The Kondo effect and mesoscopic quantum coherence in a 2D electron gas of magnetically undoped AlGaN/AlN/GaN heterostructures

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Abstract. We report an observation of the Kondo effect in two-dimensional electron gas (2DEG) of magnetically undoped AlGaN/GaN high electron mobility transistor heterostructures and analyze the 2DEG magnetoresistance oscillations to reveal the small-scale structure of the confining potential. Temperature-dependent zero-field resistivity data exhibit an appreciable upturn below 120 K, followed by the standard low-temperature weak-localization (WL) behaviour below 50 K, crossing over to a pronounced weak antilocalization (WAL) picture at T < 3 K. Magnetotransport characterization was carried out in the temperature range 100 mK ÷ 300 K in the magnetic fields B up to 8 T, applied perpendicular to the 2DEG plane. The Altshuler-Aronov-Spivak oscillations of the magnetoresistance with period $\hbar/2e$, clearly observed against the background of its smooth behavior, are determined by the inhomogeneity of the 2 DEG confinement and allows to estimate its characteristic spatial scales.

1. Introduction
Wurtzite AlGaN/GaN high electron mobility transistor (HEMT) heterostructures are being systematically studied for the last decades in the interest of the next generation high-power, high-temperature and microwave electronics. The reason is their ability to provide current density, operating temperatures, breakdown voltage and cut-off frequencies, significantly higher than those of the existing GaAs, Si and Ge systems [1]. Recent remarkable progress in the development of III-nitride functional systems is however not synonymous to the satisfactory knowledge of the physical properties of this family of semiconductor materials.

Here we report an unusual observation of the Kondo effect in two-dimensional electron gas (2DEG) of magnetically undoped AlGaN/GaN HEMT heterostructures and analyze the 2DEG magnetoresistance oscillations to reveal the small-scale structure of the confining potential.

The temperature-dependent zero-field resistivity data is shown to exhibit an appreciable upturn below 120 K, followed by the standard low-temperature weak-localization (WL) behaviour below 50 K and crossing over to a pronounced weak antilocalization (WAL) picture at T < 3 K. Magnetotransport characterization of the system was performed in the magnetic fields B up to 8 T, applied perpendicular...
to the 2DEG plane, in the temperature range 100 mK ÷ 300 K. The temperature and magnetic field dependencies were measured in both the usual van der Pauw and Hall geometries. Negative low-temperature magnetoresistance with a magnitude of order of 1% was detected in the WL temperature region. Transition from WL to WAL takes place at $B \approx 0.005$ T.

The zero-magnetic field resistance behavior is identified as a manifestation of the multichannel Kondo effect in $d_0$-magnetic materials with the spin-orbit interaction, where the source of magnetic degrees of freedom in the system is attributed with vacancy complexes of two positively charged N vacancies ($V_N$) and one doubly negative Ga vacancy and/or singly charged Ga vacancies ($V_{Ga^-}$), each inducing a net magnetic moment of $1\mu_B$, located around its negative Ga center in the 2DEG localization region. This conclusion is based on character of the quantum coherent behavior of the low-temperature low-field magnetotransport in the system, pointed above and possible only due complete screening of the magnetic defects by the Fermi sea [2, 3, 4], combined with the spectroscopic & DFT data on the defects nomenclature in GaN [5, 6] and the ARPES data [7] on the two-channel 2DEG electron structure for the same samples.

Thorough examination of the low-temperature magnetoresistance in the region of sufficiently low magnetic fields reveals the Altshuler-Aronov-Spivak (AAS) oscillations [8] with period $\hbar/2e$, observed against the background of its smooth behavior. This discovery allows one to link the heterostructure interface structure with the spatial inhomogeneity of the 2DEG confinement [9] and to estimate its characteristic spatial scales.

2. Sample preparation

The nitride heterostructures with 2DEG were grown on c-oriented sapphire substrate in SemiTeq STE3N MBE-system equipped with ammonia nitrogen ($NH_3$) source. Detailed description of the growth procedure is given in ref. [7].

3. Results and discussion

The temperature-dependent zero-field resistivity data, taken in the temperature range 100 mK ÷ 300 K given in Figure 1, exhibit an appreciable upturn below 120 K, followed by the standard low-temperature WL behavior below 50 K, crossing over, as it’ll be seen below (see Figure 2 for the example), to a pronounced WAL picture at $T < 3$ K.

![Figure 1. The temperature dependence of zero-magnetic field 2DEG resistance (circles), fitted to the numerical renormalization group n-channel Kondo model (solid line), see [10].](image)

This result is a standard manifestation of the Kondo effect in $d_0$-magnetic materials – the systems, where magnetism is not induced by magnetic impurities, but appears because of the vacancies in the cation sublattice [11]. It is worth noting, that there are several types of the appropriate defects in GaN. One of them is Ga vacancy ($V_{Ga}$) in its three different charge states, which is confirmed by Raman and
X-ray photoelectron spectroscopy [12] and associated also with the yellow emission of the photoluminescence spectrum. A neutral VGa center has composite spin 3/2 with a local magnetic moment of about $3\mu_B$, produced by spins of unpaired 2p-electrons of the three nitrogen atoms surrounding each of the Ga vacancy, while a singly charged Ga vacancy (VGa$^-$) is known to have magnetic moment of about $1\mu_B$. The net magnetic moment of $1\mu_B$, localized around the negative Ga center, is a property of VGa$^{2-}$-2VN$^+$ - complex - a vacancy system of one doubly negative Ga vacancy and two positively charged N vacancies (VN), [13].

Two decisive points are to be taken into account in order to distinguish between the possible Kondo scenarios [14]: the two-channel character of the 2DEG electron spectrum, witnessed by the ARPES data [7], and the low-temperature WL-WAL quantum coherent behavior. The result of magnetotransport system characterization, carried out in both the usual van der Pauw and Hall geometries at $T = 200$ mK and in the magnetic fields up to 0.5 T, applied perpendicular to the 2DEG plane, is given in figure 2 as an example. A significant increase in the resistance, which then turns to a sharp drop in the region of the lower fields clearly indicates the influence of quantum corrections to the resistance caused by interference of the 2DEG electron wave functions in the presence of spin-orbit coupling and electron-electron interaction in the system at sufficiently low temperatures. The latter behaviour would be impossible in a system with a random distribution of residual magnetic moments, coupled to the conduction band [2, 3, 4], leading to the conclusion, that we are dealing with the compensated two-channel Kondo effect in the system under study.

Careful examination of the low-temperature magnetoresistance in the region of sufficiently low magnetic fields reveals the AAS oscillations with period $h/2e$, taking place against the background of its smooth behaviour. Figure 3 displays the magnetoresistance of 2DEG of AlGaN/GaN heterostructure at 200 mK after subtraction of the WL and WAL contributions, the magnetic field range there is 0.005 – 0.05 T. Within this field range one clearly observes AAS oscillations with an actual period of approximately 80 G, corresponding to one half of the magnetic flux quanta per an average conducting cell, with amplitude $\Delta R =0.1 \Omega$, corresponding to $3.9\cdot10^{-6} h/e^2$ in terms of maximum universal metallic
resistance. These oscillations are a result of interferences due to time reversed carrier trajectories; in contrast to the Aharonov-Bohm conductance oscillations they do not average to zero; as expected, they decrease with magnetic field and are more smeared in comparison with demonstrated by regular conducting networks [15].

This discovery allows one to link the heterostructure interface real-space structure with the spatial inhomogeneity of the 2 DEG confinement and to estimate its characteristic spatial scales. The rich content in harmonics observed in the Fourier spectrum, given in Figure 4, reflects the distribution of cross-sectional areas of the conducting paths, chosen by the 2DEG electrons, localized near the AlN/GaN interface of the heterostructure. An actual average characteristic size of the most probable path of the 2DEG confining potential corresponds to approximate 510 nm. It is worth mentioning, that this value does not contradict to the ARPES data [7], where the uniform distribution of the sheet electron density was observed, because the ARPES detector lateral resolution was of order of 50 µm.

![Figure 4](image)

**Figure 4.** Fourier spectrum of the 2DEG magnetoresistance at T = 200 mK in the magnetic field range [-0.05 T, 0.05T]

The question, whether the 2DEG really has a random network small scale structure, or this picture tells only about significantly non-uniform distribution of the 2DEG electron density, determined by the corresponding modulation of the confining potential, [16], remains open.

### 4. Summary

2D electron gas of magnetically undoped AlGaN/GaN high electron mobility transistor turns out to be a compensated two-channel Kondo system. The Altshuler-Aronov-Spivak oscillations of the magnetoresistance with period h/2e, clearly observed there against the background of its smooth behaviour, are determined by the spatial inhomogeneity of the 2 DEG confining potential and allows to estimate the distribution of its characteristic spatial scales.

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