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Dissipative Chaos and Symmetry Breaking in ac-Driven Nanostructures

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We present results of several recent studies of the nonlinear transport and dynamics of electrons in a.c.-driven nanostructures. First, we explore electron transport in the miniband of a semiconductor superlattice (SSL) under the influence of an external, time-periodic electric field, using a semi-classical balance-equation approach that incorporates both elastic and inelastic scattering (as dissipation) and the self-consistent field generated by the electron motion. The coupling of electrons in the miniband to the self-consistent field produces a cooperative nonlinear oscillatory mode that, when interacting with the oscillatory external field and the intrinsic Bloch-type oscillatory mode, can lead to complicated nonlinear dynamics, including dissipative chaos and symmetry breaking (*e.g.*, the creation of a d.c. current in response to a purely a.c. drive). For a range of values of the dissipation parameters, we determine the regions in the amplitude-frequency plane of the external field in which chaos and symmetry breaking can occur. Our results suggest that for teraHertz external fields of the amplitudes achieved by present-day free electron lasers, symmetry breaking may be readily detectable and chaos possibly observable in experiments on SSLs. Second, we study resonant electron tunneling through a double-barrier potential, taking into account the nonlinear dynamical effects generated by charge accumulation in the inter-barrier space. We use the perturbation approach of Davydov and Ermakov, which was developed for investigating intrinsic bistability in resonant tunneling. For a slowly temporally modulated incoming electron flow, we show that the resulting nonlinear dynamics can become chaotic, with the chaos described by a strange *attractor*, despite the seemingly Hamiltonian nature of the system. We show that the effective dissipation arises from the open nature of the system, determine the conditions for the existence of this strange attractor, and estimate characteristic experimental parameters for its observation.

In the present study, we generalize our previous work by considering explicitly the role of dissipation in the balance equations describing the SSL plus field system. After recalling briefly how the conventional balance equations recover the standard results of Bloch oscillations and negative differential conductivity, we show that our extension of the balance equations to account for collective effects on the electron's motion can (for certain conditions) result in chaotic dynamics, both transient and stationary, even in the presence of damping. We discuss and exploit analogies between the electrons in an SSL plus field system and the dynamics of lasers and optical bistable systems and of damped, driven Josephson junctions; the extensive tradition of studying dissipative nonlinear dynamics in these problems allows us to use these analogies to guide our studies of the semiconductor system. In this paper we use a balance equation approach to formulate (phenomenological) equations of the motion for the electron in the SSL in the presence of an external ac field, including the self-consistent field generated by the electron current. We show how to incorporate various dissipative channels in these equations and illustrate that the solutions to these equations capture the anticipated behavior in several simple limiting cases, including those of (undamped) Bloch oscillations and (stationary) negative differential conductivity. In preparation for our study of the general case, we introduce a re-scaled (pseudo-spin) representation of the equations of motion and demonstrate the analogy with the optical systems, in which chaotic behavior is well established. We present the details of our study of the dissipative chaotic dynamics of the SSL plus field system. First, we show that our equations reduce (in two different limits) to the equations of two well-known chaotic systems, the Lorenz equations and the damped, driven pendulum. Second, we present numerical studies of the full equations. Our results suggest that, for a wide range of values of the frequency and amplitude of the external field and for experimentally relevant values of the damping, stationary chaotic dynamics should be observed, interspersed with transient chaos leading eventually to periodic motion. We provide detailed confirmation of the chaotic behavior in the form of Lyapunov exponents, power spectra, and direct time evolution traces. We summarize our results, examine critically the possible parameter ranges in which the effects we predict can be observed in experiments, discuss how these effects might manifest themselves in experimental observables, and mention a number of open theoretical issues.

Let us conclude with a brief speculative comment related to the possible consequences and relevance of chaotic behavior in SSLs. Based on the earlier experience of studying chaos in semiconductor devices used for infra-red radiation detection, mapping out the boundary of chaos experimentally is important to reliable use of the devices in the "normal" regime. However, recent developments in "controlling chaos" suggest that one might actually deliberately choose to drive the SSL into a chaotic regime, in order to take advantage of the myriad possible behaviors there for device applications. Alternatively, using methods of chaotic control, one may be able to suppress the onset of chaos, as was recently done in an experimental laser system. Chaotic control and reduction of chaos are also likely to be important for future nano-fabricated semiconductor integrated circuits, where the expected chip densities will be of the order $10^9/cm^2$. At such densities, the devices actually form a *lateral surface superlattices* (LSSL), and device-device interactions can

generate both cooperative effects and additional instabilities. In any case, a large number of exciting experimental and device-related problems remain.

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