Ultrafast Fiske Effect and the Question of Chaotic Electron Motion in Semiconductor Superlattices

Anne Beate Hummel, Yuriy A. Kosevich, Ernst Mohler, Alvydas Lisauskas, Nataliya V. Demarina, Klaus Köhler and Hartmut G. Roskos

Abstract— **We report on the experimental observation of a self-induced quasi-dc current in a semiconductor superlattice subjected to tilted electric and magnetic fields and excited by femtosecond laser pulses. This current appears at the resonance between the magneto-Bloch and in-plane cyclotron oscillations. The semiclassical theory shows that the effect has a profound analogy to the Fiske effect in superconductor Josephson junctions and superfluid weak links. Monte Carlo simulations predict that the existence of the Fiske effect in superlattices survives the development of chaotic electron orbits which arise for relevant experimental conditions.**

It is well known that there exists a profound analogy between the dynamics of electrons in semiconductor superlattices and that of Cooper pairs in Josephson junctions – Bloch oscillations and the AC Josephson effect being the best-known examples for the similarity arising from the tunneling nature of coherent transport in both systems. Here, we present yet another example.

The Fiske effect is a coherent transport phenomenon originally known from superconductor Josephson junctions (and superfluid weak links). If a Josephson junction is coupled to an electromagnetic resonator and the bias voltage across the junction is varied, one observes, in addition to the AC Josephson effect, a DC current whenever the Josephson frequency matches the frequency of an eigenmode of the resonator.

A. B. Hummel is with the Physikalisches Institut, Johann Wolfgang Goethe-Universitaet Frankfurt, 60435 Frankfurt, Germany.
Y. A. Kosevich is with the N. N. Semenov Institute of Chemical Physics, Russian Academy of Sciences, 119991 Moscow, Russia
E. Mohler is with the Physikalisches Institut, Johann Wolfgang Goethe-Universitaet Frankfurt, 60435 Frankfurt, Germany.
A. Lisauskas is with the Physikalisches Institut, Johann Wolfgang Goethe-Universität Frankfurt, 60435 Frankfurt, Germany.
N. V. Demarina is with the Nizhny Novgorod State University, Gagarin Ave. 23, 603950 Nizny Novgorod, Russia.
K. Köhler is with the Fraunhofer-Institut für Angewandte Festkörperphysik, D-79108 Freiburg, Germany.
H. G. Roskos is with the Physikalisches Institut, Johann Wolfgang Goethe-Universitaet Frankfurt, 60435 Frankfurt, Germany (e-mail: roskos@physik.uni-frankfurt.de).

We have found an analogous effect in the coherent transport of electrons in semiconductor superlattices subjected to a tilted magnetic field. When electron wavepackets are excited by femtosecond laser pulses, the Fiske effect manifests itself in a quasi-DC current when the magneto-Bloch oscillations are resonant to the in-plane cyclotron oscillations. This can be explained such that the coherent coupling of the oscillators opens an elastic rectifying transport channel, and this coherent current enhancement is associated with a level alignment, i.e., it occurs when Landau states of neighboring wells align at certain ratios of the electric and magnetic field strengths.

We explore the dynamics of the superlattice effect both theoretically and experimentally. In time-resolved experiments, we detect the Fiske effect in a GaAs/AlGaAs superlattice electrooptically taking advantage of the intrinsic electrooptic effect in the zincblende crystal structure of the superlattice itself. The Fiske effect is identified as a resonant, ultrafast build-up of a DC screening field. The measured transient Fiske current can be adequately modeled in a semiclassical picture if the damping of both types of coupled electron oscillations is properly taken into account (see our results in [1,2]).

Beyond these findings, interesting questions arise in conjunction with the chaotic nature of carrier motion discussed for superlattices in magnetic fields by Fromhold et al., in [3,4]. In the collisionless limit, the wavefunction delocalization associated with the Fiske effect gives rise to chaotic electron orbits. For real superlattices, scattering cannot be neglected. While the anticipated orbits do not have time to fully develop, still our Monte Carlo simulations predict chaotic behavior to arise for relevant experimental conditions. This is related with the critical dependence of the electrons' Lorentz force on their velocity right at the moment of scattering.

The Monte Carlo simulations predict that the Fiske effect in superlattices does not vanish with the occurrence of chaos. This may seem surprising as the Fiske effect is a quantum coherence phenomenon and scattering rapidly destroys the coherence of the carrier ensemble. We will show, however, that scattering and chaotic carrier motion affect the *relative* phase of the magneto-Bloch oscillations and the cyclotron oscillations in a limited manner only, and this stability of the phase correlation ensures that a uni-directional Fiske current survives.

REFERENCES

[1] Y. A. Kosevich, A. B. Hummel, H. G. Roskos, and K. Köhler, "Ultrafast Fiske Effect in Semiconductor Superlattices", Phys. Rev. Lett. vol 96, 137403, 2006.

[2] Y. A. Kosevich, A. B. Hummel, H. G. Roskos, and K. Köhler, "Generation of a DC Fiske current by coupling of Bloch and in-plane cyclotron oscillations in a semiconductor superlattice", Phys. stat. sol. (b) vol. 243, p. 2405, 2006.

[3] T. M. Fromhold, A. Patanè, S. Bujkiewicz, P. B. Wilkinson, D. Fowler, D. Sherwood, S. P. Stapleton, A. A. Krokhin, L. Eaves, M. Henini, N. S. Sankeshwar and F. W. Sheard, "Chaotic electron diffusion through stochastic webs enhances current flow in superlattices", Nature vol. 428, p. 726, 2004.

[4] T. M. Fromhold, A. A. Krokhin, C. R. Tench, S. Bujkiewicz, P. B. Wilkinson, F. W. Sheard, and L. Eaves, "Effects of Stochastic Webs on Chaotic Electron Transport in Semiconductor Superlattices", Phys. Rev. Lett. vol. 87, 046803, 2001.