AUTOREFERAT (w języku angielskim)

1. PERSONAL DATA

Name, surname: Witold Aleksander Jacak
Date and place of birth: 10.08.1981, Łódź
Employed by: Wrocław University of Technology, Faculty of Fundamental Problems of Technology

2. DEGREES

- MSc Eng.in Physics, Faculty of Fundamental Problems of Technology, Wrocław University of Technology 2005
- MSc Eng. in Computer Science, Faculty of Computer Science, Wrocław University of Technology 2005
- PhD in Physics, Faculty of Fundamental Problems of Technology, Wrocław University of Technology 2008, Thesis title: „Decoherence of orbital and spin degrees of freedom in quantum dots"

3. EMPLOYMENT TRACK

- 2005 – 2008 PhD student in Institute of Physics, Wrocław University of Technology
- 2008 – 2009 Assistant in Institute of Physics, Wrocław University of Technology
- 2009 – Assistant Professor in Institute of Physics, Wrocław University of Technology, since 2014 in Department of Quantum Technologies, Faculty of Fundamental Problems of Technology, Wrocław University of Technology (after closure and reorganization of Institute of Physics at WUT)

4. INDICATION OF THE SCIENTIFIC ACHIEVEMENT

a) The title of the achievement:

Radiative properties of plasmons in metallic nanoparticles and of plasmon-polaritons in metallic nano-chains and in ionic systems along with applications

b) List of publications included to the habilitation dissertation:

1. **W. Jacak,** *Plasmons in finite spherical electrolyte systems: RPA effective jellium model for ionic plasma excitations*, **Plasmonics** (Springer) **11/2,** 1-15 **(**2016), on-line publication, Open Access, 2015, DOI: 10.1007/s11468-015-0064-6

2. **W. Jacak,** *Size-dependence of the Lorentz friction for surface plasmons in metallic nanospheres,* **Optics Express 23**, 4472-4481 (2015)

3. **W. Jacak,** *Propagation of Collective Surface Plasmons in Linear Periodic Ionic Structures: Plasmon Polariton Mechanism of Saltatory Conduction in Axons*. **J. Phys. Chem. C 119(18),** 10015−10030 (2015)

4. **W. Jacak,** *Lorentz Friction for Surface Plasmons in Metallic Nanospheres,* **J. Phys. Chem. C 119(12),** 6749–6759 (2015)

5. **W. Jacak,** *Exact solution for velocity of plasmo-polariton in metallic nano-chain,* **Optics Express 22,** 18958-18965 (2014)

6. **W. Jacak,** *On plasmon-polariton propagation along metallc nano-chain,* **Plasmonics** (Springer) **8**,1317-1333 (2013)

7. **W. Jacak,** J. Krasnyj, A. Chepok, *Plasmon-Polariton Properties in Metallic Nanosphere Chains,* **Materials, 8**, 3910-3937 (2015)

8. **W. Jacak,** A. Henrykowski, K. Marszalski**,** *Plasmon enhanced photovoltaic effect in metallically nanomodified photocells,* **Sol. Energy Mater. Sol. Cells 117**, 663-666 (2013)

9. **W. Jacak,** J. Krasnyj, J. Jacak, W. Donderowicz, L. Jacak, *Mechanism of plasmon-mediated enhancement of PV efficiency,* **J. Phys. D: Appl. Phys. 44**, 055301-1-14 (2011)

10. **W. Jacak**, J. Krasnyj, J. Jacak, L. Jacak, *Plasmons in metallic nanospheres: Towards efficiency enhancement of metallically modified solar cells*, **Opt. Mater. 33**, 1449-1452 (2011)

11. **W. Jacak,** J. Krasnyj, J. Jacak, R. Gonczarek, A. Chepok, L. Jacak, D. Z. Hu, D. Schaadt, *Radius dependent shift in surface plasmon frequency in large metallic nanospheres: Theory and experiment*, **J. Appl. Phys. 107**, 124317 -1-14 (2010)

12. J. Jacak, J. Krasnyj, **W. Jacak,** R. Gonczarek, A. Chepok, L. Jacak, *Surface and volume plasmons in metallic nanospheres in a semiclassical RPA-type approach: Near-field coupling of surface plasmons with the semiconductor substrate,* **Phys. Rev. B 82**, 035418-1-14 (2010)

13. **W. Jacak,** J. Krasnyj, J. Jacak, A. Chepok, L. Jacak, W. Donderowicz, D. Z. Hu, D. Schaadt, *Undamped collective surface plasmon oscillations along metallic nanosphere chain,* **J. Appl. Phys. 108**, 084304-1-13 (2010)

14. E. Placzek-Popko, K. Gwóźdź, Z. Gumienny, E. Zielony, R. Pietruszka, B. S. Witkowski, Ł. Wachnicki, M. Godlewski, **W. Jacak,** Liann-Be Chang, *Si/ZnO nanorods/Ag/AZO structures as promising PV plasmonic cells,* **J. Appl. Phys. 117**, 193101-1-8 (2015)

15. K. Kluczyk, **W. Jacak**, *Damping-induced size effect in surface plasmon resonance in metallic nano-particles: comparison of RPA microscopic model with numerical finite elemen simulation (COMSOL) and Mie approach*, **Journal of Quantitative Spectroscopy & Radiative Transfer 168,** 78-88 (2016), http://dx.doi.org/10.1016/j.jqsrt.2015.08.021

16. M-J. Jeng, Zih-Y. Chen, Y-L. Xiao, L-B. Chang, J. Ao, Y. Sun, E. Popko, **W. Jacak**, L. Chow, *The efficiency enhancement of silicon and CIGS solar cells by the incorporation of metal nanoparticles,* **Materials 8** (2015), 6761–6771; doi:10.3390/*ma8105337*

17. **W. Jacak**, E. Popko, A. Henrykowski, E. Zielony, K. Gwóźdż, G. Luka, R. Pietruszka, B. Witkowski, L. Wachnicki, M. Godlewski, L-B. Chang, M-J. Jeng, *On the size dependence and the spatial range for the plasmon effect in photovoltaic efficiency enhancement,* **Sol. Energy Mater. Sol. Cells 147,** 1-16 (2016)

18. **W. Jacak,** *On energy transfer in metallically nanomodified photo-cells via surface plasmons in metallic nanoparticles: inclusion on nanoparticle size effect* **Proc of SPIE West (San Francisco 2013)** w **Proceedings SPIE 8620, Physics, Simulation, and Photonic Engineering of Photovoltaic Devices II**, 862006, pp 1-15

19. **W. Jacak**, *Plasmon mediated energy transport in PV systems with photo-active surface modified*

metallically in nano-scale and in metallic nano-chains [1-15pp, chapter 18], invited chapter to the monograph, **Plasmonics - Principles and Applications**, **Intech, ISBN 978-953-308-91-2**, edited by Ki Young Kim, 2012

c) Description of the results

Introduction

The dissertation entitled as „Radiation properties of plasmons in metallic nanoparticles and of plasmon-polaritons in metallic nano-chains and in ionic systems along with applications" embraces 19 author publications in this field (including 17 publications in journals form Philadelphia List with total IF 55.9 [in average IF 3.3 per publication]). The whole number of author publications is 46. Papers included into the dissertation concern the period 2010-2016, when the author carried investigation in the plasmonics field. The former research including his PhD thesis (2008) was related to other subject, namely "Decoherence of charge and spin degrees freedom in quantum dots" and was based on 14 other publications. After PhD the author published also another 13 publications out of the present dissertation, though 5 of these additional publications are closely related to the habilitation dissertation and play a supplementary role (invited chapters to international monographs and conference proceedings). The remaining 8 publications after PhD concern quantum information processing and decoherence issues mostly in quantum dots. W. Jacak is also a co-author of 3 monographs: 1) "Decoherence of orbital and spin degrees of freedom in quantum dots" 2009 WUT UP, 2) "Introduction to quantum information and communication" 2011 WUT UP (in Polish and translated to English, Printpap 2012), 3) Introduction to quantum cryptography: implementation of QKD on nonentangled photons (system Clavis II) and on entangled photons (system EPR S405 Quelle)" and the author of several invited chapters to international monographs in the field of plasmonics and of quantum dots.

In the field of coherent control over quantum dots, developed by W. Jacak upon his PhD thesis, he gained an assessment of usefulness of semiconductor nanostructures to quantum information processing. He formulated the so-called "three order limit" in the relation to the famous diVincenzo conditions—the requirements needed to be fulfilled for quantum computer construction [h1,h2][1]. The "three order limit" criterion summarized the inconvenient decoherence of charge and spin in nanostructures controlled upon local quantum mechanics which appears to be located in the middle of the required diVincenzo windows of 6 orders difference between control time and decohence time-scale (at least for solid state nanostructures, including QDs controlled by light). W. Jacak originally indicated also some advantages of spin degrees of freedom in magnetic QDs [h3] related to the so-called freeze of magnon dephasing [h4]. The expertise in the QD nano-physics allowed him next for beginning (ca. at 2010) a new research field related to plasmons in metallic nanoparticles. This issue met with an increase of interest in the world in opportunities of subdiffraction light manipulations by plasmon excitations in metallic nanoparticles [8] and with rapid development of new fields of nano-plasmonics overlapping with nano-photonics [6] with huge application prospects [5-10].

From quantum physics point of view the metallic nanoparticles are quite different systems than semiconductor QDs despite the similar size of spatial confinement. The latter, in nutshell, are manufactured of nanometer size and relatively shallow quantum wells (without singularity as is

---

[1] References are here referred to the Bibliography list in the page 22 of the present text; with 'h' are indicated the author papers not included to his habilitation dissertation, whereas with 'H' are indicated publications included to the habilitation dissertation

present in the Coulomb confinement) located in semiconductor surroundings and able to trap band electrons (holes or excitons) in analogy to ordinary atoms, though without the electron number limit caused by instability of the atom nucleus. QDs can be thus filled with unlimited in principle number of carriers (limited, however, in practice by the depth of the QD well). The analogy of QDs and ordinary atoms is somewhat misleading (especially due to strong dephasing od states in QDs by collective excitation in surroundings by several order larger than in atoms [h2]) but the concept of QD is physically straightforward and allows easy and efficient numerical modeling. In the case of metallic nanoparticles the situation is different and related with much more complicated physics of metals (developed for bulk metals in 60. of XXth century by application of advanced methods developed for multiparticle systems mostly in Geeen function terms [11]). The quantum degeneration of Fermi liquid of electrons (actually of Landau quasiparticles stable exclusively on the Fermi surface [11]) determines the quantum system different than usually classical of Boltzmann type subsystem of low-populated band carries in semiconductors which can fill QDs. In metals an additional complication is caused also by crystalline positive ion background essential for the related quantum system definition. Many attempts to describe charge density excitations in metals were successfully undertaken since 50. of XXth century utilizing quantum statistics many body theory methods. In relation to bulk metal in 1952 the very efficient theory of high energy excitations typical for metals and called plasmons were described by the random phase approximation (RPA) approach developed by D. Pines and D. Bohm [12,13], which allowed for quantitative and relatively simple description of plasmons [14]. Owing to energy incommensurability of plasmons and Landau qusiparticles on (close to) the Fermi surface (representing electrons in metals), plasmons do not interact with electrons, despite that actually electrons build plasmons. One cannot thus excite plasmons by use of low energy electrons as the plasmon energy in bulk metal is typically of order of 10 eV exceeding usually the Fermi energy being of order of 7-8 eV. Plasmon energy is similar in scale to UV photons and plasmons can be excited by sufficiently hard radiation. When it has been occurred that energy of plasmons in confined metallic nanoparticles is considerably lower [15-19] and in noble metals (Au, Ag, Cu) fit with the visible photon energies, there had begun the new nanotechnology revolution related to modification and control over visible light by metallic nanostructutres [6-9] with spatial size much lower than the wave-length of light, thus referred to subdiffraction manipulations. It must be noted that plasma and their excitations were the subject of interest also earlier [16] and were investigated in relation to high energy plasma also of proton type in stellar kernels, tokamaks, as well as in galaxy ion clouds or in the ionosphere. This interest has been supported by a development of the radar/antiradar technology and, in last years, in achievements in the metamaterial construction allowing for control over light different than ordinary reflection and refraction.

Development of model description of plasmons included to author habilitation dissertation

The main objective in the field of the present dissertation was the construction of an effective theory of plasmons in metallic nanoparticles in as most as possible analytical version allowing for universal applications and not constrained as previously studied numerical models. The developed in 80. of XXth century numerical methods of *ab initio* calculus for plasmons in metallic clusters were limited to approximately 300 electrons (since strong numerical complexity of solution of Cohn-Sham-type equation for number of particles beyond 300) [17,18]. In view of these problems the insight into plasmonics of metallic nanoparticles was ranged to rather phenomenological approach with experimental-aided modelling [20] of dielectric function for solution of Fresnel equations for electromagnetic field boundary problem with spherical geometry of metallic particle and with incident planar wave. The analytic solution of this problem is known as the Mie approach [15] resulting in formulae for scattering and extinction cross- sections of incident light on metallic sphere including phenomenological modelling of absorption (according to the simple Drude-Lorentz model) [15]. The same approach in numerical version for solution of Maxwell equations with boundary problem is offered upon the commercial numerical system COMSOL (not limited to spherical geometry only) utilizing the finite element method of solution of differential equations but also only phenomenological in terms of plasmon dynamics. Therefore any progress in recognition of plasmon excitations in metallic nanoparticles within a microscopic framework (at the best in the analytical form) may have the great significance for improvement of mentioned above very popular Mie-type and COMSOL approaches utilizing, however, declaring in advance phenomenological dielectric functions for objects under study. Such an issue has been solved with participation of the author via the development of the microscopic model of surface and volume plasmons in metallic nanoparticles in the form of Random Phase Approximation method accommodated to finite geometry [H21] being a generalization of the Pines-Bohm theory [12,13]. W. Jacak together with co-authors have obtained analytical description of all multipole modes (in spherical symmetry) for surface plasmons and for volume ones (the latter originally described by them for metallic nanoparticles) within RPA model for metallic nanoparticles in good agreement with experimental and former, mostly of numerical type, results [H21].

Surface plasmons correspond to translational collective oscillation modes of all electrons when noncompensated by static jellium local charge fluctuations occur only on the nanoparticle surface. It is in opposition to volume plasmons being modes of compressional type with varying charge density along the nanoparticle radius. The author together with collaborators found formulae for resonance frequencies of all the modes numbered by multipole numbers in the case of spherical symmetry [H21,19,16,22]. Remarkably, the surface plasmons have resonance energies lower than $\hbar\omega_p$ -- the energy of plasmons in bulk, $\hbar\omega_l = \hbar\omega_p\sqrt{\frac{l}{2l+1}}$, (for l=1, $\hbar\omega_1$ coincides with the classical Mie frequency [16], l – multipolar number), whereas the volume plasmons in the nanosphere have resonance energies larger than that for bulk $\hbar\omega_p$, $\hbar\omega_{nl} = \hbar\omega_p\sqrt{1+\frac{x_{nl}^2}{a^2k_T^2}}$, ($x_{nl}$ is the n-th zero of l-th spherical Bessel function, k_T - is the inverse Thomas-Fermi length, a – is the nanosphere radius) [H21]. Both types of plasmon excitations – the surface plasmons and the volume ones – do not occur in bulk metal (though for the geometry of half-space there are surface plasmons with the frequency $\omega = \omega_p\sqrt{\frac{1}{2}}$, so-called Ritchie frequency [9]). Main results of the author with respect to mentioned above issues are presented in a synthetic manner within the Point 1. of the following list.

1. PRA description of surface and volume plasmons in a metallic nanoparticle

It must be emphasized that the essential difference between RPA Pines-Bohm model for bulk metal [14] and RPA theory for metallic nanoparticle consists in explicit definition of the finite rigid jellium (defining the shape of the nanoparticle) [H21], unlike to RPA Pines-Bohm theory where the infinite jellium in bulk was out-renormalized via ideal compensation with uniform long-wavelength coherent fluctuation of electrons (the plasmon mode with $k \to 0$). In the case of a finite nanoparticle such a renormalization is impossible due to absence of translational invariance, different quantum numbers for plasmon excitations in finite nanoparticle and due to explicit presence of the jellium rim. The dynamics equation in Heisenberg representation determines here self-modes for collective local charge density fluctuations. The gradient operator from the kinetic energy term produces the Dirac delta singularities in this equation arising from the derivative of the Heaviside step functions defining the jellium border. These singularities are located on the edge of the nanoparticle which after tedious but fully analytical procedure allows for separation in the dynamic equation [H21] of its part for surface and volume plasmon components [H21]. Mutual dependence of both excitations was also explicitly shown within the RPA approach. Moreover, the problem of so-called spill-out of electron liquid above the rim of the jellium has been analyzed in the constructed RPA theory. The spill-out appeared on the scale of the Thomas-Fermi length and thus is unimportant for nanoparticles larger those with radius of ca. 5 nm, though for smaller metallic clusters (of size of 2-3 nm) spill-out considerably dilutes density of electrons and red-shifts resonance plasmon frequencies (proportional to square root of the charge density [17-19]). The surface effects, like spill-out and also the so-called Landau damping (the latter corresponds to decay of plasmon onto a pair of distant to the Fermi surface quasiparticles and thus unstable) are of lowering importance with growth of the nanoparticle size and for nanospheres with radii > 5 nm are negligible [17]. The reduction of the role of the spill-out for particles larger than of few nm radius supports in this scale usability of RPA approach in a quasiclassical version [H21] with the separation of volume and surface plasmon excitations. In ultra-small clusters [17] the initial mixing of surface and volume excitations occurs up to ca. 60 electrons when the shell effects contribute [17,19], but for larger size of nanoparticles the separation surface-volume is the better the larger number of electrons is [H21] and is almost ideal for nanospheres with radii larger than ca. 3 nm.

The dynamics equation (the Heisenberg equation for the second order time derivative of local electron density operator) has a complicated form caused by the finite jellium presence and after RPA simplification (including quasiclassical averaging of the kinetic energy of electrons – according to so-called 5/3 Thomas-Fermi formula [14]) describes a pletora of plasmon modes in the nanoparticle [H21] in comparison to only single volume mode in the case of bulk metal [14].

An important advantage of the developed RPA model is a possibility to include dissipation effects taking into account scattering of electrons on other electrons, phonons, admixtures and defects and on boundary of the nanoparticle. The resulting shift of the plasmon resonance caused by scattering-induced damping of plasmons scales as $\frac{1}{a}$, a a is the nanoparticle radius (because of the fact that reflection of electrons by the boundary of nanoparticle is not of mirror type but rather intermediate between the diffusive and specular regimes which gives the damping time scale of order of nanoparticle $\frac{1}{\tau_0} \approx \frac{v_F}{a}$, where v_F is the Fermi velocity) [22] – which agrees with experimental observations for the radius range, 5 nm < a < 10 nm (Au in vacuum) [23].

Nevertheless, the inclusion of the plasmon damping caused by the irradiation effects, as was done by the author with collaborators [H21], leads to the pronounced cross-over in size dependence of plasmon attenuation and to the related resonance red-shift in the region for nanosphere radius $10-12$ nm (Au in vacuum, the region in general depending on the material and dielectric surroundings). At this size region the significant change takes place from the lowering of plasmon damping as $\frac{1}{a}$ to the strong its increase as the radius in cube, a^3 [H24]; the third power of radius is linked with participation in plasmon oscillations and their radiation of all electrons, number of which is proportional to the nanoparticle volume even in the case of surface plasmons [H21].

Contribution of all electrons expressed by the volume factor (a^3 , a -- nonosphere radius) causes the similar scaling of radiative damping of plasmons accounted for by so-called Lorentz friction [H26,H24], i.e., the loss of energy of oscillating charged particles due to irradiation of electromagnetic wave for sufficiently large number of electrons inside the nanosphere. At sufficiently large radius (for Au $a > 12$ nm) the Lorentz friction dominates over other channels of plasmon damping which causes the crossover in the size-dependence of plasmon attenuation and related size-dependence of ithe resonance frequency red-shift. The irradiation energy losses expressed as the Lorentz friction damping quickly grows initially as radius in cube [H27,H28], but, as it has been originally proved by the author, exclusively in the size region when the perturbative solution of the dynamics RPA equation holds. Outside this region the perturbation regime breaks down and the size scaling of plasmon damping again changes its form in a rapid manner [H24,H25].

W. Jacak demonstrated [H24,H25] that for large nanoparticles (with radius > 20 nm, Au in vacuum) the perturbative solution cannot be applied and he found the exact solution of the RPA equation including accurately the Lorentz friction beyond the perturbation approsch. This exact solution strongly differs from the perturbative one and the apparent discrepancy rapidly grows with the nanoparticle radius (as is visible Fig. 1 – the red curve versus the blue one). This behavior indicated that inclusion of the Lorentz friction considerably changes the regime of plasmon oscillations – they are not of harmonic type. The harmonic model appears to be incorrect for plasmons in large metallic nanoparticles and many simplified harmonic models popular in literature (e.g., used by the Atwater group in Caltech [22]) turn out to be misleading. The strong (nonperturbative) Lorentz friction causes considerable change in plasmon dynamics. Instead of increase of damping as radius in cube, correct for perturbative approach for medium size nanospheres, for larger its radii there occurs damping saturation (near the radius of 60 nm for Au in vacuum) and next its lowering with further size growth, quite different in comparison to simplified harmonic oscillator model (Fig.1). The overdamped regime typical for harmonic damped oscillator, which would terminate oscillations at ca. 57 nm (Au in vacuum) within the harmonic model does not exist upon accurate solution. This strong difference is caused by the third order time derivative in the Lorentz friction term [H24,H25] and the related third order differential equation always has oscillatory solution unlike the second order one. The exact solution of the third order dynamics differential equation is distinct that that one for the harmonic oscillator and the harmonic oscillator relation between the frequency and damping, $\omega' = \sqrt{\omega_1^2 - \frac{1}{\tau^2}}, \omega_1 = \frac{\omega_p}{\sqrt{3\varepsilon}}$, does not hold any more. The exact relation between the frequency and damping, beyond the harmonic model, has also an analytical form and has been originally derived by W. Jacak [H24]. It can be written as follows:

$$\omega' + i\frac{1}{\tau} = -\frac{i}{3l} + \frac{i(1+i\sqrt{3})A}{3\times 2^{2/3} lB} + \frac{i(1-i\sqrt{3})B}{6\times 2^{1/3}}, \quad l = \frac{2}{3\sqrt{\varepsilon}}\left(\frac{a\omega_p}{c\sqrt{3}}\right)^3, A = 1+6lq,$$

$$q = \frac{\sqrt{3\varepsilon}}{\tau_0\omega_p}, \quad B = \left(2+27l^2+18lq+\sqrt{-4A^3+(2+27l^2+18lq)^2}\right)^{1/3},$$

which allows us to notice strong differences with respect to ordinary damped harmonic oscillations – as illustrated in Fig. 1 (red – the exact solution, blue – the harmonic oscillator approximation).

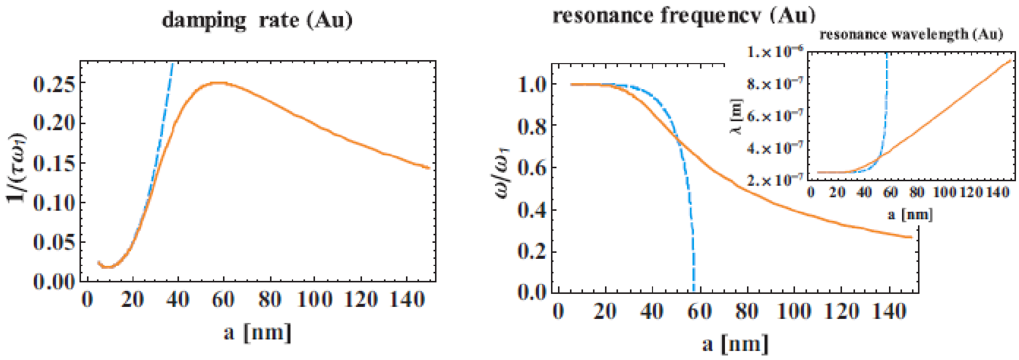

Fig.1. Comparison of the resonance frequency (right) and of damping (left) for accurately included Lorentz friction of surface plasmons in metallic nanoparticle (Au) of radius a [H24] – red line, with the perturbation harmonic solution – blue line (the discrepancy rapidly grows for radii larger than ca. 30 nm, moreover, the approximate harmonic solution disappears at 57 nm due to overdamped regime, which is, however, an artifact of perturbative solution and is dismissed by the exact solution)

The exact solution of the Lorentz friction problem for plasmons in metallic nanoparticles [H24] allowed the author to achieve a very good coincidence of the theory with experiment (in respect to the size dependence of plasmon resonance in metallic nanospheres [H25]). This result allows for more precise modeling of the dielectric function of metal in specific size configuration [H25], which has been next applied to modify numerical study upon the system Comsol [H29] and Mie-type calculation scheme [h30], both utilizing the predefined dielectric function of the analyzed systems. The result has been also confirmed experimentally for Au and Ag in nanoparticle radius region 5 – 75 nm by own measurements [H31] (in collaboration with the group of D. Schaadt [Clausthal]) and by other author measurements reported in the literature (as illustrated for Au in Fig. 2).

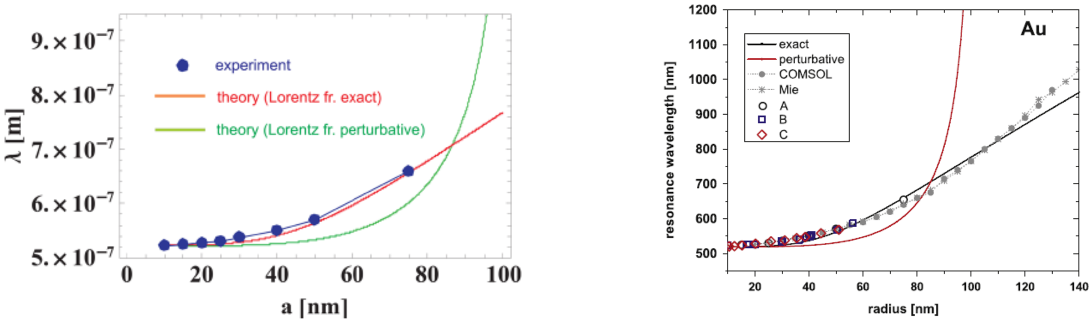

Fig. 2. Good agreement with experiment for size dependence of surface plasmon resonance in Au nanoparticles (the resonance wavelength is shown versus the nanoparticle radius) of theoretical prediction with accurate inclusion of the Lorentz friction [H25] – own measurement results [H31] – left, other author experimental data, A, B, C [H29] – right

The developed RPA theory of plasmons in metallic nanoparticles and their radiative properties turn out to be useful for modeling of so-called plasmonic aided photo-voltaic (PV) effect:

2. Microscopic explanation of plasmonic enhancement of photoelectric effect utilized in solar cells metallically improved in the nano-scale

The damping of plasmons changes radically when in the near surroundings of the metallic nanoparticle with plasmons the another electrical system is placed, e.g., the semiconductor substrate with band electron system. In such a case the extremely strong flow of energy from plasmons to band electrons – the receiver in the substrate semiconductor takes place, which causes that resulting damping of plasmons highly exceeds the Lorentz friction losses in the case of dielectric surroundings. The new and strong channel of energy transfer can be described by use of the Fermi golden rule applied to quantum interband electron transitions induced by near-field of plasmons in metallic nanoparticles deposited on the semiconductor substrate [H32]. Mediation by plasmons in energy harvesting in photoactive semiconductor layer turns out to be a significant modification of the photoelectric effect [H33].

This phenomenon is of high practical importance in view of present rapid development of photo-voltaics (let us mention that in 2015 the world-wide total power of all PV solar cell installations reached ca. 250 GW, whereas, for comparison the whole power of Polish conventional coal/gas energy plants is ca. 29 GW). An increase in efficiency of solar cells (in particular of thin film solar cells or organic ‘plastic’ cells) by only 2-3% due to mediation of plasmons in metallic nanoparticles deposited on cell surface (with small density, $\sim 10^{8-10}\,/\mathrm{cm}^2$, and thus of low cost and easy accessible for industry technology) [38] may have a great economy impact in the field of renewable sources of energy [34-38].

Au, Ag or Cu nanoparticles with radii ~ 10-50 nm enhance efficiency of the photo-effect in laboratory setups of photo sensitive diode by a factor 2-10 due to mediation of energy transfer from incident photons to substrate semiconductor by plasmons in surface deposited metallic components [H34,H35,H38,34,35,36,37,38]. It must be, however, emphasized that in solar cells the efficiency of the photo-effect is only one factor form the long series of other factors defining a final efficiency of a cell and its large increase causes much modest increase of the solar cell total efficiency.

W. Jacak demonstrated by quantum calculus upon the Fermi golden rule scheme [H39,H40,H41] that the near-field coupling of dipole mode of surface plasmons in metallic nanoparticles deposited on the top of semiconductor with the semiconductor band system is very effective, i.e., it causes strong increase of interband transition probability per second and per single incident photon in comparison to the ordinary photo-effect when plane wave photon interacts directly with band electrons. The advantage of the obtained result is its analytical form (similar to the formula for the ordinary photo-effect in semiconductor, though the calculus in the case of plasmon mediation is much more complicated, but also analytically attainable [H32]), which allows for analysis of various competitive mechanism leading to the final efficiency of the photo-effect aided by plasmons [H41].

The core of this calculus resolves to the explicit demonstration that an absence of the translational invariance in the case of the nanoparticle coupled in dipole type near-field with the substrate semiconductor dismisses the constrains to only vertical interband transitions (conserving electron momentum) which in the case of the ordinary photo-effect strongly reduced the transition probability. Small momentum of the incident photon with energy beyond the forbidden energy gap of the semiconductor is negligible in comparison with momenta of Bloch states of electrons involved, which results in ‘veritical’ interband transition constraint in the ordinary photo-effect. This constraint is removed when the translational symmetry is violated in the case of a small metallic nanoparticle presence. Coupling of the plasmon dipole in the near-field regime admits all skew interband transitions enhancing the total probability of interband excitations of carriers in the substrate semiconductor. This effect prefers smaller metallic nanoparticles, but conversely, the larger ones have larger dipoles which also enhance transition probability. In the result the trade-off of these opposite tendencies defines the optimal size of metallic components for the increase of the photo-effect efficiency. Moreover, the important role plays the type of the deposition of the metallic nanoparticle on the semiconductor surface – the most convenient, though problematic from technology point of view, would be to completely embed metallic nanoparticles into the semiconductor layer. In the paper [H21] the mediation of plasmons was accounted for in the ‘atomic’ limit $a \to 0$, whereas in the papers [H32,H41] the theory has been developed for nonzero radius allowing for analysis of mentioned above size trade-off and the role of the deposition type of nanoparticles on the photodiode surface.

Once more we emphasize, that the derived analytical formula for plasmon channel of photo-effect [H32,H41] is of some importance in the theory sense – offering the closed new mostly analytical formalism, and also is of some practical importance for optimization of plasmon effect in real industry solar cells (e.g., in Si for ordinary photo-effect a participation of supplementary excitation – phonons or admixture/defect states – was required because the genuine skew Si band structure, and utilization of small metallic nanoparticles with plasmons opening skew interband transitions might be especially convenient). At present, W. Jacak coordinates the theory part of the Polish-Taiwanese project targeted on optimization of plasmonic effect in solar cells –carried out recently new experiments in Taiwan confirmed the proposed theory [H41,H42,H43].

$$\delta w_0 = \frac{4\sqrt{2}}{3}\frac{\mu^{5/2}e^2}{m_p^2\omega\varepsilon\hbar^3}\left(\frac{\varepsilon E_0^2 V}{8\pi\hbar\omega}\right)(\hbar\omega - E_g)^{3/2} \quad ordinary\ photoeffect$$

$$\delta w = \begin{cases} \dfrac{4}{3}\dfrac{\mu\sqrt{m_n m_p}(\hbar\omega - E_g)e^2 D_0^2}{\hbar^5\varepsilon^2}, & for\ a\xi << 1 \\ \dfrac{4}{3}\dfrac{\mu^{3/2}\sqrt{2}\sqrt{\hbar\omega - E_g}\,e^2 D_0^2}{a\hbar^4\varepsilon^2}, & for\ a\xi >> 1 \end{cases} \quad with\ plasmons$$

Comparison of analytical formulae for interband transition probability in semiconductor for ordinary photo-effect with formula for this probability when energy transfer is mediated by plasmons in metallic nanoparticles with radius *a* deposited on the semiconductor surface; $\xi = \sqrt{2(\hbar\omega - E_g)(m_n + m_p)}/\hbar,\ m_{n(p)}, \mu, E_g$ - effective mass of band electrons (holes), reduced mass, forbidden gap, D_0 - amplitude of dipole-type plasmons [H32,H39,H41]

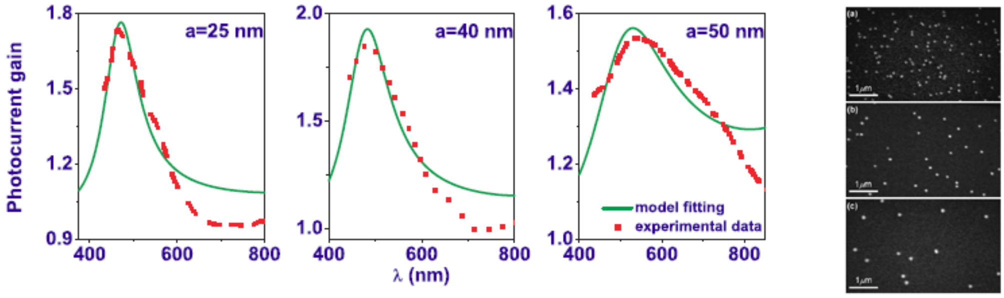

Fig. 3. Good agreement of resonance dispersion in the photo-response of Si photodiode with Au nanoparticles of various size – experiment – red broken line, Schaadt [35], theory – green line [H41], at small surface concentration of Au nanoparticles [35] (right), respectively, $6.6\times10^8, 1.6\times10^8, 7.7\times10^7/\text{cm}^2$ for *a* = 25, 40, 50 nm (constant total mass of metallic components is conserved); maximal increase of photocurrent (1.8 ×) at $a = 40$ nm

The channel of energy transfer through the sub-photon near-field (on the length-scale lower than the photon wave-length) coupling with surface plasmon dipole turns out to be very efficient. This high efficiency of energy transfer results in large damping of plasmon, much larger than radiative damping due to the Lorentz friction or due to the electron scattering [H32] and elucidates the giant plasmonic PV effect. Prospects for utilization in large scale of this effect in industry and in commercial photovoltaics link with methods of practical deposition of nanoparticles on the cell surfaces, which usually reduce the net effect similarly as too large density of metallic particles revealing inconvenient interference reflection effects of the metallic nano-cover. Nevertheless, at low surface concentrations of metallic nanoparticles the theoretically found resonance curves very well coincide with experimental ones [H41,H42,H43]. In particular the excellent coincidence has been achieved for several test samples of photodiode with various coverings with dilute Ag nanoparticles coverings, illustrated in Fig.3. The other experiment elucidated by the developed theory concerns the two layer structure Si/ZnO(*nanopillars*) – thick layer of p-Si covered with n-ZnO vertical nano-rods with diameter of 200-300 nm and hight of ca. 1000 nm (samples were prepared in IP PAS and the measurement was performed at NLTK WUT) [H41]. It has been observed twice increase of the photo-response when the structure was covered from the top with silver nanoparticles with radii 5, 20, 50 nm, this increase has been identified as caused in part by ZnO sub-gap transitions but also by Si substrate with characteristic size dependence [H32], which proved that the range of the plasmonic effect is not lower than 1 micrometer, conveniently for thin-layer solar cell technology [36-38]. Very good agreement with our theory predictions recently has been obtained also by the team form Taiwan upon the common project [H43]. Via studying of over 40 various solar cells improved by Au and Ag nanoparticles (of ca. 50 nm for radius) and with distinct concentration coverings, it has been shown that the multicrystalline Si solar cells gain even 5.6% (Au) and 4.8 % (Ag) of efficiency increase, whereas the CIGS (copper-indium-gallium-diselenide) cells 1.2% (Au), 1.4% (Ag), respectively [H43]. It has been also demonstrated that too high concentration of metallic covering diminishes efficiency of solar cells (due to screening and reflection effects).

Successful theoretical RPA description of plasmons in a single metallic nanoparticle and recognition of their radiative properties allows also for the development of the RPA model onto interacting systems (arrays) of metallic nanoparticles, in particular on metallic nano-chains which may play the role of low-loss plasmon-polariton wave guides.

3. Plasmon-polaritons in metallic nano-chains

Besides the pronounced plasmon photo-voltaic effect there exists another significant and promising plasmonic effect – i.e., an almost lossless kinetics of plasmon-polariton being collective wave-type mode of surface plasmons hybridized with the electro-magnetic wave along the periodic chain of metallic nanoiparticles in analogy to surface mode of plasmons propagating along the metal-insulator interface and also called as plasmon-polariton [9,10]. The change of the geometry configuration of the electro-magnetic field near the metal/insulator interface around the metallic wire is a known effect utilized in high-frequency micro-wave technique (e.g., in single-wire Goubau transmission lines [46]). It appears an interesting issue of similar propagation along discrete metallic nano-chains [44,45,47-51]; related experiments confirmed lossless propagation of dipole collective wave-type oscillation on the experimetally verified range of several micrometers [45,47] and with the group velocity at least 10 times lower than c (the light velocity). The latter property allows for reducing of diffraction constraints [44] severely ranged the miniaturization of opto-nano-electronics, where the wave length of photons with energy corresponding to the scale of nano-electronics (meV) highly exceeds dimensions of the related nano-scale of electronic elements, precluding the miniaturization. Exchange of the electro-magnetic signal by the 10 times (at least) shorter in wave-length plasmon-polaritons with the same frequency as photons, allows for avoiding of diffraction limits and is prospective for future nano-scale plasmon-opto-electronics [8,44,49].

W. Jacak developed an analysis of plasmon-polariton kinetics in metallic nano-chain upon original far-reaching analytical formulation of RPA theory [H51,H52,H53] (being a significant progress in comparison to former numerical studies [48-50]). The analytical formulation allowed for the precise identification of various factors being previously resistant against the particular insight in complex numerical approach [49]. These problems with detailed identification of the role of various

overlapping factors in numerical modeling was the source of ambiguities in the literature of the subject, which were now resolved via application of analytical methods (an example of unclear and misleading interpretation of numerical studies was the postulating of existence of some extraordinary modes of plasmon-polaritons with lower damping and longer range [49], whereas actually theses modes occurred to have the same damping as others but possessing the higher group velocity attain the longer range [H52,H53]; the other confusing numerical result was the suggested superluminal propagation of some plasmon-polaritons
[54], which in fact is the result of numerical artifact caused by approximate numerical procedure of solution of Green function problem perturbative in essence and cut on some step by approximate numerical procedures – this artifact disappears, however, if the nonlinear dynamics is solved accurately preventing perturbative approximation – as was proved by the author [H52]).

An accurate taking into account of radiation in near-, medium- and far-field zone including retardation effects is the crucial property allowed the author to identify of the instability of plasmon-polariton dynamics [H51,H55,H56] – as illustrated Fig. 4. This instability occurs in the popular in the literature simplified regime of only near-field coupling for electro-magnetic interaction of plasmons in a nano-chain (e.g., used by the group of Atwater in Caltech) [45,47]. The accurate treatment dismiss also superluminal plasmon-polariton kinetics erroneously observed in some numerical approximate simulations (e.g., by the group of Markel in Penstate) [49,54]. With regard to plasmon-polaritons in metallic nano-chins the author has contributed originally with the following:

a) He showed that the accurate inclusion of all terms of dipole interaction in near-, medium- and far-field zones, together with retardation effects (frequently neglected in the literature [45,47]) leads to the *ideal* compensation of the Lorentz friction in each nanosphere in the chain by the radiation income from remaining nanoparticles in the chain [H51]; it evidences that the propagation of plasmon-polariton in the chain is radiatively lossless [H51,H52,H53]; taking into account that the Lorentz friction in large metallic nanosphere (with radius > 12 nm, for Au w vacuum) highly exceeds scattering losses of energy (i.e., irreversible dissipation of energy converted finally into Joule heat by scattering with electrons, phonons, admixtures, defects and boundaries), the metallic nano-chain behaves as almost lossless ideal waveguide for plasmon-polaritons [H52]; this agrees with the experimental observations [45,47,49] and points on possible applications in subdiffraction plasmon-opto-electronics due to low group velocity (and lower wave-length in comparison to same energy photons) of plasmon-polaritons [H51,H52].

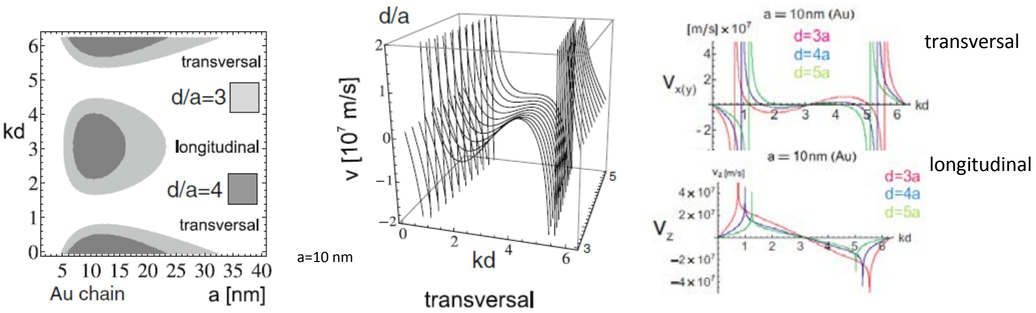

Fig. 4. Indication of instability regions (grey color) of plasmon-polariton dynamics when only near-field zone of interparticle interaction in the chain has been taken into account (*a* – nanoparticle radius, *d* – separation in the chain, *k* – wave vector) (left) [H51]; the example of divergence of the group velocity of plasmon-polaritons upon the perturbative solution of the dynamics (middle) [H51]; the comparison of perturbative singularities for plasmon-polariton transverse and longitudinal polarization group velocities – respectively: sum of the logarithmic singularity and of the hyperbolic one (transverse) and solely the logarithmic singularity (longitudinal) [H53]

b) Developed by the author of RPA model of plasmon-polariton [H51,H52] allowed for original noticing that the ideal compensation of the Lorentz friction takes place only inside the light cone, whereas outside the light cone the damping of plasmon-polaritons is even strengthened above the Lorentz friction scale (this damping out of the light cone increases with the change of the wave number (vector in 1D) in a continuous manner for longitudinal plasmon-polariton polarization (dipole oscillations along the chain direction), and in a step-wise manner for transverse polarization [H51,H52,H53].

c) On the light cone (in 1D there are only two points in Brillouin zone for periodic chain, and the light cone here is rather a triangle in function of the chain separation) the logarithmic singularity of dynamics equation occurs [H51]; this singularity is caused by the constructive interference of radiation of nanospheres in the chain in the far-field zone and occurs only for the transversal polarization of plasmon-polaritons; this singularity causes in turn the similar divergence of any order term of the perturbation series for dispersion [H51]; the logarithmic perturbative divergence in dispersion causes next the hyperbolic singularity in the group velocity for transversal polarized plasmon-polaritons, observed in many numerical simulations presented in the literature [50] (in numerical solution of the dynamics one deals actually with some kind of perturbative solution resulting from unavoidable cutting of the Green function infinite accurate series – this produces an numerical artifact erroneously interpreted as the superluminal propagation [54]).

d) The above pointed error has been explained in details and excluded by the exact (nonperturbative) solution of the dynamics equation for plasmon-polaritons through the special nonperturbative method utilized by the author [H52] (i.e., by solution of the nonlinear problem separately in 20 000 points in the Brillouin zone upon the procedure of Newton-type) which allowed for definition of the dispersion and damping of the plasmon-polariton beyond any perturbative step [H51,H52] – this solution revealed the precise cutting of the ‘perturbative’ singularity in the group velocity (in particular of hyperbolic one for transversal polarization) at the light velocity in the dielectric surroundings [H52] in agreement with the Lorentz invariance;

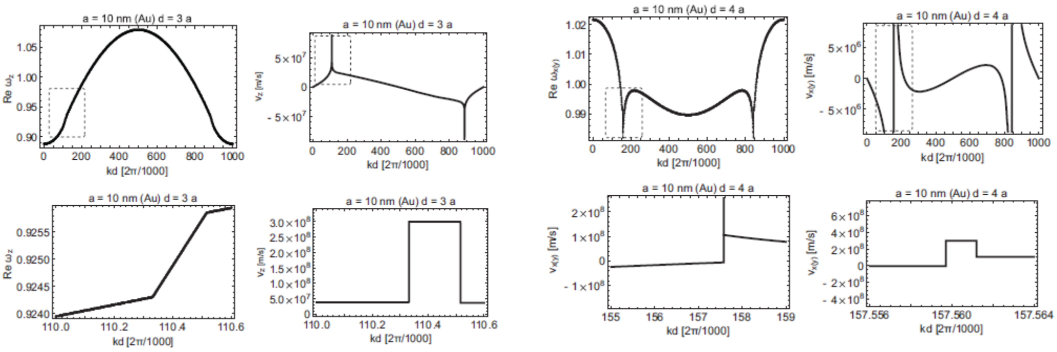

Fig. 5. Illustration for the exact solution of the dynamics equation for plasmon-polaritons in metallic nano-chain for longitudinal polarization (left) and transverse one (right) – broken line marks singular regions; all singularities in group velocities are truncated accurately at the light velocity [H52] (lower panels zoomed the singular regions)

e) The author identified also other singularities in both polarization group velocities of plasmon-polariton – these singularities occur also on the light cone, they are of logarithmic character and are caused by constructive interference in the medium-field zone in dynamics equation for plasmon-polaritons [H52,H53] (again manifesting themselves at any perturbation step) (they are linked with the derivative with respect to k of the medium-field zone contribution, $\sum_n \frac{\sin(nk)}{n^2}$, which is logarithmic divergent at $k=0$, $\sum_n \frac{\cos(nk)}{n} = \frac{-\ln(2-2\cos(k))}{2}$); again via the exact nonperturbative solution the author demonstrated that these group velocity singularities (without dispersion singularity) are excluded and cut exactly at the light velocity level [H52].

f) This analysis elucidates misleading interpretations of numerical approximate simulations being in fact of artifact nature caused by perturbative approach [54,H52] – interesting might be here the analogy to be drawn: in the quantum field theory one deals also with singularities at any step of perturbation which are, however, neglected upon the renormalization procedures – hence the analyzed above problem of plasmon-polariton dynamics is actually the example of explicitly performed renormalization or rather exact solution of the highly nonlinear problem regularized, however, by the Lorentz symmetry.

g) In the similar manner it has been explained also the problem of numerically observed long-range plasmon-polariton mode close to the light cone [H50]; in contrast to the former explanation (in literature) as the extraordinary mode with lowered damping, this longer range has been associated rather with local increase of the group velocity for thin wave packet close to the cut singularity which gave several times longer range of propagation at the same level of damping.

h) By means of the analysis of the convergence of appropriate series related to the radiation effects in the chain the author has demonstrated [H51,H53] a small impact of the finiteness of the chain on the plasmon-polariton kinetics and the usability of the infinite chain results to the finite length periodic structures in practice (even 10 periodic elements in the chain reveal almost the same plasmon-polariton behavior as an infinite chain, due to the very quick convergence of the radiation series, except for those series resulting in singularities – and these ones do not occur in finite chains at all) [H51,H52].

i) The developed theory of plasmon-polariton in metallic nano-chain demonstrates the propagation of collective surface plasmon mode with whole the electro-magnetic field compressed along the chain (which agrees with COMSOL simulations and SNOM microscopy) [45,47]. Due to large incommensurabilty of photon wave-length and the wave-length of plasmon-polariton with the same energy any mutual perturbation of both these excitation is precluded – thus neither the detection or excitation nor perturbation of plasmon-polariton by free photons is possible, which makes plasmon-polariton immune to electro-magnetic perturbations [H51-H53]; moreover, the lossless subdiffraction plasmon-polaritons mode controlled by chain parameters [H51] might be utilized to sensing of nano-deformations in various mechanical construction with strain – by use of elastic substrates with metallic nano-chains simply pasted on strained elements and changing in a step-wise the regime of the plasmon-polariton kinetics due to a small length deformation of the elastic dielectric substrate fixed to the construction [H53].

The effective microscopic RPA type theory of plasmons and plasmon-polaritons in metallic nanostructures creates opportunity to develop the similar approach to other (ionic) charged multiparticle systems:

4. Plasmons and plasmon-polaritons in finite ionic systems

The plasmon and plasmon-polariton RPA theory in metallic nanostructures developed by W. Jacak has been applied by him to the description of ionic plasmons and plasmon-polaritons in finite electrolyte systems (confined by dielectric membranes frequent e.g., in bio-cell organization) [H57]. This generalization required the following steps:

a) The accommodation of the RPA model defined for finite quantumly degenerated Fermi liquid of electrons in metal to Boltzmann-type nondegenerate liquid of ions (fermions or bosons) required a substitution of the so-called 5/3 Thomas-Fermi formula for degenerated electron gas with the classical estimation of the averaged kinetical energy acc. to the Maxwell-Boltzmann distribution; simultaneously the Fermi velocity must be substituted by the Boltzmann average velocity of ions – both these changes introduced the specific temperature dependence absent in metallic RPA model.

b) The core element of the ionic theory of plasmons consists in an introduction of auxiliary fictitious two-component jellium for a binary electrolyte. In any electrolyte both sign ions are dynamical components of the system unlike in metals where the positive jellium of crystal defines the stiff shape of the nanoparticle. Nevertheless, via the thorough modeling of the Hamiltonian in the case of binary electrolyte one can introduce the two component fictitious mutually cancelled jellium (thus without any change of the total energy) [H57]. For small local charge excitations in the electrolyte the two component fictitious jellium model allow for plasmon excitations in analogy to metals in the form of two mutually coupled ionic excitations.

c) This model admits classification of ionic plasmons for volume and surface ones (compressional and translational modes, correspondingly) with various polarities for spherical symmetry and estimation of their energy and damping [H57].

d) Because of larger mass of ions in comparison to electrons and typically lower their concentration in electrolytes in comparison to free electron concentration in metals, the characteristic size scale of plasmonic dimension (defined as the size of finite system with maximal irradiation of plasmons) shifted for ions towards micrometers instead of nanometers for metals and the plasmon frequency is strongly reduced by many order of magnitude depending on the ion concentration and their mass [H57].

e) All elements of the generalized to finite ion systems RPA model found their counterparts in metals including characteristic behavior of surface and volume plasmons (the latter exhibit, however, temperature dependence for ions which was absent for electrons in metals [H57]) and the similar radiation effects including Lorentz friction larger than ordinary scattering losses (depending in the ion case in quite different way with respect to the temperature in comparison to electron archetype, which is caused by substitution of the practically time independent Fermi velocity in metals by the temperature dependent averaged velocity of ions in an electrolyte).

Besides the plasmon excitations in separated single finite electrolyte the theory of ionic plasmons has been developed originally by the author onto periodic ionic finite systems with ionic plasmon-polaritons [H59]. In analogy to plasmon-polaritons in metallic nano-chains there were described all similar properties of ionic plasmon-polaritons in periodic ionic micro-chains. The wave-guide kinetics of plasmon-polaritons in ionic chains has been analyzed with respect to wide range of parameters of ions and confinement scale including also overlap with additional in electrolytes specific vibrational and rotational excitations of the solvent molecules (water).

5. Plasmon-polariton model of saltatory conduction in myelinated axons

W. Jacak applied originally the developed model of plasmon-polaritons in periodic finite ion systems to explain the unknown and to some extent mysterious mechanism of a quick and efficient so-called *saltatory conduction* [61,58] observed in periodically myelinated axons in neurons of peripheral nervous system and in white substance of brain and spinal cord [61]. The standard cable model [60] (originated yet by William Thomson in XIX century) well describes of diffusion type kinetics of electric signal along dendrites and nonmyelinated axons (in grey substance in the central nervous system). The velocity of a signal according to the cable theory depends on the conductivity of the inner-neuron cytoplasm and on the capacity across the cell membrane between inner and outer cytoplasm [61] and is stiffly confined and reaches at most 1-2 m/s; such a signal velocity is too small for transduction of nerve signal over longer distances. Moreover, it has been observed that in myelinated axons, i.e. periodically wrapped with the white lipid substance – myelin, the action signal somehow jumps between consecutive so-called Ranvier nodes separating segments wrapped with the myelin sheath. In this way signal accelerates greatly and its velocity reaches 100-200 m/s required for proper signaling and functioning of the body. The mechanism of these jumps is unknown and has been searched for a long time without, however, a progress, and is only called as the *saltatory conduction*. All agree that the myelin sheath is crucial for the saltatory conduction – nevertheless, it is much thicker layer than that needed for isolation only, moreover any deficit in its thickness results is severe disease Multiple Sclerosis manifesting itself in slowing down of the saltatory conduction. Myelin is produced by so-called Schwann cells for neurons in peripheral system, whereas in the central system by another cells – so-called oligodendrocytes [61]. Remarkably, the length of myelinated sectors is typically of 100 μm and myelinated sectors are separated by bare nonmyelinated very short fragments called as Ranvier nodes [61,58]. On the Ranvier nodes the spikes of the action potential are formed according to the very well know mechanism on the time scale of few ms [61], but the mechanism of jumping of the initiation/ignition signal to the neighboring Ranvier nodes cannot be explained by any model on the cable theory basis.

Upon the original assumption that the saltatory conduction has ionic plasmon-polariton character in neuron periodically wrapped with the thick myelin sheath, the author obtained a satisfactory coincidence of the signal velocity at realistic parameters for electrolyte of the neuron cytoplasm [H59].

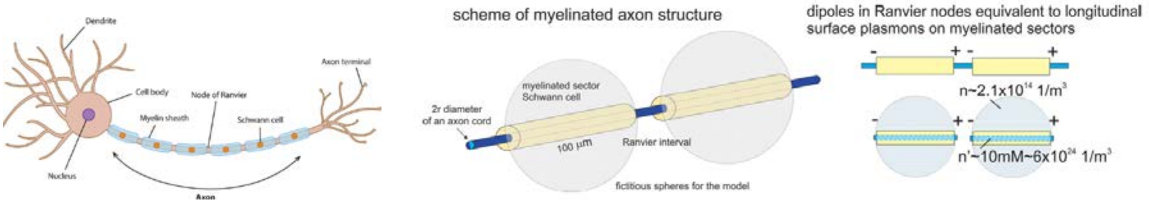

Fig. 6. Pictorial scheme of the myelinated axon and of the idea of plasmon-polariton model for saltatory conduction [H59]

In the model it has been achieved the well coincidence with various features of saltatory conduction observed in myelinated axons [H59], including the following:

a) Large group velocity of the wave packet of plasmon-polariton in agreement with observed velocity in myelinated axons and for real parameters of electrolyte inside the axon.

b) Absence of radiative damping of plasmon-polariton and reducing its attenuation to the level of only Ohmic losses (in lower step than for ordinary conduction) – at small energy supplementation one can achieve forced undamped mode of plasmon-polariton which can propagate without deformation on arbitrary long distance.

c) The energy supplementation takes place residually during the generation of the action potential spikes on consecutive Ranvier nodes upon the known [61] mechanism. This mechanism employs ion channels across the unmyelinated axon cell membrane at Ranvier node, it is a final fragment of a cycle when the steady conditions are restored and the external energy supply is needed to active transfer of ions (Na^+ and K^+) across the cell membrane against concentration gradient. The energy is supplied by ADP/ATP mechanism in the cell and it residually covers also Ohmic losses (transferred finally into Joule heat) of plasmon-polariton.

d) The wave type of the saltatory conduction is confirmed by observation of the maintenance of axon ignition even if the axon is broken into two separated nearly located pieces (this property is impossible to be explained upon the cable theory or upon other electrical current type mechanism, but pretty well fits to the plasmon-polariton properties which can propagate either along the continuous fiber or along the discontinuous chain) [61]. There agrees well also one-way direction of propagation when axon is initiated from the synapse and two-way propagation when the passive neuron is ignited from its center. Plasmon-polariton mechanism agrees also with the observation that firing of axon is continued even if several Ranvier nodes are damaged and inactive [61].

e) It agrees also the temperature dependence typical for ionic plasmon-polaritons, dependence of the plasmon-polariton group velocity on the cross-section of the thin inner cord of the axon, the role of the myelin beyond only insulation (the sufficiently large thickness of myelin sheath is required to build the dielectric tunnel around the inner cord needed for formation of plasmon-polariton; reducing in thickness of this myelin tunnel results in slowing down of the plasmon-polariton propagation which is actually observed at Multiple Sclerosis) [61]

f) It agrees also the exclusive property of plasmon-polaritons, that they cannot be ignited, perturbed or detected by electromagnetic-waves (photons, here of very low energy, do not interact with plasmon-polaritons) and therefore plasmon-polariton signaling is immune to electro-magnetic perturbations (note that the ordinary current conduction in grey substance can be detected by electro-magnetic means [EEG,MEG] and even perturbed electro-magnetically).

The explanation of mechanism of saltatory conduction in myelinated axons via kinetics of ion plasmon-polariton may be important for better recognition of electro-physiology of the nervous system especially with respect to new concept for the role of the myelin and of its deficit at Multiple Sclerosis emphasizing the usability of soft plasmonics developed for finite ion biology systems.

Summary[2]

In the present dissertation consisting of the series of 19 papers (8 single-author papers and few others with dominating contribution of W. Jacak) the author resolved some important problems in the field of plasmonics. In the framework of originally formulated quasiclassical quantum RPA model of metallic nanoparticle there were identified plasmon resonances of volume and surface type in

---

[2] In the paragraph **Summary** the citations are referred to the habilitation dissertation contents i.e., the collection of paper included to the dissertation as presented in the list in point 4 b) on the page 1 (A indicates – author)

spherical metallic nanoparticles of varying size, material and dielectric surroundings [A12][A18]. It has been investigated dumping of these plasmons with particular emphasizing of radiative energy losses due to the Lorentz friction [A2][A4][A11], which has been accounted for in an accurate manner beyond the heuristic and partly misleading model of harmonic plasmon oscillations [A2][A4]. The strong discrepancy between perturbative harmonic approximation and the exact model has been identified by the author and confirmed experimentally [A11][A4]. The analytical formula for size dependence of plasmon damping occurred to be useful for correction of popular Mie formalism and numerical commercial COMSOL system with respect to extension of the limit for so-called *intrinsic size-effect regime* [A4][A15]. It has been explained a mechanism for strong plasmon photo-voltaic effect of enhancement of solar cell efficiency by application of surface metallic nanocomponents [A9][A10][A8]. The size dependence of this effect has been originally identified [A17][A18][19] taking into account competitive factors: admission of skew interband transitions in the semiconductor substrate coupled in near field to plasmons in metallic nanoparticles deposited on the cell surface, which prefers small particles, versus the increase of dipole amplitude requirement preferring larger ones. The very well coincidence with experiment has been achieved [A17][A16][19]][14] including recent progress upon the common international project (Polish-Taiwanese) targeted on optimization of plasmon effect in commercial cells [A16][A14][A17]. The original model of RPA type for plasmon-polaritons in metallic nano-chains has been developed [A7][A13][A18]. By application of analytical methods it has been originally proved the ideal radiatively lossless character of plasmon-polariton kinetics [A6][A7]. The characteristics of this kinetics has been identified (energy, group velocity, damping for particular modes) with respect to parameters of nanoparticles, of chains and of surroundings [A5][A6][A7]. Some artifacts (present in the subject literature, mostly of numerical type) have been elucidated via direct accurate nonperturbative solution of the nonlinear dynamics equation with singularities specific for transversal and longitudinal plasmon-polariton modes [A5][A6][A7]. By application of nonperturbative methods it has been demonstrated an absence of singularities in solutions despite divergences present in the dynamics equation (in agreement with Lorentz invariance) [A5]. In particular it has been shown that the group velocity of plasmon-polariton in the chain locally grows due to interference in medium- and far-field zone near the light cone [A6][A7] but never exceeds the light velocity, though the perturbative approach reveals superluminal kinetics [A5][A6][A7]. Local increase in group velocity rises the range of an appropriately selected plasmon-polariton wave packet, which has been erroneously interpreted in numerical studies as an *extraordinary* lowering of damping [A7][A5]. The damping occurs to be reduced uniformly inside the light cone but never beneath Ohmic losses [A5][A7]. Differences in range of various modes and their packets have been explained by distinct their group velocities and enhancement of damping outside the light cone, which might be utilized as the ultrasensitive strain/deformation sensors in the form of metallic nano-chain on elastic substrate trough observation of rapid change of plasmon-polariton kinetic regimes due to nano-scale substrate deformation [A7]. Suitable for plasmon-opto-electronic applications subdiffraction features of plasmon-polaritons have been pointed out and analyzed [A5][A6][A7]. The next issue was the original formulation of the theory of ionic plasmons in the case of finite electrolyte micro-systems (confined by e.g., insulating membranes frequent in the bio-cell organization) in analogy with plasmonics of nano-metals [A1]. In particular the author applied the model of ionic plasmon-polaritons in periodically modified finite electrolyte structure to explanation of still unknown and searched mechanism of very efficient (exceeding the standard electric models) transduction of action potential along myelinated axons in central and peripheral neural systems, called as saltatory conduction [A3]. The model allowed for a new recognition of the role of myelin sheath in saltatory conduction, quite different from conventionally assumed its isolating role, but important and not well as of yet understand in context of slowing down neuron signaling caused by myelin deficit at the Multiple Sclerosis [A3].

The results presented in the dissertation meet with current intensive development of nano-plasmonics of metallic structures and of subdiffraction photonics with rapidly growing area of applications including new and unexplored previously fields like ion micro-plasmonics developed by the author.

6. Elaboration of remaining scientific achievements of the author:

After PhD the author published 13 other publications (in it 3 monographs) not included to the present habilitation dissertation. These publications are as follows:

1) **W. Jacak,** *Radiative properties of plasmons in metallic nano-particles: photo-voltaic and photonic applications,* invited chapter to the monograph **Handbook of Functional Nanomaterials Volume 2 - Characterization and Reliability**, Chapter 15, Nova Science Publishers, USA, 2012, **ISBN: 978-1-62948-172-2**

2) **W. Jacak,** J. Krasnyj, J. Jacak, A. Henrykowski, L. Jacak, *Mechanism of Plasmon Enhancement PV Efficiency for Metallic Nano-Modified Surface of Semiconduc)tor Photo-Cell,* **Intern. Rev. Phys. (I.R.E. Phy.) vol 4(6)**, 335-348 (2010) (invited chapter)

3) A. Henrykowski, K. Marszalski, **W. Jacak**, *Efficiency of energy transfer in nanomodified photocells via plasmons in metallic nanoparticles*, invited chapter to the monograph **Fuelling the Future: Advances in Science and Technology for Energy Generation, Transmission and Storage**, pp 178-182, edited by A. Mendez-Vilas Brown Walker Press, USA (2012), **ISBN 978-1-61233-556-2**

4) K. Kluczyk, **W. Jacak,** *Size effect in plasmon resonance of metallic nano-particles: RPA versus COMSOL,* **Acta Phys. Pol. A 129,** 83-86 (2016)

5) **W. Jacak,** J. Krasnyj, J. Jacak, *Mechanism of plasmon effect in surface metallically modified solar cells* **Plasmonics: Metallic Nanostructures and Their Optical Properties VIII**, (2010). **SPIE**, pp 77573-1-15, M. Stockman (Ed.) (2010)

6) **W. Jacak**, J. Krasnyj, L. Jacak, *Reducing of spin pure dephasing due to magnons in quantum dots,* **Phys. Rev. B 78**, 073303-1-4 (2008)

7) **W. Jacak**, J. Krasnyj, L. Jacak, *Quantum dot spin pure dephasing due to bulk magnons at low temperatures*, **Phys. Stat. Sol. C 6**, pp 841-845 (2009)

8) **W. Jacak**, J. Krasnyj, L. Jacak, W. Donderowicz, *Dephasing of QD exciton orbital and spin states due to hybridization with bulk collective excitations,* **Int. J. Mod. Phys. B 25 (10)** (2011) 1359-1375

9) **W. Jacak**, J. Krasnyj, L. Jacak, R. Gonczarek, *Dekoherencja orbitalnych i spinowych stopni swobody w kropkach kwantowych,* monograph, **Oficyna Wydawnicza PWr** (2009) pp 1-134, **ISBN 978-83-7493-461-9**

10) M. Jacak, I. Jóźwiak, J. Jacak, J. Gruber, **W. Jacak,** *Wprowadzenie do kryptografii kwantowej: implementacja protokołów kryptografii kwantowej na systemach niesplątanych fotonów (system Clavis II) i splątanych fotonów (system EPR S405 Quelle)*, 200 stron**,** monograph, **Oficyna Wydawnicza PWr**, W-w 2013, **ISBN 978-83-7493-746-7**

11) **W. Jacak**, W. Donderowicz, J. Jacak, *Wstęp do informatyki kwantowej*, monograph**, Oficyna Wydawnicza PWr**, Wrocław 2011, **ISBN 978-83-7493-604-0**

12) **W. Jacak**, W. Donderowicz, L. Jacak, *Introduction to Quantum Information and Communication,* monograph, **Printpap**, Łódź, 2011, **ISBN 978-83-62098-91-0**

13) **W. Jacak**, *On the 'three-orders time-limit' for phase decoherence in quantum dots,* invited chapter (pp 1-26), ***Quantum Dots – Theory and Applications***, **InTech** 2015, **ISBN 978-953-51-2155-8**

The above listed papers in part (1-5) refer, however, also to the habilitation dissertation subject. These are the review papers (invited chapters to international monographs) and conference proceedings contributions. The papers (1) and (2) concern the topic of the dissertation and they are invited review chapters describing the model RPA of plasmons in metallic nanoparticles and PV and subdiffraction photonics applications, the paper (3) on plasmonic enhancement of solar cell efficiency is the conference paper invited to book-edition. The paper (5) is the contribution to SPIE materials related to PV plasmonic effect. The paper (4) is the result of supervision of the author in the preparation of PhD thesis of MSc Katarzyna Kluczyk and this publication contains the presentation of W. Jacak concept confirmed next by the numerical simulations in COMSOL done by the PhD student.

The other papers (6-13) refer mostly to the continuation of the formerly developing field of scientific interest of the author, namely of the decoherence of states in quantum dots (6-9,13). The author developed in this publication the assessment of the feasibility for construction of scaled quantum computer in the quantum dot technology both with use of orbital and spin degrees of freedom and originally formulated by the author in the form of so-called ‘three orders limit’ (13) in view of the diVincenzo criterion of six order advantage in time of control over time of decoherence required to implement quantum error correction scheme. The author presented also his discovery of possible freeze of dephasing of spin in quantum dots located in magnetic surroundings, which from the one side accelerates single spin-qubit Rabi oscillations but causes, on the other side, and inconvenient decoherence of local spin by band magnons. The author argues that at low temperature this harmful decoherence by magnons can be frozen out oppositely to phonon decoherence of charges. This makes spin degrees of freedom in quantum dots more promising for quantum information processing implementations than charges (6-9,13). The other publications (10,11,12) concern a wider field of interest – quantum information processing and practical implementation of quantum cryptography. The author organized at WUT a new laboratory of quantum cryptography equipped with quantum key distribution (QKD) setups on nonentangled and entangled photons and he is co-author of the monograph in this field (10).

The results of the author were also presented on numerous international conferences (23 in the plasmonics field, and 53 in total). W. Jacak developed also international collaboration – in the area of plasmonics this collaboration is linked with:

- He is the coordinator of theory workpackage in the international project Polish-Taiwanese targeted on improvement of solar cells by plasmonic effect and entitled as *„Plasmonics for Photovoltaics: Enhancement of Solar Cell Efficiency”* (2014-2016)

- He is the representative of Poland in the Directory Committee of COST Action MultiscaleSolar, this action joins together over 40 partners from EU, Japan, Australia and US in common research in the field of photovoltaics development and applications

- He carries the bilateral collaboration with the group of prof. D. Schaadt (Karlsruhe, Klausthal) and the group of prof. J. Krasnyj (Odessa) – resulting in common publications in the field of plasmons

- W. Jacak coordinated the NCN project in plasmonics 2013-2015 (project for establishing of the new research team) entitled, *„Badanie radiacyjnych efektów plazmonów powierzchniowych w metalicznych nanocząstkach i nieliniowa teoria kolektywnych plazmono-polarytonów w metalicznych nano-matrycach"(Radiation effects for surface plasmons in metallic nanoparticles and nonlinear theory of collective plasmon-polaritons in metallic nano-matrices)*

- He was a contractor in the project NCN in the plasmonics field 2008-2010, entitled, *„Plazmony powierzchniowe w nanocząstkach metalicznych (opis RPA) – w kierunku podwyższenia sprawności nano-modyfikowanych ogniw słonecznych" (Surface plasmons in metallic nanoparticles (RPA model) – toward efficiency improvement of metallically modified solar cells)*

- He participated earlier in realization of two projects in nanotechnology upon V/VI FP EU

Worth noting is that the plasmonics is a scheduled specialization in the new opened (2016) engineer study at WUT (Faculty of Fundamental Problems in Technology) in quantum technologies. W. Jacak is an author of the study plan and of materials for plasmonics upon these studies basing in part on his own achievements and applications (it is planned a book edition of these materials). W. Jacak was the supervisor of several master theses and engineering theses and now he is a supplementary promotor of the doctor thesis (MSc K. Kluczyk, in due) related to application of COMSOL system to plasmonics of metallic nanostructures.

W. Jacak has been invited to several international conferences with plenary talks and with other presentations. He was a chairman of the large international conference in the field of quantum cryptography seQre2014, Wrocław (2014). He continues also research and development studies in the field of quantum informatics, especially of quantum cryptography including activity of by himself organized Laboratory of Quantum Cryptography in the Department of Quantum Technology WUT.

Bibliography

[1] W. Jacak, *On the 'three-orders time-limit' for phase decoherence in quantum dots*, Quantum Dots – Theory and Applications, InTech 2015

[2] W. Jacak, J. Krasnyj, L. Jacak, R. Gonczarek, *Dekoherencja orbitalnych i spinowych stopni swobody w kropkach kwantowych*, monograph, Oficyna Wydawnicza PWr 2009

[3] W. Jacak, J. Krasnyj, L. Jacak, S. Kaim, *Low-temperature properties of diluted magnetic semiconductor, spin waves*, Phys. Rev. B 76, 165208-1-10 (2007)

[4] W. Jacak, J. Krasnyj, L. Jacak, *Reducing of spin pure dephasing due to magnons in quantum dots*, Phys. Rev. B 78, 073303-1-4 (2008)

[5] H. A. Atwater and A. Polman, *Plasmonics for improved photovoltaic devices*, Nature Materials 9, 205 (2010).
[6] S. A. Maier, *Plasmonics: Fundamentals and Applications*, Springer, Berlin, 2007.
[7] F. J. G. de Abajo, *Optical excitations in electron microscopy*, Rev. Mod. Phys. 82, 209 (2010)
[8] W. L. Barnes, A. Dereux, T. W. Ebbesen, *Surface plasmon subwavelength optics*, Nature 424, 824 (2003)
[9] J. M. Pitarke, V. M. Silkin, E. V. Chulkov, P. M. Echenique, *Theory of surface plasmons and surface-plasmon polaritons*, Rep. Prog. Phys. 70, 1–87 (2007)
[10] P. Berini, *Long-range surface plasmon polaritons*, Adv. Opt. Photonics 1, 484 (2009)
[11] A. A. Abrikosov, L. P. Gorkov and I. E. Dzialoshinskii, *Methods of Quantum Field Theory in Statistical Physics*, Dover Publ. Inc., Dover, 1975
[12] D. Pines and D. Bohm, *A collective description of electron interactions: II. collective vs individual particle aspects of the interactions*, Phys. Rev. 85, 338 (1952)
[13] D. Pines and D. Bohm, *A collective description of electron interactions: III. Coulomb interactions in a degenerate electron gas*, Phys. Rev. 92, 609 (1953)
[14] D. Pines, *Elementary Excitations in Solids*, ABP Perseus Books, Massachusetts, 1999.
[15] C. F. Bohren and D. R. Huffman, *Absorption and Scattering of Light by Small Particles*, Wiley, New York, 1983
[16] G. Mie, *Beitrige zur Optik trӧber Medien, speziell kolloidaler Metallӧsungen*, Ann. Phys. 25, 376, (1908).
[17] M. Brack, *The physics of simple metal clusters: self-consistent jellium model and semiclassical approaches*, Rev. of Mod. Phys. 65, 667 (1993)
[18] W. Ekardt, *Size-dependent photoabsorption and photoemission of small metal particles*, Phys. Rev. B 31, 6360 (1985)
[19] V. V. Kresin, *Collective resonances and response properties of electrons in metal clusters*, Phys. Rep. 220, 1 (1992)
[20] S. Link, M. A. El-Sayed, *Size and Temperature Dependence of the Plasmon Absorption of Colloidal Gold Nanoparticles*, J. Phys.Chem. B 103, 4212−4217 (1999)
[21] J. Jacak, J. Krasnyj, W. Jacak, R. Gonczarek, A. Chepok, L. Jacak, *Surface and volume plasmons in metallic nanospheres in a semiclassical RPA-type approach: Near-field coupling of surface plasmons with the semiconductor substrate*, Phys. Rev. B 82, 035418-1-14 (2010)
[22] M. L. Brongersma, J. W. Hartman, H. A. Atwater, *Electromagnetic energy transfer and switchingin nanoparticle chain arrays below the diffraction limit*, Phys. Rev. B, 62, R16356–R16359 (2000)
[23] U. Kreibig and M. Vollmer, *Optical Properties of Metal Clusters*, Springer, Berlin, 1995
[24] W. Jacak, *Size-dependence of the Lorentz friction for surface plasmons in metallic nanospheres*, Optics Express 23, 4472-4481 (2015)
[25] W. Jacak, *Lorentz Friction for Surface Plasmons in Metallic Nanospheres*, J. Phys. Chem. C 119(12), 6749–6759 (2015)
[26] L. D. Landau, E. M. Lifshitz, *Field Theory*, Nauka, Moscow, 1973
[27] K. Kolwas, A. Derkachova, M. Shopa, *Size characteristics of surface plasmons and their manifestation in scattering properties of metal particles*, J. Quant. Spectrosc. Radiat. Transf. 110, 1490–501 (2009)
[28] K. Kolwas, A. Derkachova, *Damping rates of surface plasmons for particles of size from nano- to micrometers; reduction of the nonradiative decay*, J. Quant. Spectrosc. Radiat. Transf. 114, 45–55 (2013)
[29] K. Kluczyk, W. Jacak, *Damping-induced size effect in surface plasmon resonance in metallic nano-particles: comparison of RPA microscopic model with numerical finite element simulation (COMSOL) and Mie approach*, J. Quant. Spectrosc. Radiat. Transf. 168, 78 (2016)
[30] K. Kluczyk, W. Jacak, *Size effect in plasmon resonance of metallic nano-particles: RPA versus COMSOL*, Ata Phys. Pol. A (2015) (in press)
[31] W. Jacak, J. Krasnyj, J. Jacak, R. Gonczarek, A. Chepok, L. Jacak, D. Z. Hu, D. Schaadt, *Radius dependent shift in surface plasmon frequency in large metallic nanospheres: Theory and experiment*, J. Appl. Phys. 107, 124317 -1-14 (2010)
[32] W. Jacak, *Plasmon mediated energy transport in PV systems with photo-active surface modified metallically in nano-scale and in metallic nano-chains, Plasmonics - Principles and Applications*, InTech 2012
[33] W. Jacak, J. Krasnyj, J. Jacak, *Mechanism of plasmon effect in surface metallically modified solar cells*, Plasmonics: Metallic Nanostructures and Their Optical Properties VIII, SPIE, 77573-1-15 (2010)
[34] S. Pillai, K. R. Catchpole, T. Trupke, G. Zhang, J. Zhao, M. A. Green, *Enhanced emission from Si-based light-emitting diodes using surface plasmons*, Appl. Phys. Lett. 88, 161102 (2006)
[35] D. M. Schaadt, B. Feng, E. T. Yu, *Enhanced semiconductor optical absorption via surface plasmon excitation in metal nanoparticles*, Appl. Phys. Lett. 86, 063106, (2005)
[36] M. Westphalen, U. Kreibig, J. Rostalski, H. Lüth, D. Meissner, *Metal cluster enhanced organic solar cells*, Sol. Energy Mater. Sol. Cells 61, 97 (2000)

[37] A. J. Morfa, K. L. Rowlen, T. H. Reilly, M. J. Romero, J. Lagemaat, *Plasmon-enhanced solar energy conversion in organic bulk heterojunction photovoltaics,* Appl. Phys. Lett. 92, 013504 (2008)

[38] M. A. Green, S. Pillai, *Harnessing plasmonics for solar cells*, Nat. Photon. 6, 130–132 (2012)

[39] W. Jacak, J. Krasnyj, J. Jacak, W. Donderowicz, L. Jacak, *Mechanism of plasmon-mediated enhancement of PV efficiency*, J. Phys. D: Appl. Phys. 44, 055301-1-14 (2011)

[40] W. Jacak, A. Henrykowski, K. Marszalski, *Plasmon enhanced photovoltaic effect in metallically nanomodified photocells,* Sol. Energy Mater. Sol. Cells 117, 663-666 (2013)

[41] W. Jacak, E. Popko, A. Henrykowski, E. Zielony, G. Luka, R. Pietruszka, B. Witkowski, L. Wachnicki, M. Godlewski, L-B. Chang, M-J. Jeng, *On the size dependence and the spatial range for the plasmon effect in photovoltaic efficiency enhancement,* Sol. Energy Mater. Sol. Cells 147, 1-16 (2016)

[42] E. Placzek-Popko, K. Gwóźdź, Z. Gumienny, E. Zielony, R. Pietruszka, B. S. Witkowski, Ł. Wachnicki, M. Godlewski, W. Jacak, Liann-Be Chang, *Si/ZnO nanorods/Ag/AZO structures as promising PV plasmonic cells,* J. Appl. Phys. 117, 193101 (2015)

[43] M-J. Jeng, Zih-Y. Chen, Y-L. Xiao, L-B. Chang, J. Ao, Y. Sun, E. Popko, W. Jacak, L. Chow, *The efficiency enhancement of silicon and CIGS solar cells by the incorporation of metal nanoparticles*, Materials 8, 6761–6771 (2015)

[44] P. A. Huidobro, M. L. Nesterov, L. Martin-Moreno, F. J. Garcia-Vidal,. *Transformation Optics for Plasmonics*, Nano Lett. 10, 1985−1990 (2010)

[45] S. A. Maier, P. G. Kik, H. A. Atwater, *Optical Pulse Propagation in Metal Nanoparticle Chain Waveguides,* Phys. Rev. B 67, 205402−205407 (2003)

[46] G. Goubau, Surface Waves and Their Application to Transmission Lines, *J. Appl. Phys*. 21, 119 (1950)

[47] S. A. Maier, H. A. Atwater, *Plasmonics: Localization and guiding of electromagnetic energy in metal/dielectric structures,* J. Appl. Phys. 98, 011101 (2005)

[48] D. S. Citrin, *Plasmon Polaritons in Finite-Length Metal-Nanoparticle Chains: The Role of Chain Length Unravelled*, Nano Lett. 5, 985 (2005)

[49] D. S. Citrin, *Coherent Excitation Transport in Metal-Nanoparticle Chains,* Nano Lett. 4, 1561−1565 (2004)

[50] V. A. Markel, A. K. Sarychev, *Propagation of surface plasmons in ordered and disordered chains of metal nanospheres,* Phys. Rev. B 75, 085426 (2007)

[51] W. Jacak, *On Plasmon Polariton Propagation Along Metallic Nano-Chain,* Plasmonics 8, 1317 (2013)

[52] W. Jacak, *Exact solution for velocity of plasmo-polariton in metallic nano-chain*, Optics Express 22, 18958-18965 (2014)

[53] W. Jacak, J. Krasnyj, A. Chepok, *Plasmon-Polariton Properties in Metallic Nanosphere Chains,* Materials 8, 3910-3937 (2015)

[54] A. A. Govyadinov, V. A. Markel, *From slow to superluminal propagation: Dispersive properties of surface plasmon polaritons in linear chains of metallic nanospheroids*, Phys. Rev. B, 78 (2008)

[55] W. Jacak, J. Krasnyj, J. Jacak, A. Chepok, L. Jacak, W. Donderowicz, D. Z. Hu, D. Schaadt, *Undamped collective surface plasmon oscillations along metallic nanosphere chain*, J. Appl. Phys. 108, 084304-1-13 (2010)

[56] W. Jacak, *Radiative properties of plasmons in metallic nano-particles: photo-voltaic and photonic applications*, Handbook of Functional Nanomaterials Volume 2 - Characterization and Reliability, Nova Science Publishers, 2012

[57] W. Jacak, *Plasmons in finite spherical electrolyte systems: RPA effective jellium model for ionic plasma excitations*, Plasmonics (Springer) 11/2, 1-15 (2015) DOI: 10.1007/s11468-015-0064-6

[58] T. Heimburg, A. D. Jackson, *On soliton propagation in biomembranes and nerves,* Proc. of the National Academy of Sciences of the USA 102, 9790 (2005)

[59] W. Jacak, *Propagation of Collective Surface Plasmons in Linear Periodic Ionic Structures: Plasmon Polariton Mechanism of Saltatory Conduction in Axons,* J. Phys. Chem. C 119(18), 10015−10030 (2015)

[60] W. Thomson, *On the theory of the electric telegraph*, Proc. R. Soc. London 7, 382 (1854-1855)

[61] D. Debanne, E. Campanac, A. Białowąs, E. Carlier, G. Alcaraz, *Axon physiology*, Physiol. Rev. 91, 555 (2011)

[62] S. Brzychczy, R. Poznański, *Mathematical Neuroscience*, Academic Press, San Diego, 2013