Final report of OTKA NN118201 **SAFEMOST** project
2016-01-01 to 2019-06-30

The project NN118201 titled "Highly Safe GaN Metal-Oxide-Semiconductor Transistor Switch" (shortly: SAFEMOST) was a joint research program in the frame of the multinational Slovakian-Japanese-Polish-Hungarian research project of the same name which was granted in the frame of the JST-V4 call of proposals in 2015. The research within the consortium was financed by the four national funding organizations of the participating countries as well as the International Visegrad Fund (IVF). The main goal of this project was to develop GaN based metal-oxide-semiconductor (MOS) structures with a sufficiently low density of surface donors (SD) at the gate-oxide/semiconductor heterostructure interface thus allowing the realization of normally-off switching transistors. Main impact of using such switching devices would be a significant decrease of conversion losses in power electronics making up more than 10% of the total electricity consumption today.

According to the accepted plans the Slovakian colleagues at IEE SAS, Bratislava (Institute of Electrical Engineering of the Slovak Academy of Sciences) manufactured a series of samples consisting of very thin gate dielectric layers prepared by various deposition techniques onto standard GaN/AlGaN/GaN heterostructures serving as substrates. These layers were all made of Al_2O_3 but the way of deposition varied from low temperature atomic layer deposition (ALD) using various precursors to a high temperature metalorganic chemical vapor deposition (MOCVD) process. These samples were studied by a complex way by the participants of the consortium. Electrical characterization and X-ray studies were performed in Bratislava, photo-capacitance investigation, Auger electron spectroscopy and photoluminescence in SUT, Gliwice, Poland (Silesian University of Technology, Institute of Physics – Centre for Science and Education), while XPS studies and modelling of the processes in RCIQE, Sapporo, Japan (Hokkaido University, Research Center for Integrated Quantum Electronics).

Our task in this cooperation was the structural characterization of the heterostructures, particularly of the dielectric films deposited on the top surface by means of transmission electron microscopy. As soon as possible the specific results of our research work were reported internally for the cooperating partners making a valuable feedback to the sample manufacturing colleagues.

In the first series of experiments thin Al_2O_3 layers deposited by ALD with different conditions were studied. These dielectric films were proved to possess somewhat higher density of surface donor states and so were regarded as less suitable for the required parameters than e.g. MOCVD deposited dielectrics. We have observed, however, that all these ALD layers show a polycrystalline microstructure – even those deposited as low as at 100^oC.

New samples were prepared by the Slovakian colleagues to determine the crystallinity of the thin Al_2O_3 layers deposited onto various substrate materials. The ALD film deposited onto single crystalline Al_2O_3 (sapphire) was found amorphous but it turned crystalline after 1-2 minute of irradiation with the focused electron beam. As observed in the transmission electron microscope the crystallization process started at the Al_2O_3/sapphire interface. The film structure was found amorphous on silicon and GaN substrates as well. This means that our first results were not reproduced: probably due to the inappropriate substrate temperature which might have been too high during the preparation process in the first series.

The role of surface polarization compensating charge also referred as “surface donors” on the III-nitride semiconductor was systematically analysed on the MOS heterojunctions. In this case the dielectric film was deposited on the surface of GaN/AlGaN/GaN/sapphire heterostructures by high temperature MOCVD process. The skipping of HCl pretreatment step before deposition of oxide film decreased the SD (surface donor) density compared to those structures with HCl treatment and post deposition annealing. From microstructural and electrical studies it turned out that the surface donor density did not correlate with charging at the interface traps. Instead, variation of GaO_x interlayer proved by X-ray photoelectron spectroscopy correlated well with SD density suggesting it to be originating from border traps at the Al_2O_3/GaO_x interface.

The passivation of another type of MOS device was also realized: thin Al_2O_3 films were deposited by ALD on top of the layer system InGaN/GaN/AlGaN/AlN/GaN (substrate: sapphire). The electrical characterization performed by the Slovakian colleagues showed an increased threshold voltage as a result of gate recessing and insulation. Thus by the creation of large negative polarization charge at the InGaN/AlGaN interface this polarization engineering made possible a normally-off operation mode in the devices. By using a sophisticated thinning process cross sectional specimens were fabricated in our Institute for transmission electron microscopy of the same samples. With the TEM study the dielectric film structure was found first amorphous which turned crystalline after elongated exposure to the focused electron beam. Simultaneously, a coagulation of low density defects (voids) could be observed at about the middle of the thin dielectric film. This kind of defect structure can influence the surface trap density and also the electrical performance of the device. However, the applied technological steps (access region etching and post-deposition annealing) made possible the improved performance in normally-off mode of operation.

Beside the old electron microscopes used before the installation of a new aberration corrected TEM (of the type FEI Themis) in 2018 opened up new possibilities in our characterization spectrum. It was also applied to several SAFEMOST samples. The use of the aberration corrected objective lens improved the point-to-point resolution by a factor of two (down to 0.09 nm). Also several new methodologies (like scanning transmission techniques with various detectors, EDS mapping, etc.) became possible to use.

By applying the new Themis electron microscope the local variation of the of the strain tensor components were determined using the geometrical phase analysis technique. Starting from high resolution images of the cross sectional specimens and their Fourier transform, the in-plane and out-of-plane deformation components of the crystal lattice were calculated with a special software (relative to a non-deformed reference area in the same TEM lamella). It turned out that the in-plane strain component is practically zero, while the out-of-plane component followed the chemical composition of the layer structure. This means large negative strain in the AlN layer, small (1-2%) negative change in the AlGaN, and somewhat larger (3-4%) positive strain in the InGaN film. The elemental maps taken with the EDS system (also with the Themis microscope) confirmed our observation. This result supports the model of the Slovakian colleagues on the polarization effects observed by electrical measurements. These samples were found to be suitable for the realization of normally off MOS HEMT transistors after some additional processing steps. The realized positive threshold voltage reached 1 V with the above configuration. Further technological optimization of the process parameters are possible.

Summarizing the results of the international SAFEMOST project:

- The consortium proposed a new MOS-HEMT concept and also verified a new technology of normally-off GaN transistors with scalable V_{th} (threshold voltage).
- This concept involved the low temperature deposition of a dielectric oxide layer grown on AlGaN/GaN semiconductor by ALD technique which made possible the preparation of the above normally-off GaN transistors.
- The generation of so called surface donors have been analysed which play a decisive role for setting a safely high value of V_{th} of the devices. The influence of oxide layer thickness on the stability of V_{th} was also studied.
- By means of polarization engineering in etched access in InGaN/AlGaN/GaN devices another way was opened to reach normally-off operation of these switching transistors. A positive V_{th} of about 1 V was realized in this case.

All the planned aims of the project were reached.

Events for dissemination, education, etc.:

During the full period of the project several events were held to disseminate its results:

- Three project meetings were held in the duration of the project (Bratislava 2016, Kirishima 2017, Sapporo 2018)
- The Joint Visegrad 4 – Japan Seminar on Technology Transfer – Nanomaterials for Industrial Use, Tokyo, Japan, 16th June 2016, (B. Pécz, invited)
- Training of a young scientist (Dr. Blaho from Bratislava, 2017) at Hokkaido University
- Presentation of SAFEMOST project at the International Workshop on Nitride Semiconductors, 2-7 October 2016, Orlando, USA
- Presentation of SAFEMOST project at the Topical Workshop on Heterostructure Microelectronics, 28-31 August 2017, Kirishima, Japan
- Presentation of SAFEMOST project at the International Workshop on Nitride Semiconductors, 11-16 November 2018 Kanazawa, Japan
- Presentation of SAFEMOST project at the ISPlasma2019/IC-PLANT2019, Nagoya Institute of Technology 17-21 March 2019 Nagoya, Japan (J. Kuzmík, invited)
- A project website was operated by IEE SAS: http://www.safemost.sav.sk/index.html

Publication activity:

Altogether **7 papers** in peer reviewed journals, and **21 conference contributions** (out of which **4 invited**) were published in the duration of SAFEMOST project. The full list of publications of SAFEMOST project (until 30.June 2019) includes also publications with no Hungarian co-authors:

1. Jan Kuzmík, GaN-based normally-off HEMTs for switching and logic applications, ISPlasma2019/IC-PLANTS2019, Nagoya Institute of Technology, Japan March 17-21, 2019, **Invited**
2. Gregušová D, Tóth L, Pohorelec O, Hasenöhrl S, Haščík Š, Cora I, Fogarassy Z, Stoklas R, Seifertová A, Blaho M, Laurenčíková A, Oyobiki Z, Pécz B, Hashizume T, and Kuzmík J: InGaN/(GaN)/AlGaN/GaN normally-off metal-oxide-semiconductor

high-electron mobility transistors with etched access region, **Japanese J Applied Phys**, **58**, (2019) SCCD21

3. Gregušová D, Blaho M, Šichman P, Haščík Š, Pohorelec O, Hasenöhrl S, Stoklas R, Laurenčíková A, Fröhlich K, Tóth L, Pécz B, Brunner F, Wurfl J, Hashizume T, and Kuzmík J: Threshold voltage controllability and stability in InGaN/AlGaN/GaN MOS HEMTs. In: GaN Marathon 2.0. Padova, Italy 2018.
4. Ťapajna M, Drobny J, Gucmann F, Hušeková K, Hashizume T, and Kuzmík J: Impact of oxide/barrier fixed charge on threshold voltage instabilities in AlGaN/GaN metal-oxide-semiconductor heterostructures. In: Inter. Workshop on Nitride Semicond. (IWN 2018) Kanazawa, Japan 2018
5. Tóth L, Cora I, Fogarassy Z, Pécz B, Hasenöhrl S, Seifertova A and Kuzmík J: TEM study of InGaN/AlGaN/GaN normally-off MOS HEMT structures. In: Inter. Workshop on Nitride Semicond. (IWN 2018) Kanazawa, Japan 2018
6. Gregušová D, Hasenöhrl S, Stoklas R, Haščík Š, Pohorelec O, Seifertová A, Blaho M, Laurenčíková A, Tóth L, Pécz B, and Kuzmík J: InGaN/AlGaN/GaN normally-off MOS HEMT with etched access region. In: Inter. Workshop on Nitride Semicond. (IWN 2018) Kanazawa, Japan 2018
7. Pécz B, Tóth L, Cora I, Ťapajna M, Fröhlich K, and Kuzmík J: Structural study of Al_2O_3 dielectric films deposited by ALD onto AlGaN/GaN heterostructure, EMRS 2018, Warsaw, Poland September 17-18, 2018
8. Gregušová D, Blaho M, Haščík Š, Šichman P, Laurenčíková A, Seifertová A, Dérer J, Brunner F, Würfl H, Kuzmík J: Polarization-engineered n+GaN/InGaN/AlGaN/GaN normally-off MOS HEMTs. **Physica Status Solidi a 214** (2017) 1700407
9. Matys M, Stoklas R, Blaho M, and Adamowicz B: Origin of positive charge at insulator/AlGaN interface and its control by AlGaN composition, **Applied Phys Lett 110** (2017) 243505
10. Kuzmík J: GaN-based normally-off HEMTs for switching and logic applications. In 3rd Intensive Discussion on Growth of Nitride Semiconductors (IDGN-3). Tohoku Univ. Japan 2017. **Invited**
11. Ťapajna M, Gregušová D, Fröhlich K, and Kuzmík J: Current understanding and challenges of Metal-Oxide-Semiconductor gated GaN HFETs. In: 6th Inter.Symp. Organic Inorganic Electronic Mater. Related Nanotechnol. - EM-NANO 2017. Fukui, Japan 2017. **Invited**
12. Dobročka E, Hasenöhrl S, Chauhan P, and Kuzmík J: Non-conventional scans in high resolution X-ray diffraction analysis of epitaxial systems. In: 5th Int. Conf. "Progress in Applied Surface, Interface and Thin Film Science - Solar Renewable Energy News " (SURFINT-SREN V). Florence, Italy 2017. **Invited**
13. Gregušová D, Blaho M, Šichman P, Haščík Š, Hasenöhrl S, Stoklas R, Laurenčíková A, Fröhlich K, Tóth L, Pécz B, Brunner F, Würfl J, Hashizume T, and Kuzmík J: Threshold voltage controllability and stability in InGaN/AlGaN/GaN MOS HEMTs. In: 12th Topical Workshop on Heterostr. Microelectron. Kirishima, Japan 2017
14. Matys M, Kaneki S, Adamowicz B, Kuzmík J, and Hashizume T: Analysis of temperature dependent frequency dispersion in CV curves of Al_2O_3/AlGaN/GaN structures on the disorder-induced gap-state model,In: 12th Topical Workshop on Heterostr. Microelectron. Kirishima, Japan 2017
15. Tóth L, Cora I, Ťapajna M, Fröhlich K, Kuzmík J, and Pécz B: TEM study of dielectric films deposited on the surface of GaN/AlGaN/GaN MOS heterostructure, In: 12th Topical Workshop on Heterostr. Microelectron. Kirishima, Japan 2017

16. Hasenöhrl S, Gregušová D, Dobročka E, Stoklas R, Chauhan P, and Kuzmík J: MOCVD growth of GaN/AlGaN 2 DEG structures with InGaN cap for examination of polarization charge engineering concept in normally - off GaN MOS-HEMTs. In: 17th European Workshop on Metal-Organic Vapour Phase Epitaxy (EW-MOVPE 17). Grenoble, France 2017
17. Matys M and Adamowicz B: Mechanism of yellow luminescence in GaN at room temperature, **J Applied Phys 121** (2017) 065104
18. Ťapajna M, Válik L, Gucmann F, Gregušová D, Fröhlich K, Haščík Š, Dobročka E, Tóth L, Pécz B, and Kuzmík J: Low-temperature atomic layer deposition-grown Al_2O_3 gate dielectric for GaN/AlGaN/GaN MOS HEMTs: Impact of deposition conditions on interface state density, **J Vacuum Sci Technol B 35** (2017) 01A107
19. Ťapajna M, Stoklas R, Gregušová D, Gucman F, Hušeková K, Haščík Š, Fröhlich K, Tóth L, Pécz B, Brunner F, Kuzmík J: Investigation of 'surface donors' in Al_2O_3/AlGaN/GaN metal-oxide-semiconductor heterostructures: Correlation of electrical, structural, and chemical properties, **Applied Surf. Sci. 426** (2017) 656-661
20. L. Tóth, I. Cora, M Ťapajna, K. Frölich, J. Kuzmik and B. Pécz: Structure of low temperature ALD deposited dielectric films on the surface of GaN/AlGaN/GaN MOS heterostructure, Microscopy of Semiconducting Materials (MSM XX), 9-13 April 2017, Oxford, UK
21. Matys M, Stoklas R, Kuzmík J, Adamowicz B, Yatabe Z, and Hashizume T: Characterization of capture cross sections of interface states in dielectric/III-nitride heterojunction structures, **J. Applied Phys.** 119 (2016) 205304
22. Gregušová D, Blaho M, Haščík Š, Seifertová A, Laurenčíková A, Dérer J, Brunner F, Wurfl J, and Kuzmík J: Polarization-engineered n+GaN/InGaN/AlGaN/GaN normally-off MOS HEMTs. WOCSDICE 2016, Aveiro, Portugal, June 6-10, 2016
23. Ťapajna M, Stoklas R, Gregušová D, Válik L, Gucmann F, Hušeková K, Haščík Š, Fröhlich K, Tóth L, Pécz B, Micusik M, Brunner F, Hashizume T, and Kuzmík J: On the origin of surface donors in AlGaN/GaN metal-oxide semiconductor heterostructures with Al_2O_3 gate dielectric–correlation of electrical, structural, and chemical properties. In: Inter. Workshop on Nitride Semicond. (IWN 2016) Orlando, USA 2016
24. Matys M, Kaneki S, Adamowicz B, Kuzmík J, and Hashizume T: Characterization of interface states from frequency dispersion in capacitance-voltage curves of Al_2O_3/AlGaN/GaN heterostructures. In: Inter. Workshop on Nitride Semicond. (IWN 2016) Orlando, USA 2016
25. Gucmann F, Gregušová D, Válik L, Ťapajna M, Haščík Š, Hušeková K, Fröhlich K, Pohorelec O, and Kuzmík J: DC and pulsed IV characterisation of AlGaN/GaN MOS-HEMT with Al_2O_3 gate dielectric prepared by various techniques In: ASDAM, Slovakia 2016. Eds. Š. Haščík et al. IEEE 2016. ISBN 978-1-5090-3081-1. P. 9-12
26. Ťapajna M, Hušeková K, Pohorelec O, Válik L, Haščík Š, Gucmann F, Fröhlich K, Gregušová D, and Kuzmík J: Effect of HCl pretreatment on the oxide/semiconductor interface state density in AlGaN/GaN MOS-HEMT structures with MOCVD grown Al_2O_3 gate dielectric In: ASDAM, Slovakia 2016. Eds. Š. Haščík et al. IEEE 2016. ISBN 978-1-5090-3081-1. P. 207-211
27. Ťapajna M, Válik L, Gregušová D, Fröhlich K, Gucmann F, Hashizume T, and Kuzmík J: Treshold voltage instabilities in AlGaN/GaN MOS-HEMTs with ALD-grown Al_2O_3 gate dielectrics: relation to distribution of oxide/semiconductor interface state density In: ASDAM, Slovakia 2016. Eds. Š. Haščík et al. IEEE 2016. ISBN 978-1-5090-3081-1. P. 1-4

28. Matys M, Adamowicz J, Domanowska A, Michalewicz A, Stoklas R, Akazawa M, Yatabe Z, and Hashizume T: On the origin of interface states at oxide/III-nitride heterojunction interfaces, **J Applied Phys 119** (2016) 225305
29. http://www.safemost.sav.sk/index.html

From the above list 3 papers in peer reviewed journals and 8 conference contributions included Hungarian co-authors as well.