ISSN 0021-3640, JETP Letters, 2017, Vol. 106, No. 7, pp. 460–464. © Pleiades Publishing, Inc., 2017.
Original Russian Text © D.P. Pavlov, I.I. Piyanzina, V.M. Mukhortov, A.M. Balbashov, D.A. Tayurskii, I.A. Garifullin, R.F. Mamin, 2017, published in Pis'ma v Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki, 2017, Vol. 106, No. 7, pp. 440–444.

CONDENSED MATTER

Two-Dimensional Electron Gas at the Interface of $Ba_{0.8}Sr_{0.2}TiO_3$ Ferroelectric and $LaMnO_3$ Antiferromagnet

D. P. Pavlov[a], I. I. Piyanzina[a, b], V. M. Mukhortov[c], A. M. Balbashov[d], D. A. Tayurskii[b], I. A. Garifullin[a], and R. F. Mamin[a, b, *]

[a] *Zavoisky Physical-Technical Institute, Kazan Scientific Center, Russian Academy of Sciences, Kazan, 420029 Russia*
[b] *Kazan Federal University, Kazan, 420008 Russia*
[c] *Southern Scientific Center, Russian Academy of Sciences, Rostov-on-Don, 344006 Russia*
[d] *Moscow Power Engineering Institute, Moscow, 111250 Russia*
**e-mail: mamin@kfti.knc.ru*

Received September 6, 2017

The temperature dependence of the electrical resistance has been studied for heterostructures formed by antiferromagnetic $LaMnO_3$ single crystals of different orientations with epitaxial films of ferroelectric $Ba_{0.8}Sr_{0.2}TiO_3$ deposited onto them. The measured electrical resistance is compared to that exhibited by $LaMnO_3$ single crystals without the films. It is found that, in the samples with the film, for which the axis of polarization in the ferroelectric is directed along the perpendicular to the surface of the single crystal, the electrical resistance decreases significantly with temperature, exhibiting metallic behavior below 160 K. The numerical simulations of the structural and electronic characteristics of the $BaTiO_3/LaMnO_3$ ferroelectric–antiferromagnet heterostructure has been performed. The transition to the state with two-dimensional electron gas at the interface is demonstrated.

DOI: 10.1134/S0021364017190109

A high-mobility electron gas was first observed in 2004 [1] at the interface between $LaAlO_3$ (LAO) and $SrTiO_3$ (STO). After that, such heterointerfaces involving two insulating and nonmagnetic oxides were comprehensively studied. In particular, it was found that the nanometer-thick metallic phase (two-dimensional electron gas, 2DEG) is formed in the STO layers at the LAO/STO interface when the number of $LaAlO_2$ layers is larger than three [2]. Such a system undergoes a transition to a superconducting state at temperatures below 300 mK [3]. The charge carrier density in this heterostructure is as high as 3×10^{13} cm^{-2}. In addition, the LAO/STO heterostructure exhibits ferromagnetism [4]. Later on, the two-dimensional electron gas was revealed at interfaces between other nonmagnetic insulators, e.g., $KTaO_3/SrTiO_3$ [5] and $CaZrO_3/SrTiO_3$ [6]. The 2DEG was also found at the interfaces between magnetically ordered Mott insulators and, in particular, ferromagnetic $GdTiO_3$ (GTO) [7], antiferromagnetic $SmTiO_3$ [8] and $LaTiO_3$ [9], having the highest possible charge carrier density equal to 3×10^{14} cm^{-2}. Further on, the 2DEG formation was demonstrated also in $NdAlO_3/SrTiO_3$, $PrAlO_3/SrTiO_3$, and $NdGaO_3/SrTiO_3$ heterostructures [10], as well as in $LaGaO_3/SrTiO_3$ [11].

It is supposed that the conductivity arises owing to the structural and hence electronic reconstruction. However, firmly established mechanisms and commonly accepted models for the arising conductivity are still missing. It is usually assumed that the local polarity of $(LaO)^{+1}$ and $(AlO_2)^{-1}$ layers in LAO plays an important role in the formation of 2DEG. Having this in mind, we choose the heterostructure of the $BaTiO_3/LaMnO_3$ (BTO/LMO) type for our study of the relation of the structural distortions, electronic reconstruction, and the polar characteristics. This heterostructure exhibits the ferroelectric polarization related to the shift of Ti^{+4} atoms from the symmetry center of the oxygen octahedron in BTO, in spite of the electric neutrality of the BaO and TiO_2 layers. The direction of such polarization can be switched by the applied electric field. Note that it is not possible to perform the switching in LAO, since the $(LaO)^{+1}$ and $(AlO_2)^{-1}$ layers cannot interchange their positions under effect of some external field. In addition, the BTO/LMO heterostructure is interesting because $LaMnO_3$ does not exhibit the ferromagnetic order, being an antiferromagnet. There is a tempting idea to transform $LaMnO_3$ to the ferromagnetic state by an increase in the density of itinerant charge carriers [12], because this leads to the enhancement of the indirect ferromagnetic exchange interaction. This is actually