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PHYSICS

Tamm Plasmon Polaritons for Light Trapping in Organic Solar Cells

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Abstract—A model of an organic solar cell based on a Tamm plasmon polariton localized at the boundary of the active layer doped with plasmonic nanoparticles and a multilayer mirror is proposed. It is shown that the integral absorption in the active layer can be increased by 10% compared to the optimized planar solar cell.

Keywords: Tamm plasmon polariton, organic solar cell, photosensitive layer, light localization

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Organic solar cells (OSCs) based on conjugated polymers are attracting increasing attention due to their low cost, ease of manufacture, low weight, and mechanical flexibility of solar panels obtained using roll printing technologies [1, 2]. Such OSCs contain a bulk heterojunction, as a result of which a compromise is sought between the photon absorption and carrier transport efficiencies. The thickness of the photosensitive layer (PSL) in this case is no more than 100 nm, which greatly limits the efficiency of absorption of incident light. In this regard, methods of manipulating light to increase absorption in the photosensitive layer are widespread. The introduction of periodic or random structures in the PSL or in the OSC interfaces leads to a redistribution of the optical field in them and enhances the absorption of photons due to internal scattering or the plasmon resonance effect. In 2010 in optically thin films of poly (3-hexylthiophen-2,5-diyl)/[6, 6] phenyl-C61 methyl butyric acid ester (P3HT : PC61BM) with plasmon resonance silver nanoprisms, a threefold increase in charge carrier generation was observed [3]. Subsequently, this direction was widely developed due to the active development of technologies for manufacturing nanoscale objects. Another promising direction is the introduction of one-dimensional photonic crystals (PhCs) into the OSC. The location of the PhC behind the metal contact leads to the fact that almost 100% of the radiation incident on it is reflected and passes through the active layer a second time, thereby increasing the efficiency of the OSCs [4]. In this case, it becomes possible to use thinner metal films as contacts and, as a result, reduce losses in the OSCs. Replacing the transparent contact with the PhC structure leads to the fact that the active layer remains between the metal film and the PhC. Tamm plasmon polaritons (TPPs) can be excited in such structures [5], at the wavelength of which additional absorption lines of radiation appear in the active layer. This mechanism of increasing the OSC efficiency was demonstrated in [6]. In the models, the photosensitive layer is a passive absorbing element that does not participate in the formation of localized states. New is the idea of using a doped photosensitive layer as a mirror bounding a one-dimensional photonic crystal. In this case, TPP is located at their interface [7–9], which leads to the appearance of an additional absorption band of radiation incident on the structure and, as a result, to an increase in the efficiency of the OSCs. The attractiveness of such a structure lies in the fact that it is possible to abandon completely the metal contact, ensuring absorption only in the PSL layer.

DESCRIPTION OF THE MODEL

The model of the organic solar cell proposed by us is shown in Fig. 1b.

In contrast to the previously studied solar cell (Fig. 1a) [10], in our model, the photosensitive layer limits not a metal film, but a one-dimensional photonic crystal. The P3HT: PC61BM layer with a thickness of 50 nm was doped with silver nanospheres with a volume concentration of 20%. The thickness of a layer of poly (3,4-ethylenedioxythiophene) polystyrenesulfonate (PEDOT: PSS) is 20 nm. ITO films with a thickness of 15 nm and 45 nm were used as contacts. A unit cell of a photonic crystal is formed of silicon dioxide (SiO_2) and titanium dioxide (TiO_2) with the

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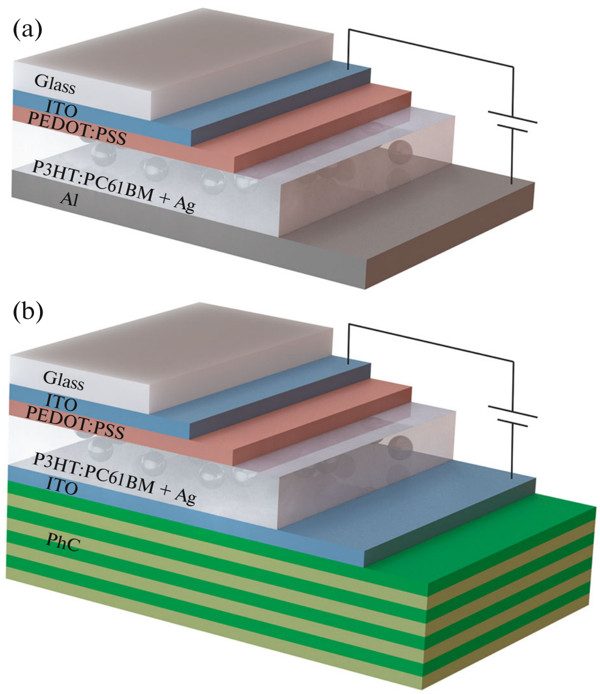

Fig. 1. (a) Schematic representation of an organic solar cell doped with plasmonic nanoparticles [10], (b) a schematic representation of a solar cell based on the Tamm plasmon polariton.

thicknesses $d_{SiO_2} = 75$ nm and $d_{TiO_2} = 40$ nm and permittivities $\varepsilon_{SiO_2} = 1.45$ and $\varepsilon_{TiOO_2} = 2.4$, respectively. The imaginary part of the refractive index of the PSL layer takes a maximum value in the wavelength range from 350 to 600 nm, and, as a result, the radiation incident on the structure is absorbed by the PSL in this spectral range. In the long-wavelength region of the spectrum, the absorption is close to zero. The effective permittivity of the PSL layer doped with plasmon nanoparticles is determined using the effective medium theory [11].

CALCULATION RESULTS

The dependences of the real and imaginary parts of the effective dielectric constant, calculated using the effective medium theory, showed that its imaginary part reaches its maximum value at a wavelength of 600 nm, which is due to plasmon resonance in nanoparticles. We also note that the real part takes negative values in a wide range of wavelengths (from 360 to 570 nm), and, as a result, in this interval the active layer acts as a metal mirror. The conjugation of an active layer with similar spectral characteristics with a photonic crystal will lead to the formation of a Tamm plasmon polariton at their interface. To confirm this fact, the transfer matrix method [12, 13] was used to calculate the integral absorption in the PSL layer for a classical planar solar cell and a solar cell conjugated with a photonic crystal. The calculation results are shown in Fig. 2a. Calculations showed that in the proposed OSC model, the integrated absorption in the studied wavelength range increases by ≈10% (from 50.52% to 55.36%), in comparison with the similar planar OSC (Fig. 1a) This is achieved due to the formation of TPP localized at the interface between the photonic crystal and the active layer doped with plasmon nanoparticles. At the TPP wavelength ($\lambda_{TPP} = 400$ nm) the effective dielectric constant of the photosensitive layer is $\varepsilon_{eff} = -1.007 + 2.716i$. The spatial distribution of the field at the TPP wavelength is shown in Fig. 3b. It can be seen from the figure that the field is localized at the interface between the photonic crystal and the photosensitive layer and decays exponentially on both sides of their interface. In this case, the field is localized in a region commensurate with the wavelength of light. It is important to note that the field intensity at the TPP

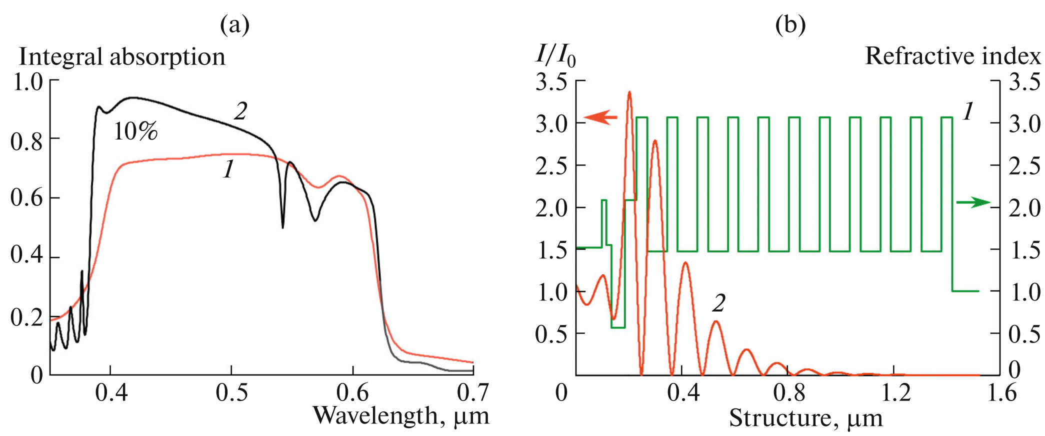

Fig. 2. (a) Integral absorption in the photosensitive layer in the structures shown in Figs. (*1*) 1a and (*2*) 1b; (b) spatial distribution of (*1*) the refractive index in the structure and (*2*) the local field intensity at the TPP wavelength.

wavelength is only 3.5 times higher than the incident field intensity.

Such a slight amplification can be explained by the formation of a Tamm plasmon polariton with a wide spectral line at the PSL–PhC boundary. The formation of such states is possible in systems with large losses, as was shown in [14]. In the structure under study, we have a similar situation, since the real part of the effective dielectric constant of the PSL at the TPP wavelength is almost three times less than its imaginary part.

CONCLUSIONS

A model of an organic solar cell is proposed in which the photosensitive layer acts not only as an absorber, but also as a mirror involved in the formation of a localized state. The energy spectra of the structure and the distribution of local intensity in it are calculated by the transfer matrix method. It is shown that in the model proposed, the integrated absorption in the photosensitive layer increases by 10% in comparison with the previously proposed OSC models. It was found that the increase in absorption in this case is achieved due to the formation of an additional absorption band in the OSC and is due to the formation of a Tamm plasmon polariton at the interface between the photosensitive layer and the photonic crystal.

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