Observation of current resonances due to enhanced electron transport through stochastic webs in superlattices


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Abstract. We present experimental and theoretical studies of a unique type of stochastic electron motion in superlattices (SLs) with a magnetic field $B$ tilted at an angle to the SL axis. The magnetic field couples electronic Bloch oscillations along the SL axis to cyclotron orbits in the plane of the layers. At discrete values of the applied voltage, this coupling transforms the localized Bloch trajectories into unbounded chaotic electron paths, which propagate through intricate “stochastic web” patterns in phase space. This abrupt metal-insulator-like transition reveals itself in our experiments as a large resonant increase in the current flow and conductance, observed at critical values of the applied voltage.

INTRODUCTION

Chaotic electron transport has been explored in experiments performed on a variety of semiconductor nanostructures [1]. Despite the diversity of these experiments, they all involve systems in which the transition to chaos occurs by the gradual and progressive destruction of stable orbits in response to an increasing perturbation. But there is also a much rarer type of chaos, known as non-KAM dynamics [2], which switches on and off abruptly when the perturbation reaches certain critical values. The theory of non-KAM chaos is of great interest due to applications in tokamaks, turbulence, and quasicrystals [2]. But, to our knowledge, such dynamics have previously been inaccessible to experiment. In this paper, we show that electrons in a SL miniband with a tilted magnetic field provide an experimentally-accessible non-KAM system. As predicted in our previous theoretical work [3], the onset of this unique type of chaotic dynamics produces a sharp increase in the current flow, which we observed as a strong resonant peak in the conductance-voltage, $G(V)$, curves.

To observe the chaos-induced conductance resonance, we use a novel type of InAs/GaAs/AlAs SL with a magnetic field $B$ tilted at an angle $\theta$ to the SL (x) axis. Details of the sample composition are given elsewhere [4,5].

EXPERIMENT AND THEORY

When $\theta = 0$, the experimental $G(V)$ plot [Fig. 1(a), lower trace] exhibits the decrease with increasing $V$ (arrow MB) associated with Bloch electron localisation. The curve for $\theta = 0$ also reveals the Stark-cyclotron resonance (arrow SC), which occurs when the quantised Wannier Stark and Landau levels are equally spaced [6]. As $\theta$ increases from 0, a much stronger resonant peak emerges (arrow SW), which has a fundamentally different origin from the Stark-cyclotron resonance, as we now explain.

To interpret the experimental data, we investigate the dynamics of electrons injected into the lowest SL miniband, using the semiclassical equations of motion $\mathbf{v} = \frac{\partial E(p)}{\partial p}$ and $dp/dt = -e[F + (v \times B)]$, where $v$ and $p$ are, respectively, the electron’s velocity and crystal momentum, $e$ is the magnitude of the electronic charge, $F$ is the electric field produced by the applied voltage $V$, $B$ is the applied magnetic field, and $E(p)$ is the energy versus crystal momentum dispersion relation for an electron moving in the first miniband of the SL [3], which is 19 meV wide. We consider motion in a tilted magnetic field which lies in the x-z plane at an angle $\theta$ to the SL axis (Fig. 2 inset).
Remarkably, it can be shown that the dynamics of a miniband electron in tilted $B$ reduce to a one-dimensional simple harmonic oscillator, of angular frequency $\omega_C \cos \theta$, where $\omega_C$ is the cyclotron frequency, driven by a time-dependent plane wave whose angular frequency equals the Bloch frequency $\omega_B$ [3,4]. So, even though the voltage and magnetic field are stationary, they act like an effective THz source. At $V$ values for which $\omega_B = n \omega_C \cos \theta$, where $n$ is an integer, the electron orbits change from localised Bloch-like trajectories [Fig. 2(a)] to unbounded stochastic orbits [Fig. 2(b)], which diffuse rapidly through intricate web patterns in phase space (Fig. 2 inset). To quantify how these webs affect the experimental data, we make drift-diffusion calculations of $G(V)$ including the effects of space-charge build up [4,7]. Our theoretical $G(V)$ curves [Fig. 1(b)] simulate all the key features of our experimental data and confirm that the large resonant peak observed in tilted $B$ (arrow SW) originates from stochastic delocalisation of the electron orbits. Quantum-mechanical calculations of $G(V)$ in a tilted $B$-field, based on the non-equilibrium Green function formalism [7], closely resemble the semiclassical calculations shown in Fig. 1(b) [8]. The quantised eigenstates change discontinuously from a highly localised character when the system is off resonance [Fig. 2(a)] to a fully delocalised form when the resonance condition is satisfied [Fig. 2(b)]. Further work is required to relate the resonances observed here for hot electrons in a tilted $B$-field with those observed for electrons close to equilibrium in weakly-coupled SL structures [9].

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REFERENCES


FIGURE 1. $G(V)$ curves (a) measured and (b) calculated for the SL [4] with $B = 11$ T, and $\theta = 0$ (bottom trace) to $90^\circ$ (top trace) at $5^\circ$ intervals. Curves for $\theta = 45^\circ$ are shown dotted.

FIGURE 2. Electron orbits in the $x$-$z$ plane (axes inset) superimposed on probability density plots (black = high) of quantised eigenstates. (a) A highly localised orbit (offset to right of wavefunction for clarity) off resonance at $\theta = 30^\circ$. (b) An unbounded chaotic orbit on the $n = 1$ resonance at $\theta = 60^\circ$. Inset: Stochastic web constructed by plotting ($p_x, p_z$) at discrete times separated by $2\pi/\omega_C \cos \theta$ [4]. $B = 11$ T.