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

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Outline

• Electrically biased superlattices: Bloch oscillations

• ... plus tilted magnetic field:
  • Ultrafast Fiske effect
  • Relationship to enhanced current associated with chaotic carrier motion (Fromhold et al., Nature 428, 726 (2004))
Bloch Oscillations, History

1928 **F. Bloch**: theory for the motion of electrons in the periodic potential of a crystal lattice.

1934 **C. Zener**: prediction of the periodic motion of electrons in a crystal under electrical bias (called Bloch oscillations).

1969 **G. H. Wannier**: theoretical prediction that under electrical DC bias, the continuous energy states split into a (Wannier-Stark) ladder of states. Bloch oscillations: quantum interference of states.

Around '90: Observation of Wannier-Stark splitting and of Bloch oscillations in semiconductor superlattices by optical experiments.

\[ \omega_B = \frac{eFd}{\hbar} \]
1970 L. Esaki and R. Tsu: suggest to use an artificial periodic structure - a semiconductor superlattice (SL) - for the observation of Bloch oscillations and as a potential source for terahertz radiation.

L. Esaki and R. Tsu, IBM J. RES. DEVELOP. 14, 61 (1970)

Two proposals concerning THz lasers

**Employing population inversion between minibands**

**Dispersive gain due to carrier transport within a single miniband**
Semiclassical Picture of Bloch Oscillations

Real-space representation:

K-space representation:

\[ E(\tilde{k}) = \frac{\Delta}{2} \left(1 - \cos(k_x d)\right) \]
(tight binding)

Group velocity in real space:

\[ \tilde{v} = \frac{1}{\hbar} \frac{\partial E}{\partial k} \]
THz-Emission Spectroscopy

- Optical excitation pulse
- THz pulse
- Paraboloidal mirrors
- Sample
- Dipole antenna
- Variable time delay (stepper)
- P(t): Polarization
- THz pulse
Bloch Oscillations Measured by THz-Emission Spectroscopy

![Graph showing Bloch oscillations measured by THz-Emission Spectroscopy. The graph displays the detected electric field amplitude over time delay and frequency with varying bias fields. The red shaded area indicates the rising electric bias field.](image)
Josephson junction

AC Josephson effect

Superlattice

Bloch oscillations

**Analogy**

AC current by DC voltage:

\[ \Phi(t) = \frac{2eU}{\hbar} t \]

\[ I(t) = I_c \sin(\Phi) \]

\[ k(t) = k(0) + \frac{e}{\hbar} Et \]

\[ v(k) = \frac{\Delta d}{2\hbar} \sin (kd) \]
Semiconductor Suprelattices vs. SIS Junctions

Shapiro effect


Superlattice analog for Shapiro effect


Fiske effect

Ultrafast Fiske Effect

Tilted fields

→ Ultrafast Fiske effect: Self-induced quasi-DC current by interaction of Bloch oscillations and in-plane cyclotron oscillations
Time-resolved Transmittive Electro-Optic Sampling (TEOS)

GaAs/AlGaAs superlattice ($\Delta=18$ meV) in He magnet cryostat
- $T = 8 \text{ K}$, $B = 0 \text{ – } 8 \text{ T}$

Ti:Sapphire laser, 100 fs, 82 MHz, $\lambda=800$ nm ($h\nu=1.55 \text{ eV}$)

Volume excitation density:
- $\sim 5 \times 10^{15}$ per cm$^3$

TEOS measures internal electric field in the superlattice:
- $\rightarrow$ Internal field dynamics
Experimental Results

Fixed bias voltage ($\omega_B = 2\pi \cdot 2.2 \text{ THz}$), variation of magnetic field $B$, $\theta = 30^\circ$
Origin of Resonant DC Current

Model of Bloch-cyclotron coupling for tilted fields

\[ F_L = e(v \times B) \Rightarrow F_{L,x} = ev_y B_z \]
\[ F_{L,y} = -ev_x B_z \]

- \( B_z \) couples \( v_x \) and \( v_y \).
- Coupling strength parameter \( \kappa = (eB/m_||)\sin\theta \)

\[ B_x = B\cos\theta \]
\[ B_z = B\sin\theta \]

Phase-locked-loop picture

Laser pulse

Bloch oscillator \( \omega_B \)

Cyclotron oscillator \( \omega_{Cx} \)

DC
Comparison – Experiment and Theory

Numerical solution of the equation of motion yields the electron displacement \( X(t) \).

Measured depolarization field

\[
F_{\text{dep}}(t) = -\frac{e}{\varepsilon_0 \varepsilon_{\infty}} N \cdot X(t)
\]

Good agreement between experiment and theory

\( \tau_C = 1.04 \text{ ps} \) (Cyclotron dephasing)
\( \tau_V = 0.70 \text{ ps} \) (Momentum relaxation)
\( \tau_e \to \infty \) (Energy relaxation)
Chaotic electron diffusion through stochastic webs enhances current flow in superlattices


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Resonant current enhancement in GaAs/AlAs superlattice at 11 T, 4.2 K

Ultrafast scattering prevents full development of orbits

θ = 50° off resonance

θ = 50° at resonance

Electron trajectories / wave functions
Frequency Spectra of $v_x$

Variation of magnetic field for weak damping

$\theta = 30^\circ$

$\omega = \omega_{Cx}$

$\theta = 60^\circ$

$\omega = \omega_B$
Origin of Resonant DC Current

In case of a scattering event:

Velocity of electron changes

↓

Lorentz force resets phase and direction of in-plane cyclotron oscillation such that the rectified current doesn’t change its direction.

Relationship between DC current of Fromhold et al. and the ultrafast Fiske effect (Fiske carrier displacement) observed by us:

DC current is the sum of unidirectional Fiske displacements between scattering events:

- Fiske contribution
- Non-Fiske contribution
- Total
Simulation of Electron Velocity $v_x(t)$

$\theta = 30^\circ$; resonance ($\omega_B = \omega_{C,x}$); $\Gamma_B = 0.1$; $\Gamma_C = 0.07$

$t \to \infty$: Esaki-Tsu current (the usual scattering-induced forward current in a superlattice)

$t \to \infty$: Esaki-Tsu current plus continuous Fiske current

- Monte Carlo (chaotic carrier motion)
- Ensemble averaging (no chaotic carrier motion)
Summary

• Semiconductor superlattice in tilted electric and magnetic fields:
  Ultrafast Fiske effect, a self-induced quasi-DC current
  → Analogous to Fiske effect of superconductor Josephson junctions in a magnetic field
  → Existence of Fiske effect is closely related with the occurrence of chaos in the electron motion
  → Ultrafast Fiske effect and DC current enhancement in I/V measurements reflect the same physics
  → Manifestation of chaos in ultrafast measurements is not well understood

$\mathbf{F} \perp \mathbf{B}$: Coherent Hall Effect

Experimental frequencies evaluated by fitting a cosine or by Fourier transformation

Semiclassical theory: Calculated frequencies

$\sim \frac{F}{B}$