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Magnetic field characterization of physical properties of two-dimensional electron gas of nitride high electron mobility transistor heterostructures

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Analysis of the magnetic field dependence of magnetoresistance and Shubnikov−de Haas oscillations allows us to determine the concentration of charge carriers, as well as temperature and electron density dependencies of the transport and quantum mobilities of the two-dimensional electron gas in AlGaN/AlN/GaN high-electron-mobility transistor heterostructures. Unlike the standard Hall method, which requires four-contact measurements and additional technological procedures for creating test modules, the proposed technique uses two contacts and allows to compare the two-dimensional electron gas parameters in finished high-electron mobility transistors and in the initially synthesized heterostructures.

Keywords: Nitride high electron mobility transistors, two-dimensional electron gas, Shubnikov−de Haas effect.

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1. Introduction

Nitride high electron mobility transistors (HEMT) based on AlGaN/AlN/GaN heterostructures have been broadly used in practice as basic components of stable microwave electronics devices [1]. However, the progressive development of their production technology is still hampered by the lack of effective methods for characterizing the physical properties of the main working element of the system — two-dimensional electron gas (2DEG) in the finished HEMT. The fact is that at this stage, standard galvanomagnetic Hall measurement methods do not allow determining the key parameters of 2DEG, on which the quality of the product significantly depends — the density of 2DEG electrons and their mobility, without subjecting the objects of study to a number of very invasive technological procedures for creating Hall bars in them, although the effect of the processes occurring in this case on the physical properties of 2DEG is actually unknown. All this does not allow establishing a completely reliable correlation between the features of HEMT synthesis technology and the results of its application, which greatly narrows the field of possibilities for its development.

This paper presents a technique for characterizing the electronic properties of 2DEG nitride HEMTs by analyzing data from a single experiment — two-contact measurements of 2DEG magnetoresistance in a system based on well-known results of the theoretical description of the Shubnikov−de Haas effect [2,3]. In particular, the temperature dependence of the magnetoresistance of the samples reflects the temperature dependence of the transport relaxation frequency $(1/\tau_{tr})$ of 2DEG electrons, the analysis of the period of Shubnikov−de Haas oscillations occurring in fields $B \geq 7\,\mathrm{T}$, by parameter 1/B and observed at temperatures of $T < 30\,\mathrm{K}$, allows finding the 2DEG electron density, and the behavior of their amplitude as a function of the magnetic field and temperature for studying the temperature dependence of the quantum relaxation frequencies $(1/\tau_q)$ of 2DEG electrons. Finally, the results of a comparative analysis of the data obtained on the behavior of transport and quantum relaxation frequencies in the system (the former, unlike the latter, is known to be insensitive to small-angle scattering of conduction electrons) contain very useful information not only about the nature of elastic carrier scattering processes in the 2DEG, which dominate the studied temperature range, but also about the type of static defects that cause them [3].

It is very important that, unlike the standard Hall procedures, this approach is also applicable to studying heterostructures with a gate, where it is impossible to make measurements using the four-contact method in principle.

2. Experiment details

The two-gate transistors studied in this paper (see Figure 1), formed on nitride heterostructures of domestic production synthesized by the MOCVD method on Si(111) silicon substrates at the Ioffe Institute of Physics and Technology. The growth features and composition of the heterostructures that were used to create transistors are shown in Figure 1 in Ref. [4].

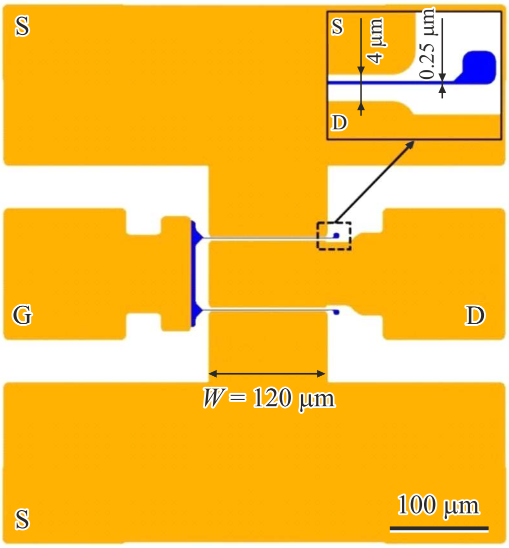

Figure 1. Schematic representation of the studied HEMT. All sources have contact with the metallization on the underside of the substrate.

The dimensions of the gate periphery were 2×80, 2×120 and $2 \times 180\,\mu$m with a source-drain distance and gate length of 4 and $0.25\,\mu$m, respectively. The contacts to the 2DEG are made by epitaxial accretion of gallium nitride doped with silicon, followed by their metallization. The structure was passivated with 500 nm thick silicon nitride layer using PECVD method. The sources of all transistors created on the plate have contact with the metallization on the underside of the substrate.

The electronic structure of 2DEG HEMT heterostructures was studied in detail earlier (see [5]): experimentally by Hall measurements and angular resolved photoelectron spectroscopy, theoretically by first-principle quantum chemical calculations using the density functional method and numerical solution of the Schrodinger and Poisson equations. It is shown that the two lowest subbands of dimensional quantization (QWS_1 and QWS_2) are partially filled in the 2DEG electronic spectrum, each of which is split twice by the spin-orbit interaction as was later established in Ref. [6].

The carrier concentration in the studied heterostructures practically does not change in the temperature range of $T = 5{-}300$ K according to the data from Ref. [5], and the decrease of 2DEG resistance with a decrease of temperature is attributable to an increase of the carrier mobility mainly due to a decrease of the contribution of electron-phonon collisions. Finally, according to the same source, the occupancy of the upper of the two partially filled dimensional quantization subbands, QWS_2, is ~ 20 times less than the occupancy of the lowest one, QWS_1.

The presented results of magnetotransport studies of the system in magnetic fields up to 14 T applied perpendicular to the 2DEG plane, in the temperature range of 10–300 K, were obtained at the EFM resource center of SRC „Kurchatov Institute“; measurements of the 2DEG resistance at temperatures from 10 mK in the magnetic field up to 1 T tests were carried out at the CUC of Lebedev Institute of Physics, RAS. The HEMT drain-source resistance was measured using a two-contact method. Magnetotransport in heterostructures without a gate has also been studied in Van der Pauw geometry and in the standard geometry of the Hall cross.

3. Results and discussion

The temperature dependence of the drain-source resistance of the test structure (B120-4) is shown in Figure 2.

Figure 3 shows the magnetic field dependences of the drain-source resistance of two transistors formed on the same substrate (structures A120-4 and B120-4). The dependencies $\Delta R_{\mathrm{A}} = R_{\mathrm{A}}(\mathrm{B}) - R_{\mathrm{A}}(\mathrm{B} = 0)$ and $\Delta R_{\mathrm{B}} = R_{\mathrm{B}}(\mathrm{B}) - R_{\mathrm{B}}(\mathrm{B} = 0)$ are almost identical. The main course of the dependence $R(\mathrm{B})$ obeys the quadratic law; Shubnikov–de Haas oscillations are observed against this background at low temperatures.

It is known [7] that in a two-dimensional semiconductor with a large cross-section with one type of carrier, which is equivalent to a Corbino disk with respect to electronic transport, in the range of non-quantizing magnetic fields above the region of weak localization $\delta R(\mathrm{B})/R(0) \approx (\mu_{tr}\mathrm{B})^2$, where $\delta R(\mathrm{B}) = R(\mathrm{B}) - R(0)$, $\mu_{tr} = e\tau_{tr}/m^*$ — transport mobility, and τ_{tr} is the 2DEG electron transport relaxation time. Fitting the curves in Figure 3 with a second-order polynomial allows us to determine the value of μ_{tr}. In particular, we obtain $\mu_{tr} = 3.76 \cdot 10^3\,\mathrm{cm}^2/(\mathrm{V \cdot s})$ at $T = 10$ K, which, taking into account the decrease in 2DEG mobility with the temperature increase, is quite consistent with the value of the typical 2DEG mobility of gateless heterostructures at room temperature, which lies within $1.5{-}2.0 \cdot 10^3\,\mathrm{cm}^2/(\mathrm{V \cdot s})$. Finally, for the corresponding electron relaxation transport time of 2DEG, we obtain: $\tau_{tr} \approx 4.3 \cdot 10^{-13}$ s.

The details of the analysis of the Shubnikov–de Haas oscillations (Figure $4, a, b$) should be discussed in more detail. The paper in Ref. [6] devoted to the study of extended and narrow Hall bars made of heterostructures on the basis of which the HEMTs studied here are grown showed that *a*) Shubnikov–de Haas oscillations in their magnetoresistance are anisotropic and represent a superposition of two pairs of contributions corresponding to two partially filled subbands of dimensional quantization QWS_1 and QWS_2, each of which is split twice by the spin-orbit interaction, and *b*) only the spin-unsplit contribution of the lower subband, QWS_1, „survives“ under averaging of their magnetoresistance over the angle of 120° which allows to determine its contribution to the 2DEG electron density. The formal reason for this result, which is beyond the scope of this paper, is apparently conditioned by the symmetry of 2DEG and the nontrivial geometric properties of its band structure.

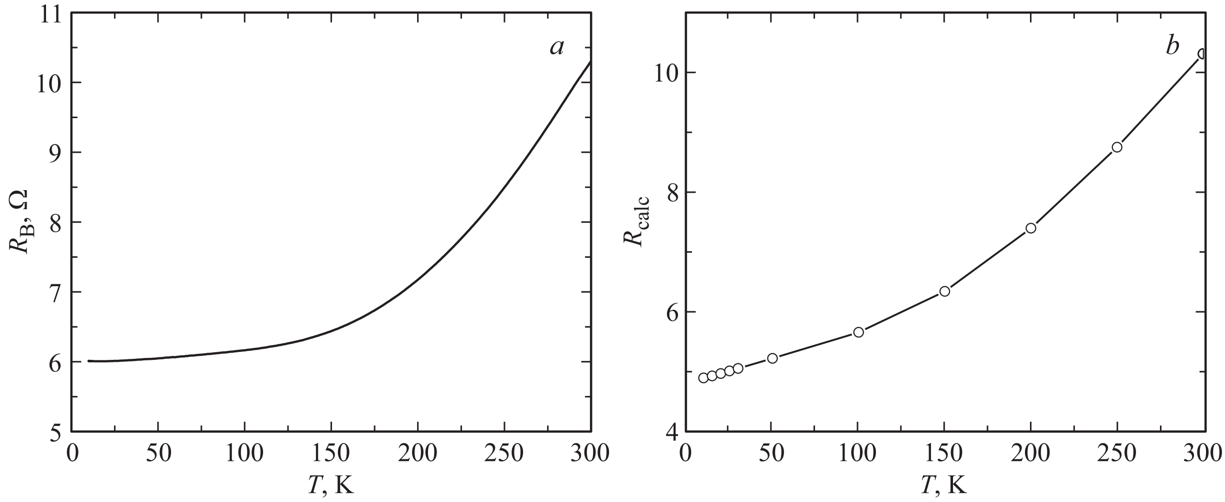

Figure 2. *a* — temperature dependence of the drain-source resistance of the 2DEG structure B120-4. *b* — 2DEG resistance, calculated from the temperature dependence of transport mobility, assuming that the concentration of 2DEG carriers does not depend on temperature.

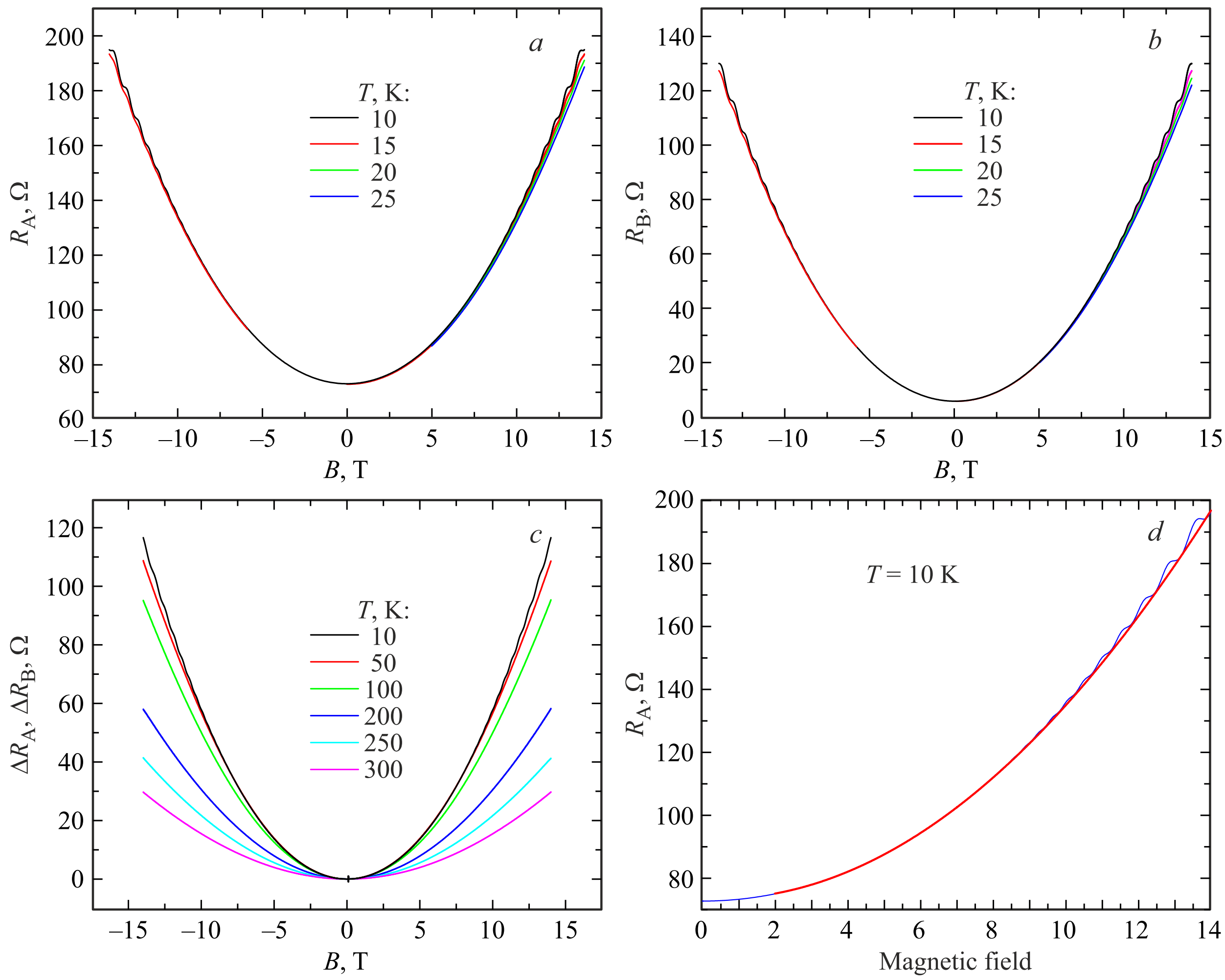

Figure 3. Magnetic field dependencies of the drain-source resistance in a transistor *a*) A120-4 and *b*) B120-4; the source is connected to the gate. *with* — dependencies $\Delta R_A = R_A(B) - R_A(B=0)$ and almost identical ones $\Delta R_B = R_B(B) - R_B(B=0)$. *d* — Shubnikov–de Haas oscillations on the background of the main course of dependence $R_A(B)$.

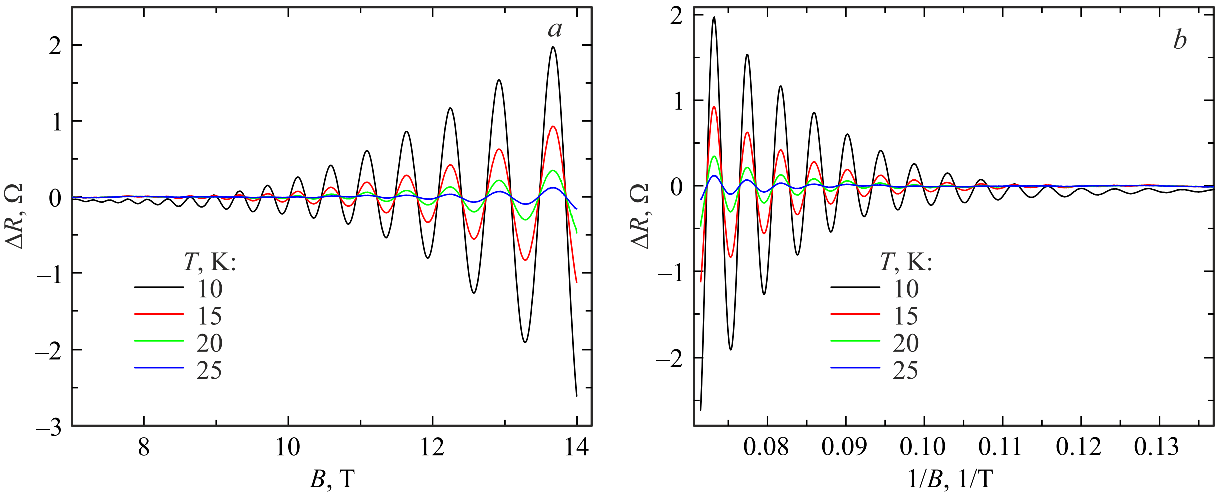

Figure 4. *a* — 2DEG magnetoresistance minus the main stroke, ΔR(B). *b* — dependence ΔR(1/B), Shubnikov–de Haas oscillations (both graphs for the sample B120-4).

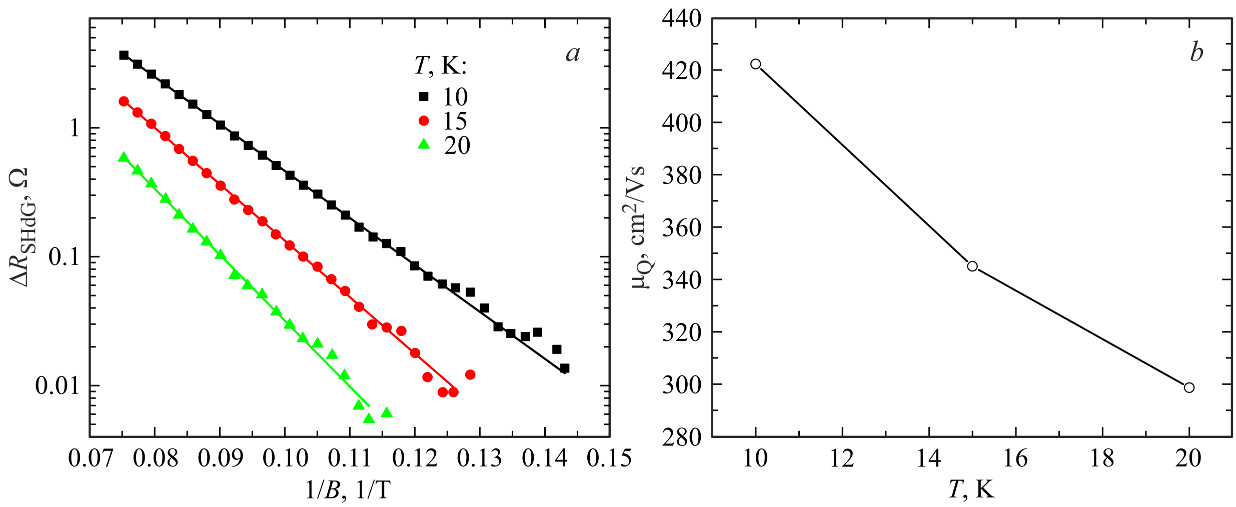

Figure 5. *a* — magnetic field dependence of the amplitude of the Shubnikov–de Haas oscillations at different temperatures in the B120-4 structure. *b* — the corresponding temperature dependence of the quantum mobility of 2DEG electrons.

The system studied here is a real space 2DEG rectangle short from source to drain and relatively wide in diameter, and the equivalence of its geometry to the Corbino disk is confirmed, in particular, by the parabolic dependence of its magnetoresistance on the magnitude of the external magnetic field (Figure 3). This latter means, in particular, that the Shubnikov–de Haas oscillations (Figure 4, *a, b*) result, in fact, from the averaging of the magnetoresistance of the 2DEG studied here over the angles in the interface plane, and in the light of the above-mentioned result in Ref. [6] allows to findthe contribution of QWS_1 to the 2DEG electron density, which practically determines the total electron density within the error margin of the present experiment.

Thus, the standard calculation based on the data of Figure 4, *b* on the frequency of oscillations of the magnetoresistance as a function of 1/B gives the electron density of the studied 2DEG: $n \approx 1.20 \cdot 10^{13}\,\mathrm{cm}^{-2}$.

It should be emphasized that the analysis of the Shubnikov–de Haas oscillations (Figure 4, *b*) makes it possible to find not only the density of 2DEG electrons, but also their quantum mobility even in finished HEMT, unlike the standard Hall methods, which are applicable without reservations only to the study of AlGaN/AlN/GaN gateless heterostructures and requiring four-contact measurements. Indeed, the behavior of the amplitude of the Shubnikov–de Haas oscillations in the magnetic field $\Delta R_{\mathrm{ampSdG}}$ (B) is known to be caused by the elastic scattering of charge carriers on static defects in the system. The logarithmic scale dependence $\Delta R_{\mathrm{ampSdG}}$ (1/B) has the shape of a straight line (Figure 5), the slope modulus to the 1/B axis is $\pi m^*/e\tau_q = \pi/\mu_q$, where τ_q is the 2DEG electrons quantum relaxation time, μ_q is their quantum mobility. So in our case (see Figure 5), for example, for $T = 10\,\mathrm{K}$ we obtain $\mu_q \approx 420\,\mathrm{cm^2/(V \cdot s)}$ and, respectively, $\tau_q \approx 4.8 \cdot 10^{-14}\,\mathrm{s}$.

As we can see, the quantum relaxation frequency of the conduction electrons in the studied 2DEG is an order of magnitude higher than the relaxation frequency of their momentum. The latter means that the main elastic scattering mechanism of 2DEG electrons in the system is small-angle scattering, which is characteristic, in particular, for their motion in the long-range potential of ionized impurities, static lattice defects with a non-zero dipole moment, dislocations and (or) grain boundaries in the region of 2DEG localization, in contrast to electron scattering on neutral point defects or the interface imperfections, which is known to be isotropic (see, for example, ch. 23 [3]).

A more detailed comparative analysis of the entire array of data that the technique used here allows us to obtain, including the temperature dependences of relaxation times and their dependences on the 2DEG electron density, with the results of model calculations, will probably make it possible to come to greater certainty in this issue.

4. Conclusion

It is shown that data on the 2DEG magnetoresistance in the region of relatively weak magnetic fields allows to establish the dependence of electron transport mobility on temperature and electron density in the 2DEG of the gated heterostructures, and the characteristics of the Shubnikov–de Haas oscillations allow obtaining similar information about electron quantum mobility in 2DEG and calculating the electron density in the system.

The diagnostic capabilities of the procedure are demonstrated here by analyzing data from magnetotransport studies of 2DEG AlGaN/AlN/GaN transistor heterostructures on (111) single-crystal silicon).

The authors believe that the presented technique can serve as a useful tool for analyzing a large class of conductive high electron mobility interfaces: unlike the standard four-contact Hall methods, it is applicable to studying a wide range of parameters of complex geometry heterostructures, uses only two contacts, and therefore does not require the creation of additional test measuring modules, nevertheless allowing to compare the 2DEG parameters in ready-made transistors. and in initially synthesized heterostructures.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] A.F. Medjdoub, K. Iniewski (eds.). *Gallium nitride (GaN): physics, devices, and technology* (N. Y., CRC Press, 2016).
[2] D. Shoenberg. *Magnetic Oscillations in Metals* (Cambridge University Press, 2009).
[3] V.A. Kulbachinsky. Fizika nanosistem (M., Fizmatlit, 2022), p. 5.1.1, p. 143. (in Russian).
[4] A.V. Sakharov, D.S. Arteev, E.E. Zavarin, A.E. Nikolaev, W.V. Lundin, N.D. Prasolov, M.A. Yagovkina, A.F. Tsatsulnikov, S.D. Fedotov, E.M. Sokolov, V.N. Statsenko. Materials, **16**, 4265 (2023). https://doi.org/10.3390/ma16124265
[5] L.L. Lev, I.O. Maiboroda, M.-A. Husanu, E.S. Grichuk, N.K. Chumakov, I.S. Ezubchenko, I.A. Chernykh, X. Wang, B. Tobler, T. Schmitt, M.L. Zanaveskin, V.G. Valeyev, V.N. Strocov. Nature Commun., **9** (1), 2653 (2018). https://doi.org/10.1038/s41467-018-04354-x
[6] N.K. Chumakov, A.A. Andreev, I.V. Belov, A.B. Davydov, I.S. Ezubchenko, L.L. Lev, L.A. Morgun, S.N. Nikolaev, I.A. Chernykh, S.Yu. Shabanov, V.N. Strocov, V.G. Valeyev. JETP Letters, **119** (8), 604 (2024). https://doi.org/10.1134/S0021364024600769
[7] A. Fowler, F. Fang, W. Howard, P.J. Stiles. Phys. Rev. Lett., **16** (20), 901 (1966). https://doi:10.1103/physrevlett.16.901

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