Electrically controlled spin polarization in suspended GaAs quantum point contacts

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Abstract. We report on the observation of the lateral electric spin polarization effect in a suspended GaAs-based quantum point contact (QPC) separated from the substrate. The effect manifests itself in the experiment as the appearance of an additional half-integer plateaus at $0.5 \times 2e^2/h$ when the asymmetric voltage is applied to the side gates in zero magnetic field. The appearance of the plateaus has been attributed to the spin degeneracy lifting caused by the spin-orbit coupling associated with the lateral electric field in the asymmetrically biased QPC. We have experimentally demonstrated that, despite the relatively small g-factor in GaAs, the observation of the spin polarization in the GaAs-based QPCs becomes possible after the suspension due to the enhancement of the electron-electron interaction and the effect of the electric field guiding. These features are caused by a partial confinement of the electric field lines within a suspended semiconductor layer with a high dielectric constant.

1. Introduction

An opportunity to manipulate the electron spin by purely electric means without ferromagnetic materials and external magnetic field seems attractive for future spintronic devices [1, 2]. It has been shown earlier that electron spin in a quantum point contact (QPC) can be controlled via lateral spin-orbit coupling (LSOC) effect caused by lateral electric field applied to QPC by means of side gates [3, 4]. This effect has been steadily observed in QPCs fabricated from InAs-based materials, where the intrinsic g-factor is high. Previously, it has been concluded that the electron-electron interaction plays a crucial role in the observation of the effect. Namely, calculations show that in the absence of the electron-electron interaction, the effect is not observed [5]. On the other hand, if the electron-electron interaction is strong enough, this effect should be observable even in low g-factor materials, such as for example GaAs. However, in QPCs, fabricated from GaAs, there has been no clear experimental evidence of the effect. It should be noted that, since the spin coherence length in GaAs is much higher than that in InAs, it seems more interesting for practical applications to control the spin polarization in GaAs.

The lateral spin-orbit coupling [3], associated with the electric field, is described by the term in the Hamiltonian

$$\hat{H}_{\text{LSOC}} = \gamma \sigma \cdot [k \times E],$$

where $\gamma$ is the lateral spin-orbit interaction constant, $\sigma$ is Pauli vector, $k$ is electron quasimomentum, and $E$ is electric field in the QPC channel.
In previous studies, we have shown that one possible way to enhance the electron-electron interaction is to suspend a nanostructure [6-8], i.e. to detach it from a substrate. Electron transport in such suspended nanostructures has features originating from additional mechanical degrees of freedom [9], poor heat coupling to the bulk [9], and the electron-electron interaction [6-8] being enhanced due to electric field confinement in a high-dielectric membrane. Many types of the semiconductor suspended nanostructures, including quantum dots [6, 7], ring electron interferometers [11], Hall bars [10], antidot lattices [8, 12, 13] have been implemented.

Suspended QPCs have been studied earlier [14-18]. The sensitivity of the QPC conductance to mechanical deformations has been successfully used to detect mechanical vibrations of resonators [17, 18]. In Ref. [14], integer quantization in suspended QPC was demonstrated, and it was also shown that the suspension leads to an increase in the spacing between the one-dimensional subbands. Earlier, we have found that the suspension of the QPCs results in the appearance of an additional anomalous 0.7×2e²/h conductance plateau, which also could be explained by the enhancement of the electron-electron interaction after suspension [15].

In the present paper, it is experimentally shown that QPCs fabricated from GaAs with low intrinsic spin-orbit coupling and being detached from substrate (suspended), demonstrate the LSOC effect and, thus, a pure electric spin manipulation.

2. Experimental details
The experimental samples were fabricated on the basis of GaAs/AlGaAs heterostructures with a two-dimensional electron gas (2DEG), grown by means of molecular-beam epitaxy. First, the 400 nm-thick Al₈₀Ga₂₀As sacrificial layer were grown on the substrate. Then the 166 nm-thick GaAs/AlAs heterostructure was grown above the sacrificial layer. The heterostructure contains the 2DEG in the 13 nm-thick GaAs layer, which forms a symmetric square quantum well for electrons, and resides at a depth of 90 nm beneath the surface (see Figure 1). The electron mobility and the 2DEG density are 2 × 10⁶ cm²/Vs and (5-7) × 10¹¹ cm², respectively. The lateral form of the samples was defined using electron-beam lithography followed by reactive ion etching. The samples were suspended, i.e. detached from the substrate, by means of selective wet etching of the sacrificial layer from under the created nanostructures in 1:100 HF water solution. QPCs represented adiabatic 2DEG constrictions with a lithographic width of 800-900 nm (see Figure 2). The QPCs were equipped with two side gates separated from the channel by 100-150 nm wide trenches. The measurements were carried out using the lock-in technique in the linear response regime with the alternating voltage of the magnitude 30 μV and the frequency 70 Hz at the temperature 4.2 K. Conductance G (= I_{AC}/V_{AC}) was measured as a function of DC voltages V_{G1} and V_{G2} applied to the gates, and the source-drain voltage V_{SD}. To create spin polarization in the channel, an asymmetric voltage was applied between the gates ΔV_{G} = V_{G1} – V_{G2}. We have checked that leakage currents to both side gates are absent by means of dc measurements in the range from –10 V to +10 V.

![Figure 1](image-url) Schematic representations of the heterostructure with a sacrificial layer.
3. Results and discussion
At zero bias between the side gates ($\Delta V_G = 0$) the conductance $G$ of the QPC as a function of $V_G = V_{G1} = V_{G2}$ demonstrates conventional integer quantization [19, 20] in the units of $2e^2/h$, while non-integer plateaus are not observed. An anomalous plateau $0.5 \times 2e^2/h$ emerges when an asymmetric voltage $\Delta V_G \neq 0$ is applied to the side gates of the suspended QPC (see Figure 3 (b)). In non-suspended QPCs (the samples before the suspension) an asymmetric lateral bias $\Delta V_G \neq 0$ does not lead to an appearance of the 0.5-plateau (see Figure 3 (a)).

The appearance of the 0.5-plateau can be attributed to the spin degeneracy lifting caused by the spin-orbit coupling associated with the lateral electric field in the asymmetrically biased QPC. We believe that observation of spin polarization after the QPC suspension becomes possible due to the following two features of the suspended QPC compared to their non-suspended analogues: (i) enhanced electron-electron interaction, and (ii) amplified value of the lateral electric field in the QPC at given $\Delta V_G$. Both of these features can be attributed to the separation of the QPC channel from the substrate, leading to a confinement of the electric field lines inside a suspended semiconductor layer with a high dielectric constant $\varepsilon_{\text{GaAs}} \approx 13$ (this can be compared with magnetic field lines confined and guided in a core material with high magnetic permeability). The enhancement of the electron-electron interaction can be also explained by the removal of a part of the polarizing medium from under the QPC channel, that attenuates the electron-electron coupling.

Figure 3 Conductance of the QPC before (a) and after (b) suspension. Different curves correspond to different $\Delta V_G$ ranging from 0 to 8 V in 2 V steps. Curves corresponding to different values of $\Delta V_G$ are shifted in the horizontal direction.
4. Conclusions
In conclusion, we have experimentally observed 0.5×$e^2/h$ plateaus in QPCs based on low g-factor GaAs material in zero magnetic field. The 0.5-plateaus are observed only with an asymmetric bias $\Delta V_G \neq 0$, leading to a lateral electric field in the QPC channel. We associate the appearance of this feature with the spin polarization caused by LSOC-effect. The half-integer plateaus are observed only in the suspended QPCs, originating from the spin polarization that can be attributed to the enhancement of the electron-electron interaction in suspended QPCs.

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