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REGULAR ARTICLE

Photoemission Current from Metal Nanoparticles in Silicon

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This study provides insights into the phenomenon of surface photoemission from metal nanoparticles, considering the excitation of Localized Plasma Resonance (LPR). LPR induces significant changes in electron density and electric field, resulting in enhanced photoemission compared to macroscopic structures. Theoretical formulations, including expressions for photoemission probability, are elucidated, enabling a deeper understanding of the process. Practical implications are discussed, emphasizing the development of optoelectronic devices and efficient photodetectors using nanoparticles. Results demonstrate the spectral dependence of photoemission probability and current, high-lighting the suitability of materials like copper for nanoparticle-based applications. The study con-tributes to optimizing nanoplasmonics effects and expands the material choices for efficient photoemission.

Keywords: Photoemission current, Localized plasma resonance, Nanoparticle, Surface photoemission.

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1. INTRODUCTION

As is known, the fluctuation of the electron density of metal nanoparticles has a resonant frequency in the visible and infrared parts of the spectrum – localized plasma resonance (LPR). LPR occurs when surface charges form a potential well, and the electrons in this well oscillate under the influence of an external electromagnetic field (EMF). At the LPR frequency, the energy density of the external EMF inside the nanoparticle is several orders of magnitude higher than outside. When excited by the LPR, the nanoparticle behaves like a resonator. The resonant properties of metal nanoparticles and the collection of EMFs in their environment make it possible to observe many new effects. Based on these effects, optoelectronic devices with plasmonic nanoparticles, nanosized lasers, and highly efficient solar cells have been proposed and implemented [1, 2].

One of the effects that occurs when excitation of LPR is photoemission of nanoparticles. The photoemission of nanoparticles differs sharply from the photoemission of macroscopic metal structures because the EMF in and around the nanoparticles increases sharply, and the surface-to-volume ratio of nanoparticles is much higher than that of macroscopic structures. Thus, the photoelectron emission per unit mass of nanoparticles is much greater than that of macroscopic structures. Increasing the efficiency of photodetectors using nanoparticles is of great practical importance [3-5].

Micro- and nanostructures have been created on the surface of metal photodetectors to increase their efficiency, but since these structures have good electrical contact with metal shells, it is impossible to excite LPR in them and enhance photoemission. An increase in the surface photoemission of metal nanoparticles due to the excitation of LPR has been observed in practice, but this process has not been studied theoretically and systematically [6-8].

This work is devoted to the study of surface photoemission of metal nanoparticles taking into account the excitation of LPR and it is shown that photoemission of nanoparticles is more effective than photoemission of macrostructures.

2. THEORY

In this work, surface photoemission from metal nanoparticles is considered taking into account the excitation of LPR, which takes into account abrupt changes in the electric field and electron mass on the surface, which leads to a sharp increase in photoemission. The photoemission current density from metal nanoparticles is determined from the expression [1, 9-11]

$$j = \frac{1}{4\pi^3}\int \frac{f_F(\bar{k}_0)\hbar\bar{k}_{1z} \mid C_{em} \mid^2 \Theta[k_{0z}^2 + (\frac{2m}{\hbar^2})(\hbar\omega - V)]}{m} dk_{0x}dk_{0y}dk_{0z} \quad (1)$$

Where $\hbar\bar{k}_{1z}/m$ – electron speed,

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$$f_F = \frac{1}{1+\exp\left[\frac{(\hbar k_0)^2/2m-\varepsilon_F}{k_B T}\right]} \quad (2)$$

This is Fermi function, ε_F – Fermi energy,

$$k_{1z} = \sqrt{k_{0z}^2 + (2m/\hbar^2)(\hbar\omega - V)} \quad (3)$$

k_0 and k_1 – electron wave vector before and after photon absorption, k_B – Boltzmann constant, T – temperature, Θ – theta function.

Since in integral (1) only the Fermi function depends on k_{0y}, k_{0z}, we can obtain

$$\int dk_{0x}dk_{0y}f_F(\vec{k}_0) = \frac{2\pi m k_B T}{\hbar^2}\ln\left(1+\exp[\frac{\varepsilon_F-\hbar^2k_0^2}{k_B T}]\right) \quad (4)$$

Then the photoemission probability amplitude takes the form:

$$C_{em} = \frac{e^2kTV^2}{\pi^2\hbar^5\omega^4}\times \times\int_{0,1-\hbar\omega/V}^{1} dx\sqrt{1+\frac{\hbar\omega/V-1}{x}}\ln\left(1+\exp[\frac{\varepsilon_F-Vx}{k_B T}]\right)U(x)\,|\,K_{dis}(x)\,|^2 \quad (5)$$

Where:

$$U(x) = \frac{4r_m^2}{(r_m+1)^2}\frac{x}{[x+r_m(1-x)]\{\sqrt{x+\hbar\omega/V}+\sqrt{r_m(x+\hbar\omega/V-1)}\}^2} \quad (6)$$

$$K_{dis}(x) = \frac{1}{2}(1+\frac{\varepsilon_-}{\varepsilon_+})[1+\frac{1-r_m}{1+r_m}(2x+\frac{\hbar\omega}{V}-1)] + +\frac{1}{2}(1-\frac{\varepsilon_-}{\varepsilon_+})\left[\sqrt{x+\frac{\hbar\omega}{V}}-i\sqrt{1-x}\right]^2 \quad (7)$$

– functions that take into account changes in the electric field at the boundary,

$$r_m = m/m_0, x = (k_0)^2/(2mV) = E_0/V, \quad (8)$$

$$\varepsilon_-(\lambda) = \varepsilon_m(\lambda) + (\lambda/\lambda_p)^2[\frac{1}{1+i\lambda/\lambda_f} - \frac{1}{1+(i\lambda/\lambda_f)(a_c/a+1)}] \quad (9)$$

$$\varepsilon_m(\lambda) = \varepsilon_\infty + (\lambda/\lambda_p)^2\frac{1}{1+i\lambda/\lambda_f} \quad (10)$$

$$\varepsilon_+(\lambda) = \varepsilon_\infty + \sum_{i=1}^{3}\frac{C_i}{1-(\frac{1.242}{\lambda E_i})^2 - i\frac{1.242}{\lambda E_i}\gamma_i} - F_1\chi_1^{-2}(\lambda)\ln[1-\chi_1^2(\lambda)] - F_2\chi_2^{-2}(\lambda)\ln\frac{1-\chi_1^2(\lambda)}{1-\chi_2^2(\lambda)} \quad (11)$$

Dielectric functions of nanometal can be calculated using formula 11 [6, 12, 13].

3. RESULT AND DISCUSSION

Based on the above expressions, a program was compiled in Visual Basuc-6.0 to calculate the plasma parameters of metals, as well as the photoemission current from metal nanoparticles depending on the wavelength of the incident light. The program allows you to enter and change the output energy, Fermi energy, reduced electron mass, plasma parameters, nanoparticle sizes, etc. The peculiarity of the program is that the results of calculations in a single software environment are exported to MS Excel and are ex-pressed not only in tabular, but also in graphical form [8]. The calculation results are presented in the form of graphs in Fig. 1-3.

Table 1 – Plasma parameters of metals

	λ_p, μm		λ_f, μm	ε_∞	χ^2
	Calculation	**[2]**			
Au	0.143	0.138	7.492	8.763	0.201
Cu	0.149	0.141	3.412	6.296	0.327
Ag	0.126	0.136	4.056	6.781	0.241
Al	0.050	–	0.775	28.047	1.052
Ni	0.130	–	0.908	4.950	0.040
Pt	0.164	–	1.298	0.248	0.023
Zn	0.086	–	0.631	6.145	0.573
Ti	0.149	–	0.718	3.606	0.088

The table shows the results of calculations of plasma parameters of metals. For comparison, the results of work [2] and the values of χ^2, indicating the accuracy of the calculations, are also presented there.

In Fig. 1 presents the results of calculating the spectral dependence of the probability of photoelectron emission of metal nanoparticles in silicon. The results show that as the wavelength of light increases, the probability decreases. The results indicate that not only expensive gold, but zinc or copper can be used as a nanoparticle material. Moreover, zinc and copper nanoparticles have the highest photoemission probability values.

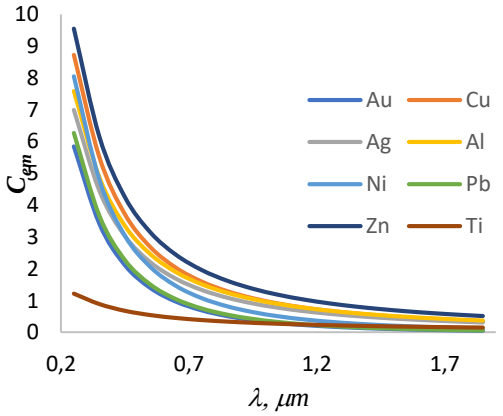

Fig. 1 – Results of calculation of the spectral dependence of the probability of photoelectron emission of metal nanoparticles in silicon

In Fig. 2 shows the results of calculating the spectral dependence of the photoemission current (J_{em}) of metal nanoparticles in silicon. As can be seen from the figure, the highest value of photoemission current is achieved for silver and copper.

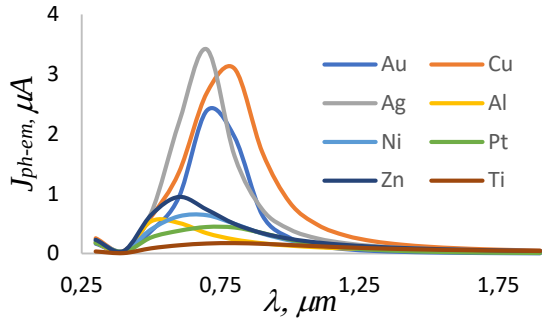

Fig. 2 – Results of calculation of the spectral dependence of the photoemission current of metal nanoparticles in silicon

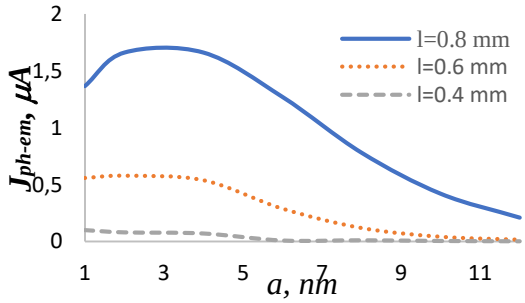

Fig. 3 – Results of calculation of the dependence of the photoemission current from metal (Cu) nanoparticles into silicon on their size

In Fig. 3 shows the results of calculating the dependence of the photoemission current from metal nanoparticles (Cu) in silicon of their size. As can be seen from the figure, the highest value of the photoemission current cross section is achieved at a = 2.4 nm.

4. CONCLUSION

Thus, the most significant results of the study are the following:

– A program has been developed in Visual Basuc-6.0 to calculate the plasma parameters of metals, as well as the photoemission current and the probability of photoemission depending on the wavelength of the incident light. The program allows you to enter and change the values of the output energy, Fermi energy, reduced electron mass, parameters of plasma processes, nanoparticle sizes, etc. The results of calculations in a single software environment are exported to MS Excel and are expressed not only in tabular, but also in graphical form;

– The optimal sizes of metal nanoparticles were determined to achieve a more efficient implementation of the nanoplasmonics effect;

–It has been shown that not only expensive gold and silver, but also copper can be used as a nanoparticle material. Moreover, copper nanoparticles have the highest photoemission current values.

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Фотоемісійний струм від металевих наночастинок у кремнії

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Це дослідження дає уявлення про явище поверхневої фотоемісії металевих наночастинок, враховуючи збудження локалізованого плазмового резонансу (LPR). LPR викликає значні зміни в електронній густині та електричному полі, що призводить до посилення фотоемісії порівняно з макроскопічними структурами. Уточнюються теоретичні формулювання, включаючи вирази для ймовірності фотоемісії, що дозволяє глибше зрозуміти процес. Обговорюються практичні наслідки, наголошується на розробці оптоелектронних пристроїв і ефективних фотодетекторів з використанням наночастинок. Результати демонструють спектральну залежність імовірності фотоемісії та струму, підкреслюючи придатність таких матеріалів, як мідь, для застосування на основі наночастинок. Дослідження сприяє оптимізації ефектів наноплазмоніки та розширює вибір матеріалів для ефективної фотоемісії.

Ключові слова: Фотоемісійний струм, Локалізований плазмовий резонанс, Наночастинка, Поверхнева фотоемісія.