Theory of photogalvanic effect in asymmetric nanostructure arrays

A.D. Chepelianskii\textsuperscript{a}, M.V. Entin\textsuperscript{b}, L.I. Magarill\textsuperscript{b,}\textsuperscript{*}, D.L. Shepelyansky\textsuperscript{c}

\textsuperscript{a}Ecole Normale Supérieure, 45, rue d’Ulm, 75231 Paris Cedex 05, France
\textsuperscript{b}Institute of Semiconductor Physics, Russian Academy of Sciences, Siberian Branch, 630090 Novosibirsk, Russian Federation
\textsuperscript{c}Laboratoire de Physique Théorique, UMR 5152 du CNRS, Univ. P. Sabatier, 31062 Toulouse Cedex 4, France

Available online 6 September 2007

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.

Keywords: Photogalvanic effect; Antidot lattices

The problem of stationary flow created by monochromatic fields in the systems with no inversion symmetry has a long history\cite{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 has been renewed in connection to quantum pumps\cite{5–8} and artificial 2D antidot lattices\cite{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 $j_i = \alpha_{ijk} E_j E_k + \text{c.c.}$ in the absence of magnetic field the symmetry of the system allows following non-vanishing components of $\alpha_{ijk}$:

$$\alpha_{xxx} = \alpha_{xxy}^*, \alpha_{xyy} = \alpha_{yxy}^*, \alpha_{yxy} = \alpha_{xyy}^*.$$  \text{(1)}

The real components $\alpha_{xxx}, \alpha_{xyy}$ determine $j_x$ response to linear polarized electric field along $x$ and $y$, the quantities Re($\alpha_{xyy}$) and Im($\alpha_{xxy}$) 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 $\alpha_{ijk}$ read

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

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

$$\text{Re}(\alpha_{xyy}) = -A \left(2 - 2s \right) d_{xyy} + \frac{C}{2} (a_{xyy} - a_{xxx}).$$  \text{(3)}

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

---

\textsuperscript{*}Corresponding author. Tel.: +7 383 33264; fax: +7 383 332771.

E-mail addresses: entin@isp.nsc.ru (M.V. Entin), levm@isp.nsc.ru (L.I. Magarill).

1386-9477/S - see front matter \copyright 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.physe.2007.08.046
scattering on impurities; τ and τc are taken at ε = εF. We assume the power dependence of τi on electron energy, τi ∝ εi. The quantities a_{ijk} depend on the model of asymmetric scatterers. For the cuts model these quantities are equal to: a_{xxx} = \frac{1}{2}, a_{xxy} = -\frac{1}{2}. For semidisks a_{xxx} = -a_{xxy} = \frac{1}{2}. 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.

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

However, in the regime with $r_d/R_L = \frac{1}{C^2}$ 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 $180^\circ$. 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 terahertz range.

This work was supported in part by the ANR PNANO project MICONANO and (for MVE and LIM) by the Program for support of scientific schools of the Russian Federation No. 4500.2006.

References