Magnetoresistance of an Asymmetric Quantum-Size Structure in a Parallel Magnetic Field: Field Asymmetry Independent of the Current Direction

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Abstract—A new phenomenon, viz., field-asymmetric transverse magnetoresistance of a doped asymmetric quantum-size structure discovered in a magnetic field parallel to the heteroboundary planes, is studied experimentally and theoretically. The magnetoresistance asymmetry relative to the field direction, which is independent of the direction of transport current, is observed when a lateral electric field is embedded in the structure with the help of alloyed metallic contacts. In the theoretical part of the paper, it is shown that the contribution to current, which is asymmetric in the magnetic field, can be consistently described in the framework of the theory of spontaneous current states and photovoltaic effect in systems without an inversion center; the reason behind the emergence of this current is associated with the asymmetry of the energy spectrum of charge carriers relative to the quasimomentum. It is shown that the change in the size and shape of Fermi contours in a magnetic field determines the magnitude of the strong negative magnetoresistance associated with the intersubband scattering under investigation and is found to be responsible for the emergence of a qualitatively new effect mentioned in the title of this paper. © 2001 MAIK “Nauka/Interperiodica”.

1. INTRODUCTION

The electronic properties of a low-dimensional systems are of considerable interest for fundamental science as well as for practical applications. Of special importance are investigations of 2D electron gas in a magnetic field, resulting in the discovery of integer [1] and fractional [2] quantum Hall effects. A 2D gas is realized in practice either at the heteroboundary between two semiconductors or in a quantum well. In both cases, the wave function of charge carriers is extended in a direction perpendicular to the heteroboundary plane and can vary in this direction under the effect of external factors (applied magnetic or electric field). Such a variation is manifested most clearly upon a transition to multilayered tunnel-coupled 2D systems asymmetric along the normal to the plane of heteroboundaries. If the role of external factor is played, for example, by a magnetic field, the above-mentioned change in the wave function may noticeably affect the behavior of the magnetoresistance. This was demonstrated experimentally in [3–5], where the magnetoresistance of two tunnel-connected quantum wells was studied in a transverse (relative to the heterostructure plane) magnetic field.

A more significant change in the configuration of the wave functions of electrons in a direction perpendicular to heteroboundaries takes place when the magnetic field is applied along the plane of a heterostructure. In this case, the confining potential of the quantum well is supplemented by a magnetic potential of the oscillator type, which depends on the location of the center of the electron orbit in the magnetic field [6]. The magnetoresistance of nanostructures consisting of tunnel-connected quantum wells in such a geometry was investigated in [7–12]. Among other things, it was found that the magnitude of magnetoresistance is determined to a considerable extent by the change in the nature of intersubband scattering of charge carriers. The intersubband scattering, in turn, is determined by the magnitude of transferred momentum Q, which in the zeroth approximation is equal to the difference in Fermi momenta in the subbands. The interband scattering probability is proportional to 1/Q. Upon a change in the magnetic field, the variations of Fermi momenta in different subbands differ considerably, which leads to the emergence of clearly manifested magnetoresistance. Since the relative change in the Fermi momenta in the subbands can be of either sign (depending on the system geometry and charge carrier concentrations in subbands), the magnetoresistance can be positive, or negative, or even alternating, as is indeed observed in experiments [8, 10, 12, 13].

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contacts near which a depleted region with an embedded lateral electric field is formed (see Subsections 3.3.1 and 3.3.2). In this case, the magnetoresistance is independent of the direction of the current through the sample and, hence, the observed effect must correspond to a contribution to current in the form

$$\delta j = \beta ((P \times H) \cdot E_0) E,$$

(2)

where $E_0$ is a certain polar vector parallel to current, which is determined by the electric field embedded in the contact region. It will be shown in the theoretical part of this paper (Section 4) that the contribution of type (2) to the current can be described consistently using the theories of spontaneous current states [15] and the photovoltaic effect [16] in systems without an inversion center. The physical reason behind the emergence of the anomalous contribution to current is associated with the asymmetry of the energy spectrum of the investigated nanostructure relative to quasimomentum. Thus, while the change in the size of Fermi contours determines the value of magnetoresistance, which is associated with the intersubband scattering discussed by us here (Subsection 3.3.3), the change in their shape is responsible for the emergence of a qualitatively new effect defined by formula (2).

2. INVESTIGATED NANOSTRUCTURE AND ITS CHARACTERISTICS

The nanostructure investigated by us is a single undoped GaAs quantum well of width 300 Å, bounded on both sides by barrier layers of Al<sub>0.34</sub>Ga<sub>0.66</sub>As (270 Å) uniformly doped with silicon up to the concentration \(2 \times 10^{18}\) cm<sup>-3</sup>. The barrier layers are separated from the quantum well by undoped Al<sub>0.34</sub>Ga<sub>0.66</sub>As spacers of width 100 Å. The entire structure is separated from the substrate by a thick (~0.5 μm) GaAs buffer layer and is covered by a protecting GaAs layer of thickness 100 Å. The profile of the bottom of the conduction band, the electron spectrum, and the wave function distribution were determined from the self-consistent solution to the system of Poisson and Schrödinger equations. It was found that the three subbands \(E_1, E_2, \) and \(E_3\) lying under the Fermi level are characterized by the Fermi energies \(E_{F1} = 32\) meV, \(E_{F2} = 26\) meV, and \(E_{F3} = 1–2\) meV. The distribution of the charge carrier concentration was calculated from the solution of the quantum-mechanical problem (using wave functions) in the region of the quantum well and according to classical formulas outside this region. Figure 1 shows the profile of the edge of the conduction band in the quantum well region, the position of the size-quantization levels (relative to the Fermi level), and the distribution of wave functions for the first two subbands. The distribution of the doping impurity in the system is such that the potential asymmetry in the quantum well is quite small: the potential difference \(\Delta U\) at the right and left boundaries of the well amounts to only 12 meV. Nevertheless, the distri-

![Fig. 1. Potential profile (curve 1), position of size-quantization levels (dot-and-dash lines), and the probability distribution for the first two levels (curves 2, 3) for the structure under investigation in zero magnetic field.](image)