton excitation. For this purpose we numerically modeled the surface plasmon-polariton excitation by a layer of active (pumped) quantum dots embedded in a semiconductor covered with a metal. The calculations were made for a particular example of InAs quantum dot layer embedded in GaAs matrix covered with an Au film. In result we show that this excitation is much more efficient if the film metal is not thick, but has a thicknesss of several nanometers. The cause of this enhancement in comparison with a thick covering metal film is the partial surface plasmon-polariton localized at the metal-semiconductor interface penetration into air. In result the real part of the metal+air half-space effective dielectric function becomes closer (in absolute value) to the real part of the semiconductor dielectric function than in the case of a thick covering metal film. This leads to approaching the point of the surface plasmon-polariton resonance (where absolute values of these parts coincide) and, therefore, the enhancement of the surface plasmon-polariton excitation.

2. Surface plasmon-polariton dispersion relations for thick and thin covering metal films

The surface plasmon-polariton is an electromagnetic wave, localized near the boundary of two media with different signs of real parts of their dielectric functions (Maier 2007). In practice one of those media can be a metal (with Re $\varepsilon_1<0$), and the other – a semiconductor (with Re $\varepsilon_2>0$). For definiteness we shall consider a situation when a metal is Au and a semiconductor is GaAs. Let us investigate the near-infrared surface plasmon-polariton frequency ω domain, where the absolute values of the imaginary parts of Au and GaAs dielectric functions are much smaller than those of their real parts so that in the above formulas the "Re" sign can be omitted. For the modeling of the frequency dependence of ε_1 we use the well-known Drude approach (Ashcroft and Mermin 1976), in which $\varepsilon_1 = 1-\omega_p^2/\omega^2$, where the Au plasma frequency $\omega_p\approx 1.37\cdot 10^{16}$ rad/s. For GaAs in this frequency range we have $\varepsilon_2\approx$const=12.32.

According to the well-known formula, for a thick (in comparison with the surface plasmon-polariton skinning length in the metal, $1/\mathrm{Im}k_{x1}$ with k_{x1} from Eq. (2) and $k_{||}$ from Eq. (1), please see below) covering metal film the surface plasmon-polariton dispersion relation is

$$k_{\|} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}}, \tag{1}$$

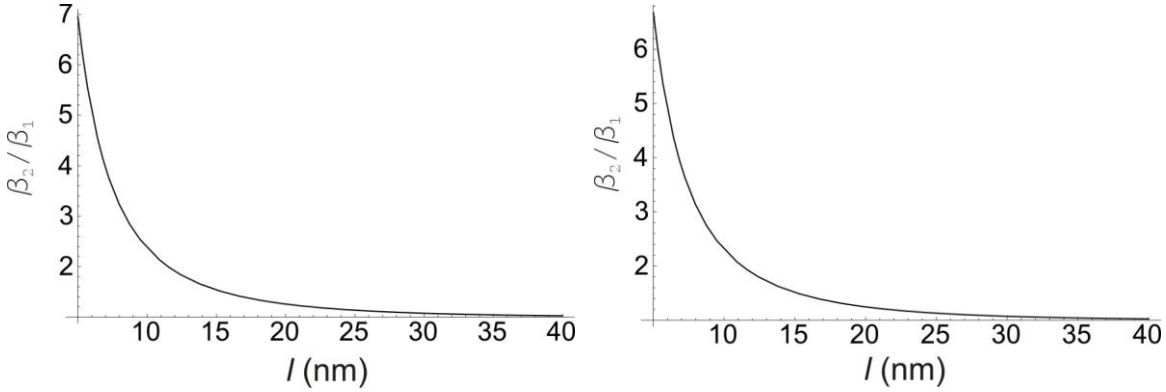
where $k_{\|}$ is the value of the surface plasmon-polariton wavevector component along the metal-semiconductor interface, c – the light velocity in vacuum. For surface plazmon-polariton frequencies and materials being considered $|\varepsilon_1|>\varepsilon_2$, so that in Eq. (1) the expression under the radical is positive. The projections of the surface plasmon-polariton wavevector on the orthogonal to the metal-semiconductor interface axis x in the metal and semiconductor, k_{x1} and k_{x2} correspondingly, are given by the formulas

$$k_{x1} = \sqrt{\omega^2\varepsilon_1/c^2 - k_{\|}^2} \text{ and } k_{x2} = \sqrt{\omega^2\varepsilon_2/c^2 - k_{\|}^2}\,. \tag{2}$$

In the case of a thin metal film there is no a simple analytical formula for $k_{\|}$ like Eq. (1). Rather, $k_{\|}$ is determined from the transcendent equation derived in details in, e.g., Yariv and Yeh 1984. Its solutions can be classified by their behavior when the metal film becomes thick in comparison with the surface plasmon-polariton skinning length in the metal $1/\mathrm{Im}k_{x1}$. It is clear that one of them has to pass into Eq. (1) thus describing the surface plasmon-polariton localized at the metal-semiconductor interface. Another passes into a formula like Eq. (1), where ε_2 has to be replaced with 1 (the air dielectric function) and thus describes the surface plasmon-polariton localized at the metal-air interface. But, because of inequality $|\varepsilon_1|>>1$ at the considered frequency domain, such a replacement gives $k_{\|}\approx\omega/c$, i.e., a vacuum-like dispersion relation. In result the surface plasmon-polariton localized at the metal-air interface has $k_{\|}$ which is smaller than $\omega\sqrt{\varepsilon_2}/c$ and therefore does not decay inside the semiconductor with the growth of the distance from the metal-semiconductor interface. Therefore, this surface plasmon-polariton is localized in axis x direction only for a metal film thicker than the surface plasmon-polariton skinning length in the metal $1/\mathrm{Im}k_{x1}$. But in this case, due to its exponential drop along axis x inside the metal, it practically does not interact with quantum dots, placed inside the semiconductor, and, therefore, can be neglected. For the metal film thinner than the surface plasmon-polariton skinning length in the metal $1/\mathrm{Im}k_{x1}$ this surface plasmon-polariton becomes delocalized along axis x and therefore does not actually exist. So, in what follows, we shall not take into account the surface plasmon-polariton localized at the metal-air interface and consider only the surface plasmon-polariton localized at the metal-semiconductor interface.

In the standard Wigner–Weisskopf method (please see, e.g., Berestetskii *et al*. 1982) of the calculation of the rate of spontaneous transition of a two-level quantum system (in our case a quantum dot) from the excited to the ground state accompanied by the emission of an electromagnet quantum (in our case the surface plasmon-polariton localized at the metal-semiconductor interface) this value is proportional to $k_{\|}dk_{\|}/d\omega$ at the frequency of this transition. In the case of a metal film thicker than the surface plasmon-polariton skinning length, when $k_{\|}$for the surface plasmon-polariton localized at the metal-semiconductor interface is given by Eq. (1), this value is given by a formula

$$k_{\|}\mathrm{d}k_{\|}/\mathrm{d}\omega \equiv \beta_1 = \frac{\omega}{c^2(\varepsilon_1+\varepsilon_2)}\left[\varepsilon_1\varepsilon_2 + \frac{\omega\varepsilon_2^2\mathrm{d}\varepsilon_1/\mathrm{d}\omega}{2(\varepsilon_1+\varepsilon_2)}\right] \tag{3}$$



(a) $\omega/(2\pi)=2.73\cdot10^{14}$ Hz (b) $\omega/(2\pi)=2.63\cdot10^{14}$ Hz

Fig. 1 Ratio β_2/β_1 as a function of Au film thickness l for two near-infrared frequencies of the quantum dot transition

(in neglect of the weak GaAs dielectric function frequency dispersion, i.e., the derivative $d\varepsilon_2/d\omega$). For a metal film thinner than the surface plasmon-polariton skinning length value $k_\parallel dk_\parallel/d\omega\equiv\beta_2$ cannot be found analytically and has to be determined from the transcendent dispersion equation derived in details, as was said above, in, e.g., Yariv and Yeh 1984. In Fig. 1 we show the ratio of these quantities as a function of Au film thickness for two near-infrared frequencies.

From this figure one can see that the rate of spontaneous transition of a quantum dot from the excited to the ground state accompanied by the emission of the surface plasmon-polariton localized at the metal-semiconductor interface growth by 6-7 times as Au film thickness decreases from a value much larger than the surface plasmon-polariton skinning length in Au down to 5 nm. The cause of this enhancement, as was said above, is the fact that in the case of a thin Au film surface plasmon-polariton localized at the metal-semiconductor interface partly penetrates into air. In result the metal+air half-space effective dielectric function becomes closer (in absolute value) to GaAs dielectric function than in the case of a thick Au layer. This leads to approaching the point of the surface plasmon-polariton resonance (where their absolute values coincide) and, therefore, the enhancement of $k_\parallel dk_\parallel/d\omega$. As a consequence, the surface plasmon-polariton localized at the Au-GaAs interface excitation by the spontaneous transitions of quantum dots from their excited to ground states becomes more efficient.

In connection with this result it should be mentioned that Fig. 1 reflects the growth of the surface plasmon-polariton localized at the metal-semiconductor interface emission rate with decreasing l only in the case if the quantum dot layer is placed at positions where the exponentially decaying surface plasmon-polariton electric field has the same strength. Obviously, these positions change with the decrease of the Au film thickness as, according to Eq. (2), its decay length in the semiconductor, $1/\mathrm{Im}k_{x2}$, depends on $k_\parallel$, which varies with the decrease of l. So, at $\omega/(2\pi)=2.73\cdot10^{14}$ Hz for l=40 nm we have $1/\mathrm{Im}k_{x2}\approx97$ nm whereas for l=5 nm we get $1/\mathrm{Im}k_{x2}\approx2$ nm. So, to provide the growth of the surface plasmon-polariton localized at the metal-semiconductor interface emission with the decrease of the metal film thickness it is necessary in the course of this decrease to put the quantum dot layer closer to the metal-semiconductor boundary.

4. Conclusions

Upon the whole, in the present work by means of analytical and numerical investigation it is shown that the decrease of the thickness of a metal film covering a semiconductor with a near-surfase layer of active (electrically pumped) quantum dots leads to a significant (by almost an order of magnitude) enchancement of the surface plasmon-polariton excittation by the spontaneous quntum dots transitions from their excited to ground states. This effect can be used in the design of effective surface plasmon-polariton Shottky diodes.

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