St. Petersburg Polytechnic University Journal. Physics and Mathematics. 2024 Vol. 17. No. 1.1
Научно-технические ведомости СПбГПУ. Физико-математические науки. 17 (1.1) 2024

Conference paper
UDC 538.9
DOI: https://doi.org/10.18721/JPM.171.114

Gurzhi effect in point contacts in GaAs

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Abstract. Hydrodynamic electron transport through point contacts of different widths in two-dimensional electron gas in GaAs/AlGaAs heterostructure is studied. Effect Gurzhi, i.e., minimum in the temperature dependence of the point contact resistance, corresponding to the conductance exceeding the ballistic limit, is experimentally observed. The minimum is shown to be observed in case when electron-electron scattering length is comparable with the point contact width. Under this condition, electrons act as viscous fluid, that leads to the resistance reduction. The experimental data including the width dependence are consistent with the theoretical prediction of the viscous contribution to the point contact conductance.

Keywords: electron-electron scattering, electron hydrodynamics, viscous electron fluid

Funding: The study was funded by the Russian Science Foundation (project 22-12-00343).

Citation: Sarypov D.I., Pokhabov D.A., Pogosov A.G., Egorov D.A., Zhdanov E.Yu., Bakarov A.K., Gurzhi effect in point contacts in GaAs, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 17 (1.1) (2024) 89–94. DOI: https://doi.org/10.18721/JPM.171.114

Материалы конференции
УДК 538.9
DOI: https://doi.org/10.18721/JPM.171.114

Эффект Гуржи в точечных контактах в арсениде галлия

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Аннотация. Исследован гидродинамический электронный транспорт через точечные контакты различной ширины в двумерном электронном газе в гетероструктуре GaAs/AlGaAs. В температурной зависимости сопротивления точечного контакта наблюдается минимум, соответствующий кондактансу, превышающему баллистический предел. Экспериментальные данные согласуются с теоретическим предсказанием вязкостного вклада в кондактанс точечного сужения.

Ключевые слова: электрон-электронное рассеяние, гидродинамика электронов, вязкая электронная жидкость

Финансирование: Работа выполнена при финансовой поддержке РНФ (проект № 22-12-00343).

Ссылка при цитировании: Сарыпов Д.И., Похабов Д.А., Погосов А.Г., Егоров Д.А., Жданов Е.Ю., Бакаров А.К. Эффект Гуржи в точечных контактах в арсениде галлия // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2024. Т. 17. № 1.1. С. 89–94. DOI: https://doi.org/10.18721/ JPM.171.114

Introduction

Electron-electron (*e*–*e*) interaction is shown to have significant impact on mesoscopic electron transport in case when *e*–*e* scattering length lee is comparable with characteristic size of the system *w* [1–12]. At the same time, the effects associated with e–e interaction, because of their many-body origin, are difficult to describe. Hydrodynamic approach can simplify the *e*–*e* interaction description by considering electrons as viscous fluid [13–15]. Hydrodynamic electron transport is overviewed in details in [16,17].

Due to total momentum conservation during *e*–*e* collisions, specific conditions are required for the hydrodynamic effects to be observed. Gurzhi showed [18] that, in case of ballistic conductors with long momentum relaxing length $l >> w$, when $l_{ee} \lesssim w$ correlations in the electrons motion act as a lubricant and prevent the momentum loss on the boundary roughness – the main momentum dissipation place. This effect leads to the resistance reduction, which has been experimentally proven in graphene [19] and GaAs [20].

In this work we present the experimental study of the hydrodynamic electron transport in the point contacts (PCs) based on the GaAs/AlGaAs heterostructure with an emphasis on the width dependence. We studied the temperature dependence of the resistance of 7 PC of different width. In the experiment we observe the PC resistance reduction below the ballistic limit with increasing temperature up to a certain value of about 20 K. For quantitative description of this effect, we employ the recent theory [21] predicting that the PC conductance enhancement due to the lubricant effect $\Delta G = G_{vis}$ is defined by the formula:

$$G_{\text{vis}} = \frac{\pi}{32}\frac{n^2e^2w^2}{\eta} = \frac{\pi}{8}\frac{e^2}{h}\left(k_F w\right)\frac{w}{l_{ee}}, \quad (1)$$

where $n = k_F^2/2\pi$ is the electrons density, k_F is Fermi quasiwavevector, *e*, *h* are the elementary charge and Planck’s constant, respectively and the electron liquid viscosity expressed as $\eta = hk_F n l_{ee} / 8\pi$ [21]. The result of the measurements confirms this prediction.

Materials and Methods

Experimental samples are created from GaAs/AlGaAs heterostructure grown by molecular beam epitaxy on a GaAs substrate (Fig. 1, *a*). Doping the heterostructure with Si δ-layers allow electrons to fill the quantum well at the heterointerface and form two-dimensional electron gas (2DEG). The mobility and concentration of electrons at $T = 4.2$ K are $\mu = 0.8{\cdot}10^6$ cm^2/(V·s) and $n = 2{\cdot}10^{11}$ cm^{-2}, respectively. Momentum relaxing length at this temperature is $l = 5.9$ μm. The quality of 2DEG in this structure is also confirmed by the observation of the quantum Hall effect [24].

Seven PCs of different lithographic width wlith, changing from 0.7 to 1.3 μm with the step of 0.1 μm, are created using e-beam lithography. The effective PC width $w = w_{lith} - w_0$, with the depletion layer thickness w_0 considered, is lower than wlith. We defined w_0 for all PCs from the resistance measurements at low temperature and relations (2–3) in the “Discussion” section. It was found out, that w_0 is universal for all PCs and equal 0.4 μm. Hereby, the PC effective width $w = w_{lith} - w_0$ varies from 0.3 to 0.9 μm. PCs are located on the Hall bar in series (Fig. 1, *b*). All PCs have a length of 0.6 μm. Both width and length of PCs are smaller than *l*, so all PCs can be considered ballistic.

Resistance measurements were performed in the cryostat in the temperature range from 4 to 65 K by means of lock-in technique at frequency of 7 Hz and the excitation current amplitude of 100 nA (Fig. 1, *b*).

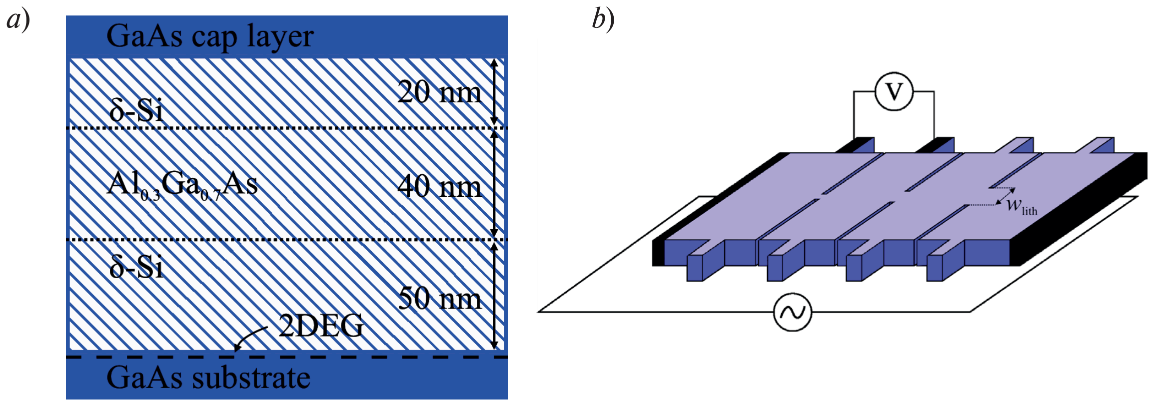

Fig. 1. Schematic images of heterostructure with 2DEG doped with Si δ-layers (*a*) and experimental sample with point contacts (*b*). Point contact lithographic width wlith varies from 0.7 to 1.3 μm

Results

Fig. 2, *a* shows the temperature dependence of the PC resistance. It is clearly seen, that, for all PCs, the resistance first falls at temperatures $\lesssim$ 20 K and then monotonically increases, demonstrating the minimum. We attribute the observed resistance reduction to Gurzhi effect [18]. The minimal resistance is lower than the low-temperature ballistic PC resistance due to the momentum loss suppression at the PC boundary, induced by the lubricant effect [21]. This effect is expected under the condition $l_{ee} \lesssim w << l$ [18]. As will be shown below, this condition is fulfilled for studied PCs in the resistance minimum.

Dotted line in Fig. 2, *a* shows that the resistance minimum position depends on the PC width *w*. The minimum shifts to the higher temperatures for smaller *w*. This trend is shown in details on the dependence of the resistance minimum position T_{min} on the w on a quadratic scale (Fig. 2, *b*).

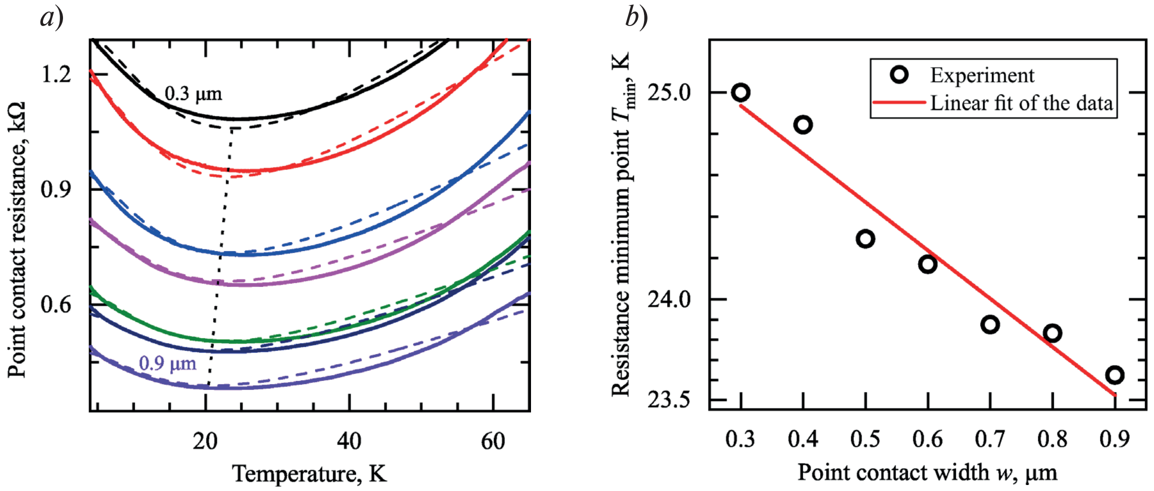

Fig. 2. Temperature dependence of PC resistance of different width *w* (*a*). Solid lines show experimental data and dashed lines show approximation by model (4). Dotted line shows that resistance minimum shifts to lower temperature as *w* increases. Resistance minimum point Tmin in quadratic scale as function of *w* (*b*). Experimental data are shown by circles. Linear approximation is shown by line

Discussion

A solid line in Fig. 2, *b* points to the linear relation between T^2_{min} and *w* that can be explained by the temperature dependence of l_{ee}. The minimal resistance is achieved when the *e*—*e* scattering rate is comparable with the rate of the momentum relaxation scattering [18]. In our case it means that $l_{ee} \sim w$. Since $l_{ee} \infty T^{-2}$ [22, 23] we have the dependence $w \infty T^{-2}_{min}$.

The resistance measurements $R(T)$ accounting viscous contribution Gvis can be presented as:

$$R(T) = R_{\mathrm{2DEG}}(T) + \left(G_{\mathrm{ball}} + G_{\mathrm{vis}}\right)^{-1}, \tag{2}$$

where the first term R_{2DEG} is the resistance of the macrocsopic 2DEG regions adjacent to the constrictions, and the second is the PC resistance including viscous G_{vis} and the ballistic G_{ball} PC conductance at zero temperature. The additive form of G_{ball} and G_{vis} in (2) is applicable for the entire temperature range studied [21]. At low temperature, when electron transport is ballistic, the PC conductance is defined by the formula:

$$G_{\mathrm{ball}} = \frac{2e^2}{h}\frac{k_F(w_{\mathrm{lith}} - w_0)}{\pi} \equiv \frac{2e^2}{h}\frac{k_F w}{\pi}. \tag{3}$$

To describe the viscous contribution to the PC conductance, the formula (1) can be rewritten with fitting parameter T_0:

$$G_{\mathrm{vis}} = \frac{2e^2}{h}\left(k_{\mathrm{F}} w\right)^2 \left(\frac{T}{T_0}\right)^2. \tag{4}$$

We use the following form of the temperature dependence of R2DEG:

$$R_{\mathrm{2DEG}} = R_0\left(1 + \frac{T}{T_{\mathrm{ph}}}\right), \tag{5}$$

where R_0, Tph are fitting parameters. Here R_{2DEG} is defined by impurity scattering R_0 and phonon scattering $R_0(T/T_{\mathrm{ph}})$. Quadratic temperature dependence of G_{vis} follows from G_{vis} dependence on l_{ee}: $G_{\mathrm{vis}} \infty\, l_{\mathrm{ee}}^{-1}$ and $l_{\mathrm{ee}} \infty\, T^{-2}$. The result of the approximation (4–5) is in acceptable agreement with experimental data (see dashed curves in Fig. 2, *a*).

Further, the results of the approximation (4) were used to obtain G_{vis}, which is shown in Fig. 3, *a* as the function of temperature. It is noteworthy, that in case when G_{vis} is divided by w^2 all the curves corresponding to different w collapse into one. This means, that the fitting parameter T_0 is universal for all PCs and G_{vis} scales as $G_{\mathrm{vis}} \infty\, w^2$.

The experimentally obtained dependence $G_{\mathrm{vis}}(T)$ allowed us to extract l_{ee}. As follows from (1) and (4), l_{ee} equals:

$$l_{\mathrm{ee}} = \frac{\pi}{16}\frac{1}{k_{\mathrm{F}}}\left(\frac{T_0}{T}\right)^2. \tag{6}$$

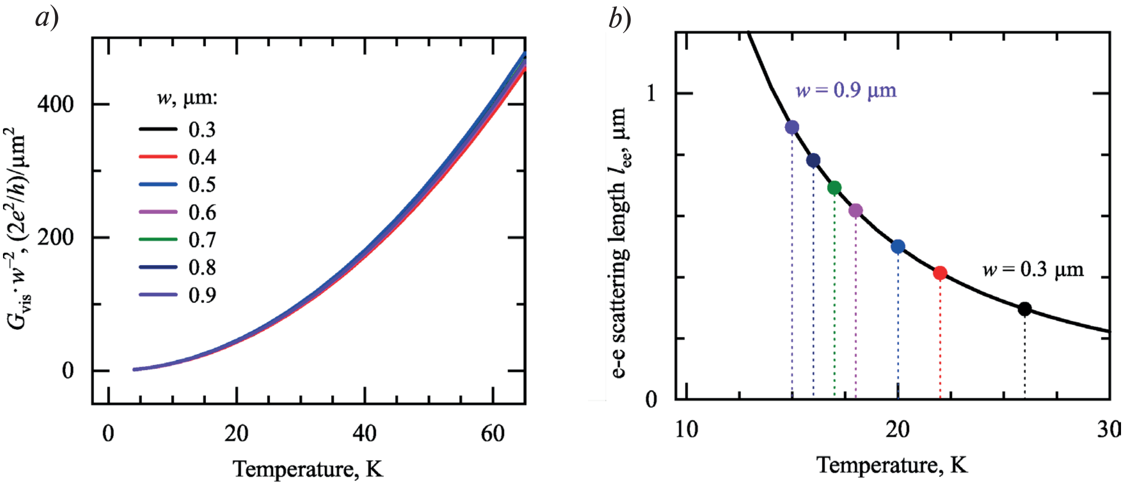

Fig. 3. (*a*) Temperature dependence of viscous contribution to conductance G_{vis} taken with weight w^2 for different PCs widths *w*. (*b*) Electron-electron scattering length lee as function of temperature. Circles correspond to experimentally studied *w*

Fig. 3, *b* shows *e*—*e* scattering length lee as the function of temperature obtained by Eq. (6) with T_0 as the fitting parameter. Vertical dotted lines in Fig. 3, *b* show the temperature range (15—25 K) in which l_{ee} lies in the actual range of *w* (0.3—0.9 μm). Thus, at the temperature range corresponding to the resistance minima (23—25 K) the condition $l_{ee} < w$ is satisfied. This inequality corresponds to the resistance minimum observation condition. Therefore, the Gurzhi requirement for the resistance minimum observation is achieved in our case.

Conclusion

We study electron transport in hydrodynamic regime through PC in 2DEG in GaAs/AlGaAs heterostructure. Gurzhi effect, consisting in the resistance reduction with increasing temperature is experimentally observed. It corresponds to the conductance exceeding the ballistic limit. The observed effect can be explained by the momentum loss suppression at the PC boundary due to the lubricant effect caused by *e*—*e* interaction. Viscous contribution to the PC resistance, attributable to the lubricant effect is extracted from the experiment. The obtained viscous contribution confirms the theoretical prediction.

REFERENCES

1. **de Jong M.J.M., Molenkamp L.W.,** Hydrodynamic electron flow in high-mobility wires. Phys. Rev. B 51 (1995) 13389—13402.
2. **Melnikov M.Yu., Kotthaus J.P., Pellegrini V., Sorba L., Biasol G., Khrapai V.S.,** Influence of e - e scattering on the temperature dependence of the resistance of a classical ballistic point contact in a two-dimensional electron system. Phys. Rev. B 86 (2012) 075425.
3. **Narozhny B.N., Gornyi I.V., Titov M., Schütt M., Mirlin A.D.,** Hydrodynamics in graphene: Linear-response transport. Phys. Rev. B 91 (2015) 035414.
4. **Alekseev P.S.,** Negative Magnetoresistance in Viscous Flow of Two-Dimensional Electrons. Phys. Rev. Lett. 117 (2016) 166601.
5. **Gusev G.M., Levin A.D., Levinson E.V., Bakarov A.K.,** Viscous electron flow in mesoscopic two-dimensional electron gas. AIP Advances 8 (2018) 025318.
6. **Levin A.D., Gusev G.M., Levinson E.V., Kvon Z.D., Bakarov A.K.,** Vorticity-induced negative nonlocal resistance in a viscous two-dimensional electron system. Phys. Rev. B 97 (2018) 245308.
7. **Narozhny B. N., Schütt M.,** Magnetohydrodynamics in graphene: Shear and Hall viscosities. Phys. Rev. B 100 (2019) 035125.
8. **Raichev O.E., Gusev G.M., Levin A.D., Bakarov A.K.,** Manifestations of classical size effect and electronic viscosity in the magnetoresistance of narrow two-dimensional conductors: Theory and experiment. Phys. Rev. B 101 (2020) 235314.
9. **Keser A.C., Wang D.Q., Klochan O., Ho D., Tkachenko O.A., Tkachenko V.A., Culcer D., Adam S., Farrer I., Ritchie D.A., Suchkov O.P., Hamilton A.R.,** Geometric Control of Universal Hydrodynamic Flow in a Two-Dimensional Electron Fluid. Phys. Rev. X 11 (2021) 031030.
10. **Khudaiberdiev D.A., Gusev G.M., Olshanetsky E.B., Kvon Z.D., Mikhailov N.N.,** Magnetohydrodynamics and electron-electron interaction of massless Dirac fermions. Phys. Rev. Res. 3 (2021) L032031.
11. **Levin A.D., Gusev G.M., Yaroshevich A.S., Kvon Z.D., Bakarov A.K.,** Geometric engineering of viscous magnetotransport in a two-dimensional electron system. Phys. Rev. B 108 (2023) 115310.
12. **Ginzburg L.V., Wu Y., Röösli M.P., Gome P.R., Garreis R., Tong C., Stará V., Gold C., Nazaryan K., Kryhin S., Overweg H., Reichl C., Berl M., Taniguchi T., Watanabe K., Wegscheider W., Ihn T., Ensslin K.,** Long distance electron-electron scattering detected with point contacts. Phys. Rev. Res. 5 (2023) 043088.
13. **Andreev A.V., Kivelson S.A., Spivak B.,** Hydrodynamic Description of Transport in Strongly Correlated Electron Systems. Phys. Rev. Lett. 106 (2011) 256804.
14. **Principi A., Vignale G., Carrega M., Polini M.,** Bulk and shear viscosities of the two-dimensional electron liquid in a doped graphene sheet. Phys. Rev. B 93 (2016) 125410.
15. **Gurzhi R.N.,** Hydrodynamic effects in solids at low temperature. Sov. Phys. Usp. 11, 255 (1968).
16. **Polini M., Geim A.K.,** Viscous electron fluids. Physics Today 73 (2020) 28—34.

17. **Narozhny B.N.,** Hydrodynamic approach to two-dimensional electron systems. Riv. Nuovo Cim. 45 (2022) 661–736.

18. **Gurzhi. R.N.,** Minimum of resistance in impurity-free conductors. Sov. Phys. JETP. 44 (1962) 771–772.

19. **Krishna Kumar R., Bandurin D.A., Pellegrino F.M.D., Cao Y., Principi A., Guo H., Auton G.H., Ben Shalom M., Ponomarenko L.A., Falkovich G., Watanabe K., Taniguchi T., Grigorieva I.V., Levitov L.S., Polini M., Geim A.K.,** Superballistic flow of viscous electron fluid through graphene constrictions. Nature Phys 13 (2017) 1182–1185.

20. **Ginzburg L.V., Gold C., Röösli M.P., Reichl C., Berl M., Wegscheider W., Ihn T., Ensslin K.,** Superballistic electron flow through a point contact in a Ga[Al]As heterostructure. Phys. Rev. Res. 3 (2021) 023033.

21. **Guo H., Ilseven E., Falkovich G., Levitov L.S.,** Higher-than-ballistic conduction of viscous electron flows. Proceedings of the National Academy of Sciences 114 (2017) 3068–3073.

22. **Chaplik A.V.,** Energy spectrum and electron scattering processes in inversion layers. Zh. Eksp. Teor. Fiz. 60 (1971) 1845–1852.

23. **Giuliani G.F., Quinn, J.J.,** Lifetime of a quasiparticle in a two-dimensional electron gas. Phys. Rev. B 26 (1982) 4421–4428.

24. **Budantsev M.V., Pokhabov D.A., Pogosov A.G., Zhdanov E.Yu., Bakarov A.K., Toropov A.I.,** Hysteretic phenomena in a 2DEG in the quantum Hall effect regime, studied in a transport experiment. Semiconductors 48 (2014) 1423–1431.

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Received 14.12.2023. Approved after reviewing 06.01.2024. Accepted 07.01.2024.