Proceedings of the 45th International School and Conference on the Physics of Semiconductors "Jaszowiec" 2016, Szczyrk

Two-Probe Measurements of Electron Transport in GaN:Si/(Ga,Mn)N/GaN:Si Spin Filter Structures

K. Kalbarczyk[a], M. Foltyn[a], M. Grzybowski[a], W. Stefanowicz[a], R. Adhikari[b], Tian Li[a], R. Kruszka[c], E. Kamińska[c], A. Piotrowska[c], A. Bonanni[b], T. Dietl[a,d,e] and M. Sawicki[a]

[a]Institute of Physics, Polish Academy of Sciences, Aleja Lotnikow 32/46, PL–02668 Warsaw, Poland

[b]Institut für Halbleiter- und Festkörperphysik, Johannes Kepler University, Linz, Austria

[c]Institute of Electron Technology, Warszawa, Poland

[d]Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, Warszawa, Poland

[e]WPI-Advanced Institute for Materials Research, Tohoku University, Sendai, Japan

Results of two-probe magnetoresistance studies in GaN:Si/(Ga,Mn)N/GaN:Si prospective spin filter structures are reported. It is postulated that transport characteristics are strongly influenced by highly conductive threading dislocations and that shrinking of the device size partially mitigates the issue. Simultaneously, maxima at ≈ 1500 Oe on overall weak, up to 2%, negative magnetoresistance are seen at low temperature, whose origin has been tentatively assigned to effects taking place at the contacts areas.

DOI: 10.12693/APhysPolA.130.1196

PACS/topics: 72.25.Dc, 73.40.Cg, 73.43.Qt, 78.55.Cr

1. Introduction

The rise of semiconductor spintronics both creates new opportunities for novel electronic devices but at the same time it poses new requirements on spin manipulation in semiconducting materials. While the search for a technology-viable magnetic semiconductor at room temperature is still the subject of active research a great deal of knowledge on the underlying physical processes can be gained from the investigation of various systems at their relevant temperatures [1]. Our material of choice is (Ga,Mn)N — an emerging ferromagnetic semiconductor whose long range ferromagnetic ordering has been confirmed at the low end of cryogenic temperatures [2, 3]. The importance of GaN-based compounds and heterostructures stems from the growing significance of wide band-gap materials in conventional electronics, particularly in opto- and high power electronics. The established a strong mid-gap Fermi-level pinning and a lack of a depletion layer, in combination with its insulating character due to a strong electron trapping by mid-gap Mn^{2+}/Mn^{3+} level [4, 5] and a sizable dielectric strength of 5 MV/cm [6], point at (Ga,Mn)N as insulating buffer material for applications in (high power) nitride devices and make it an ideal building block for spin harnessing structures like spin filters [7] and resonant tunneling devices [8]. Besides these technologically relevant concepts, the spin imbalance in these systems may allow probing spin–orbit coupling, quantum Hall effects, and pairing in unconventional superconductors [9].

In this communication, we present results of two-probe magnetoresistance studies of GaN:Si/(Ga,Mn)N/GaN:Si spin filter structures. The data indicate that the electrical transport across the stack is predominantly determined by the presence of highly conductive threading dislocations, whose non-random distribution allows to observe signatures of tunneling conductivity at low temperatures. Independently, the magnetoresistance data show the presence of features symmetric in field, and which likely originate at the electrical contacts to the structure.

2. Samples and experiment

The samples for this study have been deposited on c-plane sapphire substrate in an AIXTRON 200RF horizontal tube metalorganic vapor phase epitaxy (MOVPE) reactor using TMGa, $MnCp_2$, NH_3, and SiH_4 as precursors for Ga, Mn, N, and Si, respectively, with H_2 as carrier gas. After nitridation of the sapphire substrate, a low temperature nucleation layer is deposited at 540 °C and annealed at 1040 °C. After deposition of ≈ 1 μm thick GaN buffer layer the high quality GaN:Si/(Ga,Mn)N/GaN:Si structures are obtained by growing ≈ 150 nm of GaN:Si at 1000 °C, 5 or 7.5 nm of (Ga,Mn)N at 850 °C, ending the heterostructure with ≈ 150 nm of GaN:Si at 1000 °C. An Mn content ≈ 3% in the single crystal (Ga,Mn)N-layer is achieved by setting the $MnCp_2$ flow at 490 standard cubic centimeters per minute. The electron concentration in Si doped GaN layers exceeds the critical value for the metal-to-insulator transition (MIT) in bulk GaN, $n_c \cong 10^{18}$ cm^{-3} [10] and it guarantees the semimetallic behaviour of these layers down to the lowest cryogenic temperatures [11]. The obtained samples are systematically characterized by atomic force microscope (AFM), high resolution X-ray diffraction (HRXRD), and high resolution transmission electron microscopy (HRTEM). The AFM micrographs reveal a flat surface (rms roughness ≅ 1 nm) while HRXRD and HRTEM confirm the high crystallinity of the samples without phase separation (precipitates) which are present under different growth conditions [12].

3. Results and discussion

A transmission electron microscope micrograph exemplifying the investigated structures is presented in Fig. 1.

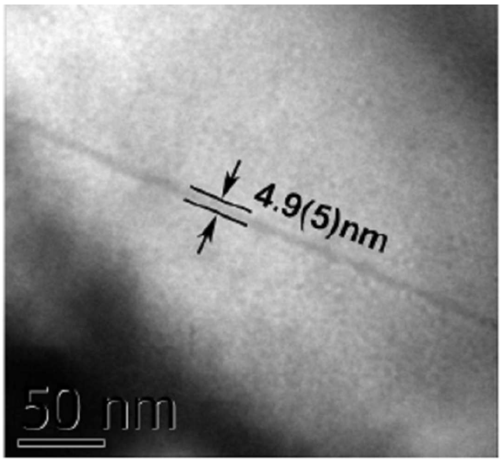

Fig. 1. Transmission electron microscope micrograph of a threading-dislocation-free part of spin filter GaN:Si/(Ga,Mn)N/GaN:Si structure consisting of a nominally 5 nm layer of 3% (Ga,Mn)N embedded in *n*-GaN:Si.

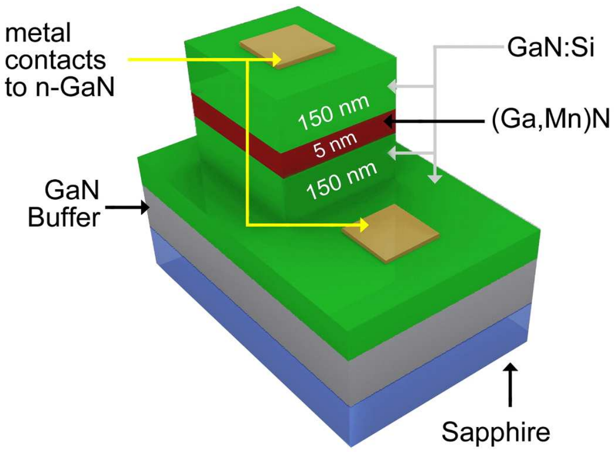

Fig. 2. A general view of the single device tested in this study. In such a two contact configuration the electrical current flows vertically across the (Ga,Mn)N layer. Several such structures are patterned on one chip of the material.

To achieve vertical transport through the (Ga,Mn)N layer 60, 90, and 200 μm mesas are lithographically masked on the top surface and the remaining part of the structure is etched down to the bottom GaN:Si layer by inductively coupled plasma reactive ion etching using BCl_3/Cl_2. During the subsequent lithographic masking the electrical contact pads on top of the mesas and on the exposed bottom GaN:Si layer are defined and electrical contacts are obtained by the evaporation of Ti(15 nm)/Al(60 nm)/Au(100 nm). Between each process step oxygen plasma is employed to clean the sample surface. Such contacts generally show an ohmic behavior at room temperature, however, additional annealing at $\approx 750\,^{\circ}$C for 30 s in nitrogen atmosphere significantly reduces their resistance. A schematic layout of the processed vertical heterostructures is presented in Fig. 2.

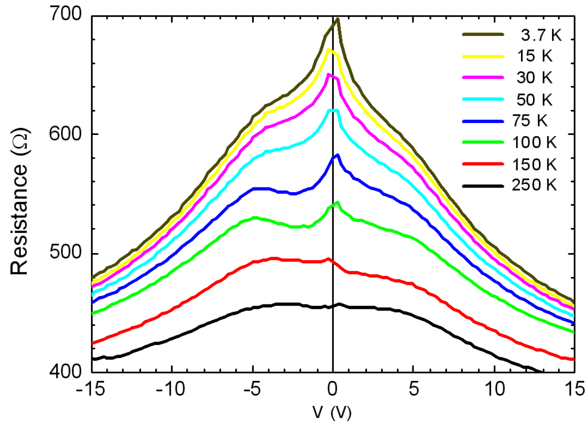

Fig. 3. Non-ohmic behaviour on lowering temperature in GaN:Si/5 nm(Ga,Mn)N/GaN:Si structure.

The character of the electrical properties has been found to clearly depend on the size of the mesa. After the annealing the two-probe resistance of 200 μm mesas keeps around 100 Ω at room temperature and increases only marginally after cooling to 4.2 K. The typical two-probe resistance of 60 and 90 μm mesas is closer to 1000 Ω and increases several times upon cooling to helium temperature, showing also a sizable non-ohmic I–V behaviour, as exemplified in Fig. 3. These higher resistances are only partially due to the reduced size of the mesa. Actually, in an ideal case, the insulating (Ga,Mn)N middle layer [4] is expected to block the current through the whole stack, and only a tunneling current weakly dependent on the mesa size should be observed. In contrast, from all tested structures only the smaller size mesas exhibit a noticeable increased resistance and nonlinear I–V characteristics. It decisively points to the detrimental role of highly conductive sapphire-GaN misfit-related threading dislocations [13], which short the insulating (Ga,Mn)N layer. The fact that the electrical characteristics of some of the 60 and 90 μm mesas are tunnel-like indicates that these highly conductive dislocations must be non-randomly distributed. Furthermore, we note that no clear dependence of the electrical properties on the (Ga,Mn)N layer thickness has been detected.

Magnetoresistance $\mathrm{MR}(H) = \frac{R(H)-R(0)}{R(0)}$ curves acquired at 4.2 K with the magnetic field directed parallel to the (Ga,Mn)N layer, that is perpendicular to the expected current path across the whole stack is presented in Fig. 4. A very weak negative magnetoresistance is measured in every case with the overall line-shape analogous to the one observed in similarly heavily Si doped GaN layers, which was well accounted for by the weak localization effect in semiconductors on the metallic side of the MIT [11]. However, on every MR(H) a symmetric maximum at around 1.5 kOe is seen. Neither the magnitude of the magnetoresistance nor the height of the maximum scales with the resistivity $R(0)$.

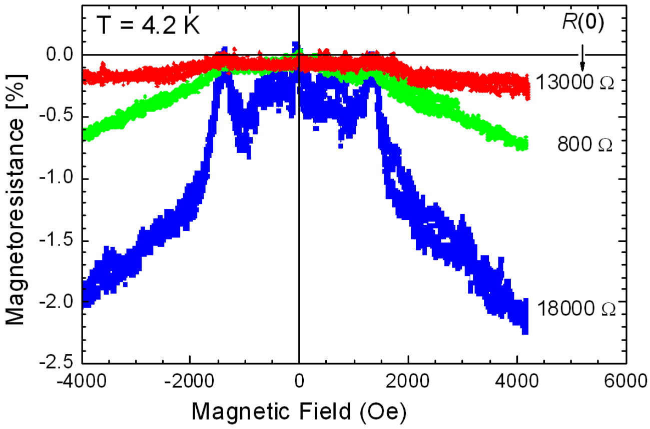

Fig. 4. 4.2 K two-probe magnetoresistance $\mathrm{MR}(H) = [R(H) - R(0)]/R(0)$ of GaN:Si/(Ga,Mn)N/GaN:Si stacks with Ti/Al/Au electrical contacts attached to both GaN:Si layers. The magnetic field is applied parallel to the (Ga,Mn)N layer, that is perpendicular to the expected current path across the structure. The shown here structures differ in their initial values of R(0), given in the figure.

4. Conclusions

The collected data does not allow to decisively conclude whether these effects are related to the electronic transport through the (Ga,Mn)N layer or through the metal–semiconductor contacts (barriers). The structure of the whole pattern allows us to probe simultaneously in two- and four-probe configurations only the bottom GaN:Si layer, so the current during such tests does not probe the (Ga,Mn)N layer. It turns out that similar MR(H) to these presented in Fig. 4 is recorded in two-probe configuration, whereas a featureless, characteristic to the weak localization, dome-like shaped MR(H) is obtained during the four-probe measurement. Having such a significant indication that the discussed features are generated at the contacts areas, we conclude that a new layout for the test structures have to be designed in order to pin point the origin of the observed effect, and to narrow the experimental yield only to the (Ga,Mn)N layer effects.

Acknowledgments

The support by the Narodowe Centrum Nauki (Poland) through project OPUS (2013/09/B/ST3/04175), by the Austrian Science Foundation — FWF (P22477, P24471, and P26830), by the NATO Science for Peace Programme (Project No. 984735), and by the EU through the 7th Framework Programmes: CAPACITIES project REGPOT-CT-2013-316014 (EAgLE), and Horizon2020 Project NMP645776 is gratefully acknowledged.

References

[1] T. Dietl, H. Ohno, *Rev. Mod. Phys.* **86**, 187 (2014).

[2] M. Sawicki, T. Devillers, S. Gałęski, C. Simserides, S. Dobkowska, B. Faina, A. Grois, A. Navarro-Quezada, K.N. Trohidou, J.A. Majewski, T. Dietl, A. Bonanni, *Phys. Rev. B* **85**, 205204 (2012).

[3] G. Kunert, S. Dobkowska, Tian Li, H. Reuther, C. Kruse, S. Figge, R. Jakiela, A. Bonanni, J. Grenzer, W. Stefanowicz, J. von Borany, M. Sawicki, T. Dietl, D. Hommel, *Appl. Phys. Lett.* **101**, 022413 (2012).

[4] A. Bonanni, M. Sawicki, T. Devillers, W. Stefanowicz, B. Faina, Tian Li, T.E. Winkler, D. Sztenkiel, A. Navarro-Quezada, M. Rovezzi, R. Jakieła, A. Grois, M. Wegscheider, W. Jantsch, J. Suffczyński, F. D'Acapito, A. Meingast, G. Kothleitner, T. Dietl, *Phys. Rev. B* **84**, 035206 (2011).

[5] T. Yamamoto, H. Sazawa, N. Nishikawa, M. Kiuchi, T. Ide, M. Shimizu, T. Inoue, M. Hata, *Jpn. J. Appl. Phys.* **52**, 08JN12 (2013).

[6] D. Sztenkiel, M. Foltyn, G.P. Mazur, R. Adhikari, K. Kosiel, K. Gas, M. Zgirski, R. Kruszka, R. Jakiela, Tian Li, A. Piotrowska, A. Bonanni, M. Sawicki, T. Dietl, *Nat. Commun.* **7**, 13232 (2016).

[7] T.S. Santos, J.S. Moodera, *Phys. Rev. B* **69**, 241203 (2004).

[8] A.G. Petukhov, A.N. Chantis, D.O. Demchenko, *Phys. Rev. Lett.* **89**, 107205 (2002).

[9] I. Zutic, J. Fabian, S. Das Sarma, *Rev. Mod. Phys.* **76**, 323 (2004).

[10] A. Ferreira da Silva, C. Persson, *J. Appl. Phys.* **92**, 2550 (2002).

[11] W. Stefanowicz, R. Adhikari, T. Andrearczyk, B. Faina, M. Sawicki, J.A. Majewski, T. Dietl, A. Bonanni, *Phys. Rev. B* **89**, 205201 (2014).

[12] T. Dietl, K. Sato, T. Fukushima, A. Bonanni, M. Jamet, A. Barski, S. Kuroda, M. Tanaka, Phan Nam Hai, H. Katayama-Yoshida, *Rev. Mod. Phys.* **87**, 1311 (2015).

[13] P. Kozodoy, J.P. Ibbetson, H. Marchand, P.T. Fini, S. Keller, J.S. Speck, S.P. DenBaars, U.K. Mishra, *Appl. Phys. Lett.* **73**, 975 (1998).