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Theory of photogalvanic effect in asymmetric nanostructure arrays

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Abstract

Free electron motion in a lattice (random and regular) of asymmetric antidots under the action of ac electric field is studied. Both analytical consideration (in the framework of Boltzmann equation) and computer simulations were used. Models of antidots include oriented semidisks and cuts with different reflectivity of sides. The stationary photocurrent is found for different polarizations of electric field.

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The problem of stationary flow created by monochromatic fields in the systems with no inversion symmetry has a long history [1–4]. Generally formulated as mechanisms for stationary flow of anything, caused by system asymmetry and external power supply, this problem attracted attention not only in physics but in biology and other sciences. As far as the interest to it has been multiply renewed, the problem any time obtained new name (optical rectification, ratchets, photogalvanic effect, electron pumps, directed transport, etc.) being partially synonyms. Recently the interest to it has been renewed in connection to quantum pumps [5–8] and artificial 2D antidot lattices [9–12].

In the present report we study electrons, treated as classical particles, in a 2D system of artificial asymmetric scatterers in a monochromatic electric field. As scatterers we considered antidots with hard boundaries, namely oriented semidisks or cuts with one specular and another diffusive sides like those depicted in Fig. 1. It is assumed that there is no potential between antidots.

The case of rare scatterers is studied analytically in the framework of kinetic equation approximation. The stationary current is described by expression $j_i = \alpha_{ijk} E_j E_k^* +$ c.c. In the absence of magnetic field the symmetry of the system allows following non-vanishing components of α_{ijk}: $\alpha_{xxx} = \alpha^*_{xxx}$, $\alpha_{xyy} = \alpha^*_{xyy}$, $\alpha_{yxy} = \alpha^*_{yyx}$. The real components $\alpha_{xxx}, \alpha_{xyy}$ determine j_x response to linear polarized electric field along x and y, the quantities $\mathrm{Re}(\alpha_{yxy})$ and $\mathrm{Im}(\alpha_{yxy})$ determine j_y component arising from tilted linear polarization and circular polarization, correspondingly.

The comparison of results for cuts and semidisks exhibits different polarization dependence. In particular, the linear polarization in x and y directions results in opposite values of electric current for the case of semidisks and different values for the model of cuts. At zero temperature the expressions for components of photogalvanic tensor α_{ijk} read

$$\alpha_{xxx} = -A[(2-2s) + C]a_{xxx}, \tag{1}$$

$$\alpha_{xyy} = A[(2-2s)a_{xxx} - Ca_{xyy}], \tag{2}$$

$$\mathrm{Re}(\alpha_{yxy}) = -A\left[(2-2s)a_{xyy} + \frac{C}{2}(a_{xyy} - a_{xxx})\right]. \tag{3}$$

Here, $A = e^3 V_F \tau^3/(\pi\tau_c(1+\omega^2\tau^2))$, $C = s(1-\omega^2\tau^2)/(1+\omega^2\tau^2)$, $\tau_c = 1/n_c v$ (cuts) or $\tau_c = \sqrt{3}R^2/(8r_d v)$ (semidisks) is the characteristic scattering time on asymmetric scatterers (n_c is the concentration of cuts, D is the cut length, R is the distance between semidisks, r_d is the radius of semidisk, $v = \sqrt{2\varepsilon/m}$ is the electron velocity), $\tau = \tau_i\tau_c/(\tau_i + \tau_c)$, where τ_i is the relaxation time of

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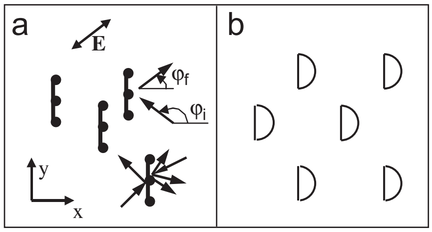

Fig. 1. Considered models of oriented scatterers. Left panel: model of vertical cuts with specular left side and diffusive right side. Right panel: model of triangular lattice of oriented semidisks. The electric field $\mathbf{E}\cos(\omega t)$ is linear-polarized under angle θ to x-axis.

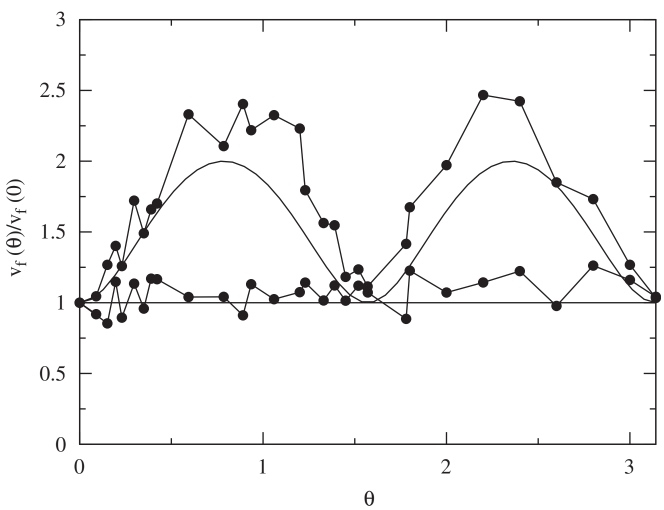

Fig. 2. Dependence of the rescaled absolute value of ratchet velocity $v_f(\theta)/v_f(\theta=0) \equiv j_x(\theta)/j_x(0)$ on the polarization angle θ for the cuts (top points at $\theta = 0.7$) and semidisk (bottom points at $\theta = 0.7$) models; corresponding theory is shown by smooth curves.

scattering on impurities; τ and τ_c are taken at $\varepsilon = \varepsilon_F$. We assume the power dependence of τ_i on electron energy, $\tau_i \propto \varepsilon^s$. The quantities a_{ijk} depend on the model of asymmetric scatterers. For the cuts model these quantities are equal to: $a_{xxx} = \frac{1}{48}$, $a_{xyy} = -\frac{1}{16}$. For semidisks $a_{xxx} = -a_{xyy} = \frac{1}{12}$. Formulas (1)–(3) with $s = -\frac{1}{2}$ also follow from the exact solution of the problem for cuts obtained in Ref. [12].

The kinetic equation applicability requires the developed chaos picture in the system. Hence, this approach describes the regular antidot lattices only partially, when the distance between the scatterers strongly exceeds their size. Many interesting features of regular lattices, including geometric resonances, disappear in the kinetic approach. They can be clarified by numerical simulations only.

We have performed numerical simulations of the regular triangular lattice of semidisks. This study was concentrated mostly on the case of moderately dense system. Nevertheless, the intersection of the applicability domains of analytical theory and simulations were also examined. The case of non-correlated collisions with cuts was simulated also.

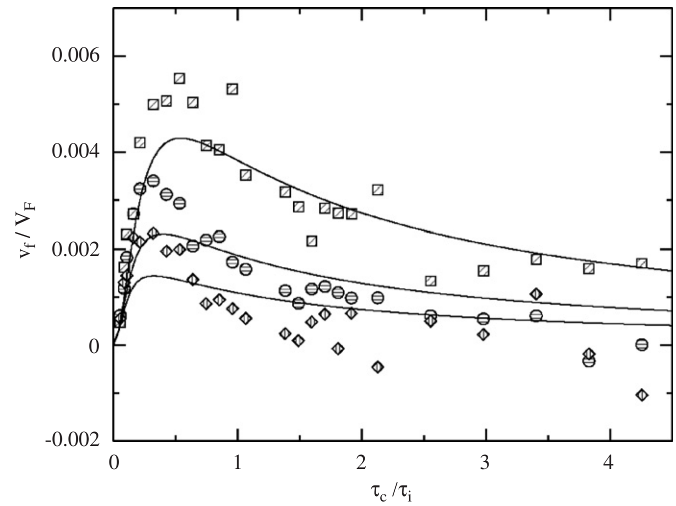

Fig. 3. Dependence of the rescaled velocity of ratchet $v_f/V_F = j_x/enV_F$ (n is electron concentration) on the rescaled collision time τ_c/τ_i obtained by numerical simulations of the cuts model (symbols) for $\omega\tau_i = 4.7$; 7.05; 9.4 (from top to bottom, respectively, at $\tau_c/\tau_i = 1$). The full curves show the theoretical dependence for corresponding $\omega\tau_i$ multiplied by a numerical factor $Q = 0.54$. Here, the equilibrium Fermi–Dirac distribution has the temperature $T/E_F = 0.1$ and $eE\tau_i V_F/E_F = 4.2$; the polarization angle $\theta = 0$.

The Newton equations were solved numerically between collisions. The Maxwell (or Fermi–Dirac) equilibrium at temperature T is generated with the help of the Metropolis thermalization algorithm as it is described in Ref. [11]. The computation time along one trajectory is about few hundred thousands of microwave periods. Some results are shown in Figs. 2 and 3. They are in a good agreement with the obtained theoretical expressions both for the cuts and semidisks models.

We also studied the effect of external magnetic field on electron dynamics in the considered systems in the presence of alternating electric field. The dense system exhibits many features of dynamic chaos. In particular, strong geometric resonances are observed in the magnetic field caused by commensurability of the cyclotron radius and the lattice period.

For experiments on photogalvanic current in asymmetric nanostructures it is important to know what are the effects of a magnetic field $\mathbf{B}$ perpendicular to the 2DES plane on the strength of current and its directionality. An analytic solution of the kinetic equation becomes much more complicated compared to the cases considered above. This is especially the case when the Larmour radius R_L of electron motion becomes comparable with the size of asymmetric antidots. Therefore, the numerical simulations in this case become especially important. For the semidisks Galton board the effects of magnetic field have been studied in Ref. [11]. They clearly show that the ratchet current becomes quite weak when the Larmor radius R_L becomes smaller than the semidisk radius r_d. This follows from the so-called "memory effects", the suppression of transport in conservative 2D system due to

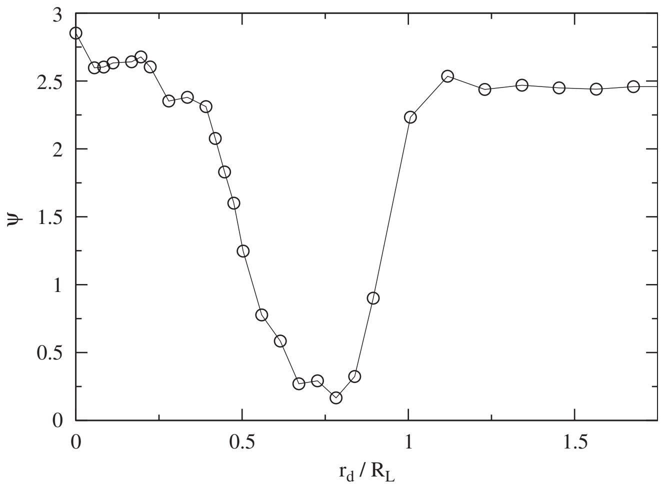

Fig. 4. Dependence of current angle ψ towards x-axis on a rescaled magnetic field $r_d/R_L \propto B$ at $\theta = 0$; curve with circles shows numerical data for the semidisks model with $R/r_d = 2.5$.

multiple returning of electron in strong magnetic field to the starting point.

However, in the regime with $r_d/R_L{\sim}1$ a relatively weak magnetic field can significantly affect the directionality of photogalvanic current. This is illustrated in Fig. 4, where a moderate magnetic field changes the direction of the current almost on 180°. We attribute the origin of this strong angular dependence to a significant change of scattering process in the regime when $r_d/R_L{\sim}1$ related to multiple collisions of electron with a semidisk.

In conclusion, we have developed a theory which determines the strength and directionality of the photogalvanic current in artificial asymmetric antidot lattices. Analytical and simulative results are in good agreement. We have found also that the direction of current can be easily ruled by magnetic field. Our estimations of drift velocity ($v_f{\sim}10^5$ cm/s at $E{\sim}1$ V/cm) give hope for utilizing the photogalvanic effect in antidot lattices for creation of room temperature detectors of radiation in teraherz range.

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