Terahertz-radiation-induced magnetic quantum ratchet effect in graphene

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I. INTRODUCTION

We report on the experimental and theoretical study of magnetic quantum ratchet effects in graphene. It is shown that single-layer graphene samples subjected to an in-plane magnetic field rectify ac electric current converting it into a dc electric signal. The dc response is observed for both linearly polarized and circularly polarized ac electric field of terahertz (THz) radiation. We show that the ratchet current in graphene is sensitive to the radiation polarization and, for circular polarization, contains a helicity-dependent component. We present a microscopic theory of the effect and show that the current stems from the asymmetry of electron transport which is caused by the mixing of π- and σ-band states in the magnetic field and structure inversion asymmetry of graphene samples. The dc current changes a sign by switching the magnetic field polarity and proportional to the square of the amplitude of the ac electric field, thus, representing the magnetic quantum ratchet effect.

II. SAMPLES AND SETUP

The experiments were carried out on single-layer graphene samples either grown on the Si-terminated face of a 4H-SiC(0001) semi-insulating substrate or synthesized by chemical vapor deposition on Si/SiO_2. For optical experiments squared shaped samples (5 x 5 mm²) with ohmic contacts were prepared. Hall measurements reveal electron concentrations of the order of (3-7) x 10^{12} cm^{-2}, Fermi energies ranging from 200 to 300 meV, and mobility of about 1000-2000 cm²/Vs. The samples were placed into an optical cryostat with *z*-cut crystal quartz windows and split-coil superconducting magnet. All experiments were performed applying normal incidence of THz radiation and in-plane magnetic fields between B = -7 T and B = +7 T, see inset in Fig. 1. Terahertz radiation was generated by a high power pulsed NH_3 laser operating at frequencies f = 3.3 THz, 2 THz or 1.1 THz with peak powers P up to 10 kW within 100 ns. The polarization of the radiation was varied utilizing $\lambda/2$ and $\lambda/4$ *x*-cut quartz plates of proper thickness. The sample temperature was varied from 4.2 up to 300 K. The current generated by THz radiation in the unbiased graphene layer was measured via the voltage drop across a 50 Ohm load resistor. The voltage was measured with a storage oscilloscope. The measured current pulses of 100 ns duration reflect the corresponding laser pulses.

III. RESULTS AND MICROSCOPIC THEORY

The excitation of graphene samples by ac electric field of THz radiation results in a photocurrent which scales linearly with the radiation intensity and the magnetic field B [1]. The current is observed in a wide range of frequencies and temperatures. Figure (1) shows the behavior of the signal under variation of the temperature T yielding that at low T it is constant whereas it decreases with the increase in T at higher temperatures. For linearly polarization radiation, the current depends on the angle between the polarization plane and the static magnetic field. For circular polarization, the current reveals both polarization-independent and helicity-sensitive components. All these observations are in agreement with the developed microscopic model, see Fig. 2, and theory of the magnetic quantum ratchet effect in graphene. The theory considers non-linear high-frequency transport of Dirac fermions in graphene in the presence of asymmetric scattering induced by static magnetic field. It demonstrates that the current emerges if the spatial symmetry of graphene layers is broken by the environment, e.g., the substrate or adatoms on the graphene surface. Thus, the magnetic quantum ratchet effect can serve as a direct and non-invasive measure of structure inversion asymmetry in graphene.

References:

[1] C. Drexler, S.A. Tarasenko, P. Olbrich, J. Karch, M. Hirmer, F. Müller, M. Gmitra, J. Fabian, R. Yakimova, S. Lara-Avila, S. Kubatkin, M. Wang, R. Vajtai, P. M. Ajayan, J. Kono, and S.D. Ganichev, Nature Nanotechnology **8**, 104 (2013).

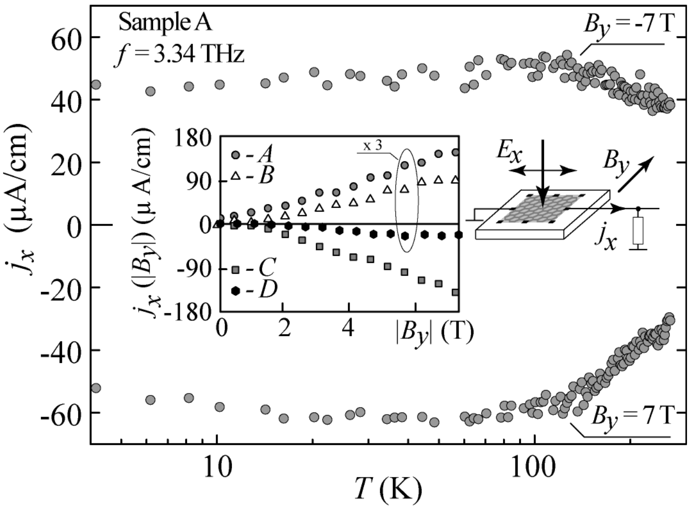

Figure (1): Experimental overview of the ratchet current in graphene.
Temperature dependence of the ratchet current j_x for the in-plane magnetic field B_y. Left inset shows the linear dependence of the current on the magnetic field for different samples. Right inset shows the experimental geometry.

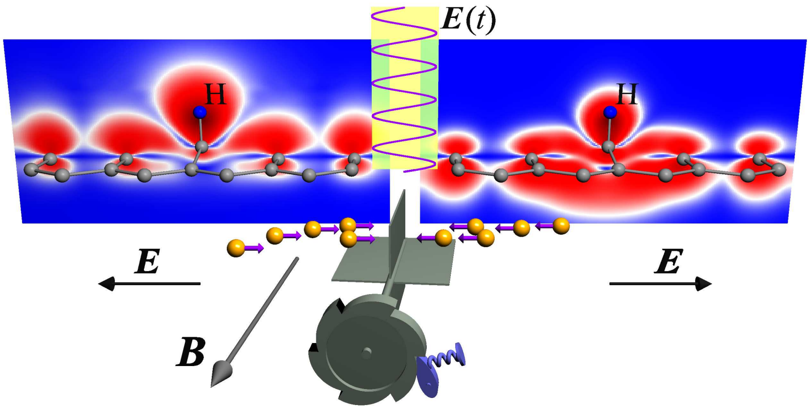

Figure (2): Microscopic model
The ratchet-and-pawl mechanism is realized due to the static magnetic field ***B*** and the spatial asymmetry of graphene induced by the hydrogen adatoms (blue spheres). The resulting spatial distribution of the electron density is shown by the red colour scheme. If electrons, at any time, are driven to the right, their orbitals are shifted upwards due to a quantum analogue of the Lorentz force (left panel). Consequently, their mobility decreases. A half a period later, when electrons flow left, their orbitals are shifted down resulting in an increased mobility (right panel). The imbalance in mobility for left- and right- moving electrons results in a net *dc* electric current.