The observation of the Aharonov-Bohm effect in suspended semiconductor ring interferometers

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Abstract. A suspended semiconductor quantum ring interferometer based on a GaAs/AlGaAs heterostructure with a two-dimensional electron gas (2DEG) is created and experimentally studied. The electron interference in suspended 2DEG is observed. The interference manifests itself as the Aharonov-Bohm oscillations of the interferometer magnetoresistance, clearly observed before as well as after suspension. The amplitude of the oscillations remains almost unchanged after suspension.

1. Introduction
The main interest in semiconductor nanostructures with a two-dimensional electron gas (2DEG) is associated with a variety of mesoscopic phenomena observed in them, including various ballistic effects, interference of electron waves, electron-electron and spin-orbit interaction et al. They have been investigated for a relatively long time [1]. Typical semiconductor devices in which the electron interference plays a key role are the ring interferometers. Usually such devices are embedded in a semiconductor bulk [2-5]. The differing from them suspended nanostructures with a 2DEG separated from a semiconductor substrate are of particular interest. They are created by etching the sacrificial layer from under nanostructures. Electronic transport in such suspended nanostructures has features originating from additional mechanical degrees of freedom [6-15], poor heat coupling to the bulk [16-17], and electron-electron interaction [17-19] being enhanced due to electric field confinement in a high-dielectric membrane. Many types of the semiconductor suspended nanostructures, including quantum point contacts [17, 20], quantum dots [19], Hall bars [15], antidot lattices [16, 18] have been implemented. At the same time, suspended semiconductor ring electron interferometers, to our knowledge, have not yet been studied.

The electron-electron interaction is known to play a crucial role in electron phase decoherence [21]. In the suspended 2DEG, new unusual conditions associated with the enhanced inter-electron interaction are realized. Technological difficulties in fabrication of the suspended devices with sizes small enough compared to the phase coherence length are a serious problem that needs to be solved in order to study the electronic interference in the suspended nanostructures. The minimum size of a semiconductor electron interferometer is limited by the size of the depletion region surrounding the
hole of the ring rather than by the electron lithography resolution. To provide access to the sacrificial layer which should be removed from under the nanostructure, fabrication of suspended nanostructures requires preliminary deep vertical etching of the heterostructure with a 2DEG, which in turn, enhances the width of the depleted region in comparison with the case of shallow etching. In this case, the contribution of the scattering on edge roughness also increases. Theoretical prediction of the role of all the described features can hardly be made totally convincing. In this connection, the interference phenomena in the suspended 2DEG require experimental investigation.

In the present paper, we report on the fabrication of the suspended semiconductor ring electron interferometer and the study of its magnetoresistance. We observed the Aharonov-Bohm oscillations before as well as after the suspension and studied their temperature suppression.

2. Experimental

The suspended semiconductor ring interferometers were fabricated on the basis of molecular-beam-epitaxy-grown GaAs/AlGaAs heterostructures with a 2DEG. The heterostructures contain 2DEG in a thin GaAs layer at a depth of 90 nm beneath the surface and a 400 nm-thick Al$_{0.3}$Ga$_{0.7}$As sacrificial layer. Total thickness of the layers grown above the sacrificial one, i.e. the thickness of the future suspended nanostructures, is 160 nm (see figure 1 (a)). The electron mobility and the 2DEG density are $2 \times 10^6$ cm$^2$/Vs and $(6 - 7) \times 10^{11}$ cm$^{-2}$ at 4.2 K, respectively. The lateral form of the samples was defined using electron-beam lithography followed by reactive ion etching. The trenches defining the interferometers were etched to a depth of at least 160 nm to provide access of the liquid etchant to the sacrificial layer (see figure 1). The samples were suspended by means of selective wet etching of the sacrificial layer from under the created nanostructures in 1:100 hydrofluoric acid water solution. The created suspended semiconductor ring interferometers have an effective radius 400–900 nm. A typical suspended interferometer is shown in figure 2.

![Figure 1](image1.png)

**Figure 1.** (a) GaAs/AlGaAs heterostructure with a 2DEG and a sacrificial layer. (b) Schematic representation of a suspended ring interferometer.

![Figure 2](image2.png)

**Figure 2.** SEM image of suspended interferometer.

The samples were equipped with Au/Ni/Ge Ohmic contacts to provide the conventional four-terminal magnetoresistance measurements. The measurements were carried out using the lock-in technique in the linear response regime with the alternating current of the magnitude 10 nA and the frequency 7–70 Hz at low temperature from 1.6 to 4.2 K. The magnetic field was applied...
perpendicularly to the 2DEG plane and varied in a range 0 – 0.6 T. The same measurements were performed on the same samples before and after suspension.

At low temperature and zero magnetic field, the rings have low resistance 0.5 – 2 kΩ depending on the illumination and cooling procedure. The value of the resistance (in comparison with $\hbar/2e^2 \sim 12.9$ kΩ) apparently indicates that the electron transport through the ring is multimode. The Aharonov-Bohm $\hbar/e$ oscillations are clearly observed in magnetoresistance of interferometers, both before and after suspension (see figure 3 (a – b)). The relative amplitude of the Aharonov-Bohm oscillations $\Delta R/R$ reaches 0.1 – 0.6 %. The fast Fourier transform (FFT) analysis indicates that the oscillations are periodic in the magnetic field with a characteristic period of 6 – 7 mT (see figure 3 (c – d)) that corresponds to the ring effective radius 650 nm. The amplitude of the oscillations demonstrates beating, which can be explained by the interference of several electronic modes.

**Figure 3.** The typical magnetoresistance of the interferometer before (a) and after (b) suspension. Fourier spectra of Aharonov-Bohm oscillations of magnetoresistance before (c) and after (d) suspension.

One can see that absolute amplitude of the Aharonov-Bohm oscillations remains unchanged after the suspension (~ 5 Ω), while the relative amplitude doubled due to a twofold decrease in resistance. Usually the mobility of a 2DEG decreases after suspension [15], which leads to an increase in resistance. The possible reason of the decrease observed in our case is the change in charge state of triangular quantum dots, that are usually formed in the inlet and outlet and affect the electron transport through the interferometer [22]. After suspension of the interferometers, the relative amplitude of the oscillations increases, and the peak in the Fourier spectrum of the oscillations becomes narrower, indicating that the number of propagating modes in the interferometer becomes smaller. Since the absolute amplitude of the Aharonov-Bohm oscillations remains unchanged after the suspension, while the effective radius of the interferometer does not change, as indicated by the peak positions in the Fourier spectrum, it can be concluded that the phase coherence length also remains almost unchanged.

We studied the temperature dependence of the amplitude of the Aharonov-Bohm oscillations in a range from 1.6 to 4.2 K. The amplitude was estimated as the difference in values between two adjacent extrema in a region of the magnetic field where this difference is maximal. The typical dependence for
the suspended interferometer is shown in figure 4. Similar behavior is typical for the non-suspended samples. One can see that the amplitude is suppressed by the temperature that confirms the interference origin of the oscillations.

![Figure 4](image_url)

**Figure 4.** The temperature dependence of the amplitude of the Aharonov-Bohm oscillations.

### 3. Conclusion
We fabricated a suspended semiconductor ring interferometer with a 2DEG demonstrating oscillations in magnetoresistance, whose temperature dependence and the Fourier spectra are characteristic of the Aharonov-Bohm effect. Relative amplitude of the observed oscillations reaches the large value 0.6%. Relative amplitude of the oscillations increases and the peak in the Fourier spectrum of the oscillations becomes narrower after the suspension, showing that the number of propagating modes in the interferometer becomes smaller, while the phase coherence length remains almost unchanged. The observed temperature suppression of the oscillations indicates their quantum-interference origin.

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### References
[1] Beenakker C W J, van Houten H 1991 Solid State Physics **44** 1
[2] Timp G, Chang A M, Cunningham J E, Chang T Y, Mankiewich P, Behringer R and Howard R E 1987 Phys. Rev. Lett. **58** 2814
[3] Ford C J B, Thornton T J, Newbury R, Pepper M, Ahmed H, Peacock D C, Ritchie D A, Frost J E F and Jones G A C 1989 Appl. Phys. Lett. **54** 21
[4] Ismail K, Washburn S and Lee K Y 1991 Appl. Phys. Lett. **59** 1998-2000
[5] Casse M, Kvon Z D, Gusev G M, Olshanetskii E B, Litvin L V, Plotnikov A V, Maude D K and Portal J C 2000 Phys. Rev. B **62** 2624-2629
[6] Ekinci K L and Roukes M L 2005 Rev. Sci. Instrum. **76** 061101
[7] Cleland A N and Aldridge J S, Driscoll D C and Gossard A C 2002 Appl. Phys. Lett. **81** 1699
[8] Shevyrin A A, Pogosov A G, Bakarov A K and Shklyaev A A 2016 Phys. Rev. Lett. **117** 017702
[9] Shevyrin A A, Pogosov A G, Budantsev M V, Bakarov A K, Toropov A I, Rodyakina E E and Shklyaev A A 2015 Appl. Phys. Lett. **106** 183110
[10] Shevyrin A A, Pogosov A G, Budantsev M V, Bakarov A K, Toropov A I, Ishutkin S V, Shesterikov E V and Arakcheev A S 2013 Appl. Phys. Lett. **103** 131905
[11] Steele G A, Hüttel A K, Witkamp B, Poot M, Meerwaldt H B, Kouwenhoven L P, van der Zant
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H S J 2009 Science 325 1103

[12] Lassagne B, Tarakanov Yu, Kinaret J, Garcia-Sanchez D, Bachtold A 2009 Science 325 594
[13] Okazaki Y, Mahboob I, Onomitsu K, Sasaki S and Yamaguchi H 2016 Nature Communications 7 11132
[14] Yamaguchi H, Okamoto H, Ishihara S and Hirayama Y 2012 Appl. Phys. Lett. 100 012106
[15] Pogosov A G, Budantsev M V, Zhdanov E Yu, Pokhabov D A, Bakarov A K and Toropov A I 2012 Appl. Phys. Lett. 100 181902
[16] Zhdanov E Yu, Pogosov A G, Budantsev M V and Pokhabov D A 2013 AIP Conf. Proc. 1566 211
[17] Shevyrin A A, Pogosov A G, Budantsev M V, Bakarov A K, Toropov A I, Ishutkin S V and Shesterikov E V 2014 Appl. Phys. Lett. 104 203102
[18] Zhdanov E Yu, Pogosov A G, Budantsev M V, Pokhabov D A and Bakarov A K 2017 Semiconductors 51 8
[19] Pogosov A G, Budantsev M V, Shevyrin A A, Plotnikov A E, Bakarov A K and Toropov A I 2008 JETP Lett. 87 150
[20] Okazaki Y, Mahboob I, Onomitsu K, Sasaki S and Yamaguchi H 2013 Appl. Phys. Lett. 103 192105
[21] Altshuler B L, Aronov A G and Khmelnitsky D E 1982 J. Phys. C 15 7367-7386
[22] Tkachenko V A, Bykov A A, Baksheev D G, Tkachenko O A, Litvin L V, Latyshev A V, Gavrilova T A, Aseev A L, Estibals O and Portal J C 2003 JETP Lett. 97 317-330