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Steady states of a microwave-irradiated modulation-doped heterostructure under perpendicular magnetic field

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Abstract

We present a theoretical model and study dynamics of the modulation-doped GaAs/$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ heterostructure under a perpendicular magnetic field and microwave radiation. We propose a mechanism, which is based on the nonlinear dynamics of real-space electron transfer and delayed dielectric relaxation of the interface potential barrier resulting from the space charge in the doped AlGaAs layer. Static analysis specifies the negative differential conductance region when the dc bias voltage varies. The self-sustained oscillations and bistability between oscillationary and stationary states are predicted. Varying with the microwave irradiation amplitude and the perpendicular magnetic field, the routes from period-doubling to chaos, quasiperiodicity, and frequency-locking are found. In addition varying with the microwave irradiation frequency can lead to time-independent homogeneous steady states spatially and result in a longitudinal resistance oscillation with period tuned by the ratio of microwave radiation frequency ω to the cyclotron frequency ω_c and local minima at $\omega/\omega_c = \text{integer} + 1/4$.

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1. Introduction

The electrical transport properties of a two-dimensional electron gas (2DEG) in a perpendicular magnetic field have been studied extensively over the past two decades in connection with the quantum Hall effects. However, recently discovered effects of the microwave induced giant photoresistance oscillations and the zero-resistance state [1,2] in very high electron mobility two-dimensional electron systems attracted much experimental [3–6] and theoretical interest [7–12]. Two distinct microsopic mechanisms for conductivity corrections have been proposed: the first is the displacement photocurrent [7–9], which is caused by photoexcitation of electrons into displaced guiding centers, and the second is the distribution function mechanism [10,11], which involves redistribution of intra-landau level population for large inelastic lifetimes. And according to Andreev's approach [12], irrespective of microscopic details, once the radiation is strong enough to render the local conductivity negative, the system as a whole will break into domains of photogenerated fields and spontaneous hall current. The key is the existence of an inhomogeneous current flowing through the sample due to the presence of a domain structure in it. All the theories above have indicated that the investigation of the stability of the modulation-doped GaAs/$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ heterostructure is important and may shed light on the nature of the zero resistance state of the system. At the same time, the n-GaAs and a number of other compound semiconductors with negative differential conductivity (NDC) have also been studied theoretically [13–16] and experimentally [17,18]. They can exhibit many interesting nonlinear effects, such as a hysteresis loop in the current-voltage curve [14], self-sustained oscillations and chaos [15], formation of current filaments [16]. This allows one to exploit their familiar relations.

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In the work we present a model and study dynamics of a modulation-doped heterostructures of GaAs/Al$_x$Ga$_{1-x}$As under a perpendicular magnetic field and a microwave radiation as well. The NDC region is specified when the dc bias and the perpendicular magnetic field B vary. We have an analysis of the dynamic behaviors. The self-sustained oscillations and bistability between oscillationary and stationary states are predicted when the control parameter is a dc bias voltage. The microwave irradiation is physically mapped as an ac-modulated bias voltage $U = U_0(1 + A\sin(2\pi n f_0 t))$ with A the relative amplitude. The routes from period-doubling to chaos, quasiperiodicity, and frequency-locking are found when the dc bias voltage U_0 is near the SNDC region.

2. The model

In this section we specify our model of a microwave-irradiated modulation-doped GaAs/Al$_x$Ga$_{1-x}$As heterostructures under magnetic field. Fig. 1 shows the energy-band diagram of a modulation-doped GaAs/Al$_x$Ga$_{1-x}$As heterostructure. L_1, L_2 are the width of GaAs and AlGaAs. The GaAs layer is undoped, while the AlGaAs layer is heavily n doped with donor density N_D. μ_1, μ_2 are the mobility of the electrons at zero magnetic field in the GaAs and AlGaAs layer, respectively.

From the equation of current continuity $\nabla \cdot J = -\partial n/\partial t$, we can get

$$\frac{dn_1}{dt} = \frac{J_{1\to 2} - J_{2\to 1}}{eL_1}, \tag{1}$$

where

$$J_{1\to 2} = -en_1\left(E_1/3\pi m_1^*\right)^{1/2}\exp(-3\Delta E_c/2E_1),$$

$$J_{1\to 2} = -en_2\left(E_2/3\pi m_2^*\right)^{1/2}\exp(-3\phi_b/2E_2).$$

$J_{1\to 2}$ ($J_{2\to 1}$) are the thermionic emission current densities from GaAs to AlGaAs(AlGaAs → GaAs) layer. The spatially averaged carrier density n_1 and n_2 in the GaAS and AlGaAs layers are defined as

$$n_1 = (1/L_1)\int_{-L_1}^{0} n(z,t)\,dz, \qquad n_2 = (1/L_2)\int_{0}^{L_2} n(z,t)\,dz.$$

For the conservation of the total number of carriers, we have

$$n_1L_1 + n_2L_2 = N_DL_2. \tag{2}$$

Here m_i $(i = 1, 2)$ are electron effective masses in GaAs and AlGaAs layers, ΔE_c is the conduction band discontinuity and ϕ_b represents interface potential barrier. $E_i = (3/2)k_BT_i$ $(i = 1, 2)$ are the mean carrier energies related with the lattice temperatures T_i. The mean energy as a function of the applied electric field E_x is then roughly estimated by $E_1 \approx E_L + \tau_E e\mu_1 E_x^2$. $E_2 \approx E_L$ is the thermal equilibrium mean energy and $E_L = (3/2)k_BT_L$. T_L is the lattice temperature, and τ_E is the energy relaxation time. In the **Z** direction, the interface barrier ϕ_b will be considered as a variable and the dynamics of ϕ_b is [13]

$$\dot{\phi}_b = \frac{e}{\varepsilon}\left[-\mu_2 N_D\phi_b + \mu_2\frac{e^2}{2\varepsilon}L_1^2n_1^2 - eL_1L_2\dot{n}_1\right]. \tag{3}$$

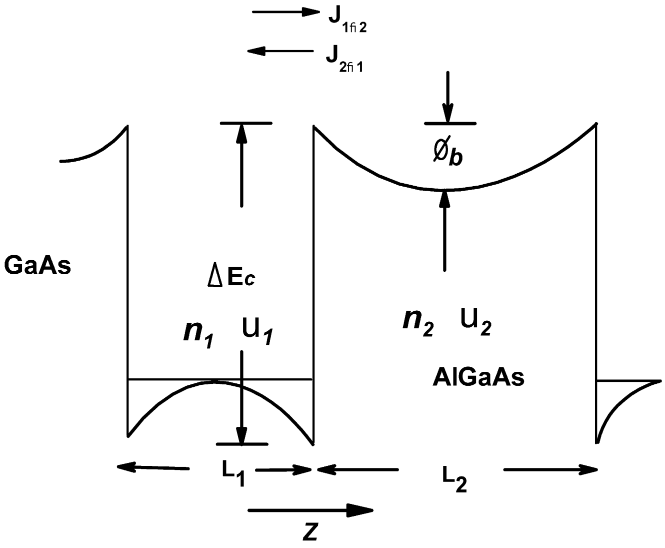

Fig. 1. The energy-band diagram of GaAs/AlGaAs.

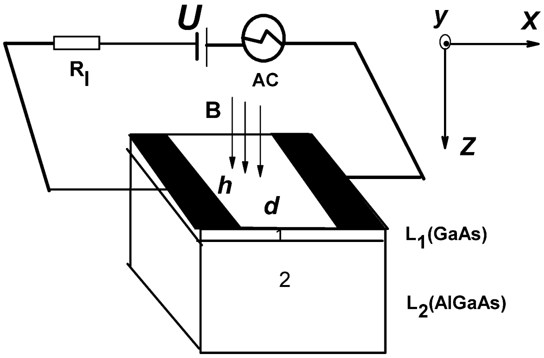

Fig. 2. The circuit diagram of GaAs/AlGaAs with lateral dimensions h, d.

Fig. 2 is the circuit diagram of the GaAs/Al$_x$Ga$_{1-x}$As heterostructure. $U = E_0 d$ is the applied voltage. Choosing the coordinate system such that the electric field lies in the junction plane, i.e. $\vec{E} = E_x\hat{X} + E_y\hat{Y}$ and a static magnetic field in the Z direction, $B = B\hat{Z}$, we obtain the dynamic equations of the GaAs/Al$_x$Ga$_{1-x}$As for the electric field [15]

$$\varepsilon\dot{E}_x = \sigma_l(E_x - E_0) + \sigma_m E_x + \sigma_n E_y, \tag{4}$$

$$\varepsilon\dot{E}_y = \sigma_m E_y - \sigma_n E_x, \tag{5}$$

where $\sigma_l = -d/(h(L_1 + L_2)R_l)$, $\sigma_m = -(en_1\mu_{1B}L_1 + en_2\mu_{2B}L_2)/(L_1 + L_2)$, $\sigma_n = eB(n_1\mu_{1B}\mu_1L_1 + n_2\mu_{2B}\mu_2L_2)/(L_1 + L_2)$, and $\mu_{iB} = \mu_i/(1 + \mu_i^2B^2)$ $(i = 1, 2)$, ε is the permittivity and E_0 is the applied field. In our numerical simulations we use the dimensionless variables: $Y_1 = n_1/N_D$, $Y_2 = \mu_1E_x/V_{ds}$, $Y_3 = \mu_1E_y/V_{ds}$, $Y_4 = \phi_b/(k_BT_l)$ $T = t/\tau_E$. The fourth order Runge–Kutta technique is used and the values of the parameters used in this Letter are listed in Table 1.

3. Stability and bifurcation

In this section we present the results of numerical simulations for this model by using the parameter values in Table 1. We consider first the case of a dc bias voltage. We find that