Microwave and Terahertz Nanodetectors based on Ratchet effect

NANOTERRA

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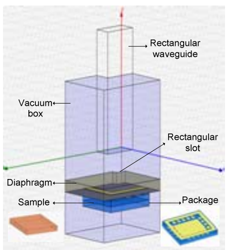
Abstract

The directed electron transport in a spatially-periodic asymmetrical system – called “ratchet” – is under study. It is a system of two-dimensional electron gas (2DEG) formed in a semiconductor heterojunction and driven by an external linear-polarized microwave (MW) irradiation. The spatial inversion symmetry of the system is broken by introducing of artificial periodic array of asymmetric antidots shaped in semi-disk form. A dc voltage of few mV was observed in the “ratchet” antidot lattice under the MW irradiation. The dc current was studied in two different materials with different antidot lattice parameters in function of magnetic field, temperature, MW polarization and power. The results are in good agreement with recent theory.

Electromagnetic Analysis of Experimental Setup used for Controlling Ratchet Effect in a Periodic Array of Asymmetric Antidots



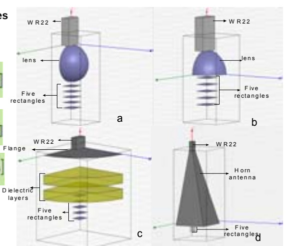
The 3D simulation model created with HFSS software for representing the experimental setup

The intrinsic performances are evaluated using the following coefficients:

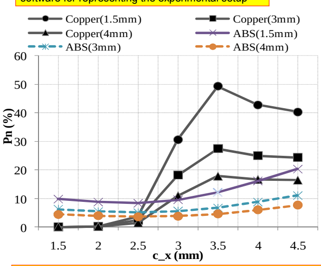
$$K_E = \min^R \frac{|\vec{E}_y|}{|\vec{E}_t|} \cdot 100\ [\%]$$

$$K_P = \frac{\min^R |\vec{P}|}{\max^R |\vec{P}|} \cdot 100\ [\%]$$

$$P_n = \frac{100}{P_{in}} \oint_R \mathrm{Real}(\vec{P}) \cdot d\vec{s}\ [\%]$$



Solutions to improve the intrinsic performances of the experimental setup:
a)Electromagnetic illumination from the WR22 aperture and a Spherical Dielectric Lens
b)Electromagnetic illumination from the WR22 aperture and a Semi-Spherical Dielectric Lens
c)Electromagnetic illumination from the WR22 and a Dielectric Multi-slab structure
d)Electromagnetic illumination from the WR22 and a Horn Antenna



Electromagnetic incident power flow across the rectangular sample surface normalized to the average power supplied by the carcinotron as a function of the material type of the diaphragm (metal or absorber), the distance (d) between the diaphragm and the WR22 end (1.5mm, 3mm, 4mm) and the length of rectangular hole (c_x). The sample and the package are not present and the sample is positioned at approximately dz=0.2 mm below the diaphragm

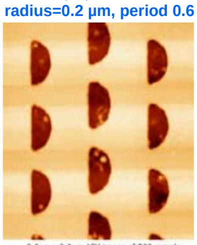
			K_E (%)	K_p (%)	P_{in} (%)	L_s	dz (mm)
WR22			88.4	36.6	23.3	-	4.5
WR22+metallic plate			93	56	15.5	0.3	4.5
WR22+absorber plate			98.3	75.4	1.8	0.5	4.5
WR22+ spherical lens	D=7mm		98.5	47.6	14.2	1	4.5
	D=14mm		98.3	38.4	3.8	2	4.5
WR22+ semi-spherical lens	D=7mm		99	73.9	8.7	0.5	4.5
	D=14mm		92.4	65.1	12.2	1	1.5
	D=21mm		96.1	52.4	6.4	1.5	1.5
	D=28mm		93.2	62.6	3.8	2	0.5
WR22+planar multilayer		S1	97.8	87.6	6.7	1.1	3.5
		S2	89	88.3	6.7	1.6	4.5
WR22+Horn antenna			98	90	6	4.5	0.5

A. Takacs, D. Medhat, H. Aubert & J.C. Portal, Electromagnetic Analysis of the Experimental Setup Used to Investigate the RATCHET Effect in Two-Dimensional Electron System Under Microwave Radiation, accepted to CAS’2009, 12-14 oct 2009, Romania
D. Medhat, A. Takacs, H. Aubert & J.C. Portal, Comparative Analysis of Different Techniques for Controlling Ratchet Effect in a Periodic Array of Asymmetric Antidots, accepted to APMC’2009, 7-10 dec 2009, Singapore

Experiment

Ratchet Photovoltage in Si/SiGe heterostructures

AFM image part of antidots lattices radius=0.2 µm, period 0.6 µm



Samples are high mobility 2DEG based on Si/SiGe heterostructures with Hall bar geometry.
The lattices of semi-circular antidots cell have the dimensions 80 × 50 µm² and the parameters: period = 0.6 µm and antidot radius = 0.2 µm.
Lattices with the same parameters but with circular antidots were also fabricated

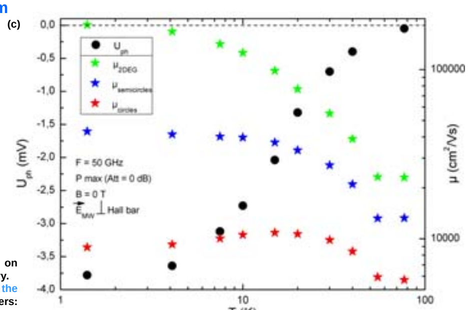
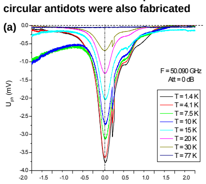


Fig. (c) shows the temperature dependence of the ratchet signal and that of the mobility in ratchet part, intact 2DEG part and circles antidots part.



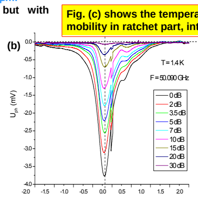


Fig. (a) and (b) presents the photovoltage measurements depending of Temperature (a) of microwave power (b) and magnetic field dependence: dc-voltage induced by the linear polarized microwaves in the ratchet antidot lattice. The effect goes to zero in weak magnetic fields. No ratchet effect in symmetric lattices and in pure 2DEG.

-The effect disappears at liquid nitrogen temperature (77 K) since the electron mean free path becomes equal to 0.3 µm at 77 K, this is comparable to the antidots spacing (0.2-0.4 µm).

-Ratchet photovoltage is measured under linear polarization of MW radiation without polarity change by any orientation of polarized radiation applied (because small period and important electronic density: $6.2\times10^{11}/cm^2$ and specific electron-electron scattering for semi-disk antidots). **(r=0.2 µm and p=0.6 µm, with cell of 80×50 µm², and of 500×500 µm²).**

-No ratchet photovoltage is observed with symmetric circular antidots with same lattice parameters

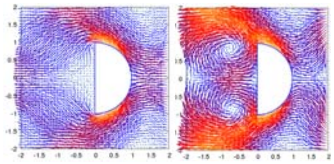
-Photovoltage ratchet requires mean free path of electrons larger than semi-disk antidot spacing

-The observation of the “ratchet” effect in antidot lattices realized on industry materials as Si/SiGe, at liquid nitrogen temperatures means that it is possible to observe “ratchet” rectification at higher temperatures.
-For this aim it is necessary to fabricate such lattices with smaller period. New antidots lattice with radius=40 nm and period=120 nm on Si/SiGe are in progress with photovoltage cell of 500 × 500 µm² where the electron mean free path becomes is close to period .
-It gives perspectives to fabricate new electromagnetic radiation detectors sensitive and having linear response to the radiation power, and operating in MW and open for terahertz frequency ranges
-An important conclusion is obtained and it is that a directed current can be created even by unpolarized radiation for typical asymmetric scatterers (effect observed recently in our Si/SiGe experiment) .This results gives a basics for creating at room temperature ,detectors ,current and voltage microgenerators of polarized or unpolarized terahertz radiation with small lattice parameters (nanostructures without external electrical source).

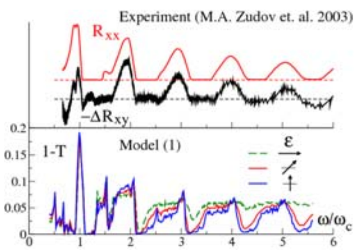
The Theory – Ratchet and Zero resistance states

Exposed to the linear-polarised microwave irradiation, asymmetric antidot lattice (mesoscopic periodical system of scattering centres realized on semiconductor heterojunction with 2DEG) will play a role of quantum ratchet, while the MW itself will serve as driving force and as external energy input (which will drive the system out of equilibrium) at the same time. ⟶ Directed electron motion induced by MW in such structures.

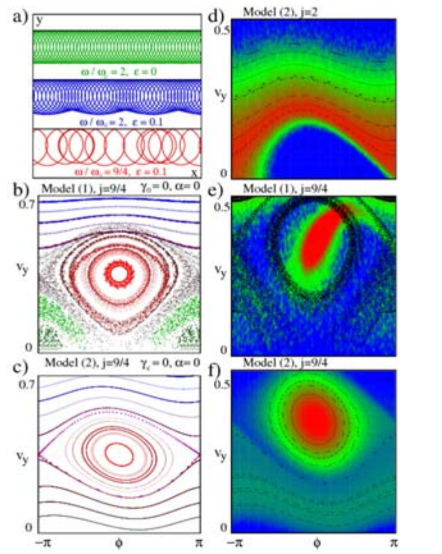
$$\frac{v_f}{V_F} = \frac{\tau(eE\tau V_F)^2}{12E_F^2\tau_c(1+\omega^2\tau^2)}$$



Left : Ratchet flow without electron-electron interactions
Right : Ratchet flow with strong interactions
Polarisation angle is □ = 0



We have show that a microwave field can stabilize edge trajectories even in the semi-classical regime leading to a transmission coefficient exponentially close to unity and to avanishing longitudinal resistance.
This mechanism gives a clear physical interpretation for observed zero-resistance states.

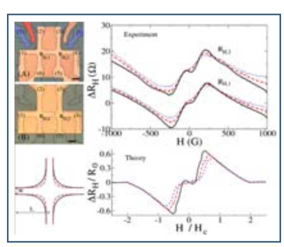


a) Examples of electron trajectories along sample edge. b) Poincaré section of for j = □□ = 9/4 and y polarization with □ = 0.02.c) Poincaré section in the same region for the Chirikov standard map giving an approximate description of dynamics in b).
(d,e,f) Density of propagating particles on the Poincaré section in presence of noise and dissipation. For j = 2 microwave repels particles from the edge (d),
while for j = 9/4 particles are trapped inside the nonlinear resonance (e,f)

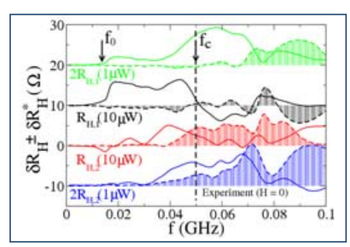
A.D. Chepelianskii & D.L. Shepelyansky, Phys. Rev. B 71, 052508, (2005); G. Cristadoro & D.L. Shepelyansky, Phys. Rev. E 71, 036111 (2005); A.D. Chepelianskii, EPJB 52, 389 (2006);
A.D.Chepelianskii, M.V.Entin, L.I.Magarill, D.L.Shepelyansky EPJB 56, 323 (2007); arXiv:0808.2970 [cond-mat]
A.D. Chepelianskii & D.L. Shepelyansky, condmat:0905.0593 (2009)

Ratchet effect in mesoscopic samples

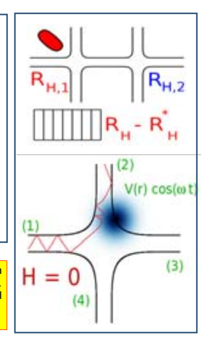
In a four terminal sample microscopic time-reversibility leads to symmetry relations between resistance measurements where the role of current and voltage leads are exchanged. These reciprocity relations are a manifestation of general Onsager-Casimir symmetries in equilibrium systems. We investigate experimentally the validity of time reversal symmetry in a 2DEG Hall bar irradiated by an external AC field, at zero magnetic field.



Commensurability resonances in the Hall resistance of a ballistic Hall probe. They are well described by the billiard model of a Hall probe. This model can be extendedto the case when microwave driving is present.



Dashed lines Change of Hall resistance under microwave irradiation on the local split-gate [S] as a function of microwave frequency. Continuous curves represent the Onsager-symmetric part of the Hall resistance, while the dashed curves show the anti-symmetric part. This signal is similar to an effective magnetic field of 10 Gauss.



In inhomogeneous AC fields we find strong deviations from reciprocity relations and show that their origin can be understood from the billiard model of a Hall junction.
Under homogeneous irradiation the symmetry is more robust, indicating that time-reversal symmetry is preserved.

A.D. Chepelianskii and H. Bouchiat, Phys. Rev. Lett. 102, 086810 (2009)
A.D. Chepelianskii, S. Guéron, H. Bouchiat et. al., Phys. Rev. B 79, 195309, (2009)

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