Towards high mobility in 2D electron gas in GaN/AlGaN

H.Teisseyre[1], B. Damilano[2], Y. Cordier[2], Z. Adamus[1], T.Wojtowicz[3], M. Boćkowski[4]

[1] Institute of Physics, Polish Academy of Sciences, Warsaw, Poland
[2] Université Côte d'Azur, CNRS, CRHEA, Valbonne, France
[3] International Research Centre MagTop, Institute of Physics, Polish Academy of Sciences, Warsaw, Poland
[4] Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw, Poland

Close on the developments in nitride visible photonics during the 1990s was the discovery of a two-dimensional electron gas (2DEG) at nominally undoped AlGaN/GaN heterojunctions.[1] The formation of these 2DEGs was found to result from the interplay of internal spontaneous and piezoelectric polarization fields combined with band offsets. Today, the Al(Ga)N/GaN heterojunction system, featuring a polarization-induced 2DEG and a large bandgap channel and barrier, is at the core of nitride-based high-electron mobility transistors (HEMTs).

PREVIOUS RESULTS

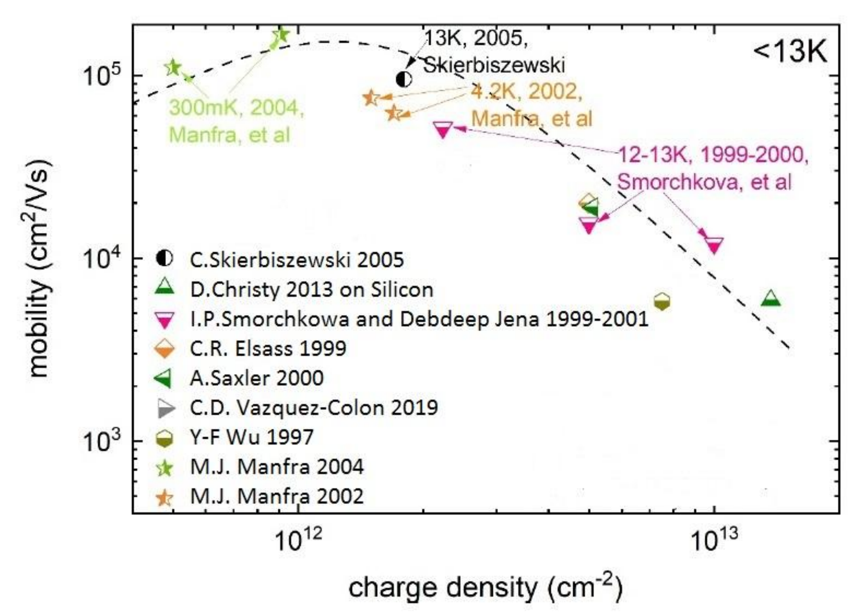


Fig. 1. Mobility versus 2DEG density relationship from different publications at low temperature

The ultrahigh mobility of 2DEG in AlGaN/GaN system is useful for;

- High-speed, high-frequency electronics (5G, radar, satellite communications)
- High-power electronics
- Harsh-environment application (space, defense, aerospace)
- Sensor and radiation detectors
- Emerging fields like quantum computing and spintronics

In AlxGa1−xAs-based material systems, low-temperature electron mobility has reached values exceeding 100 million cm²/Vs [2]. In the ZnO/ZnMgO system, low-temperature electron mobility surpasses 1,000,000 cm²/V·s [3]. However, it remains unclear why the best results in GaN/AlGaN systems achieve only a low-temperature electron mobility **record of 167,000 cm²/V·s, as reported by Manfra et al. in 2004. [4]**

by using a high-quality substrate, we aim to break this record!!!

HIGH QUALITY SUBSTRATE
Ammonothermal-GaN

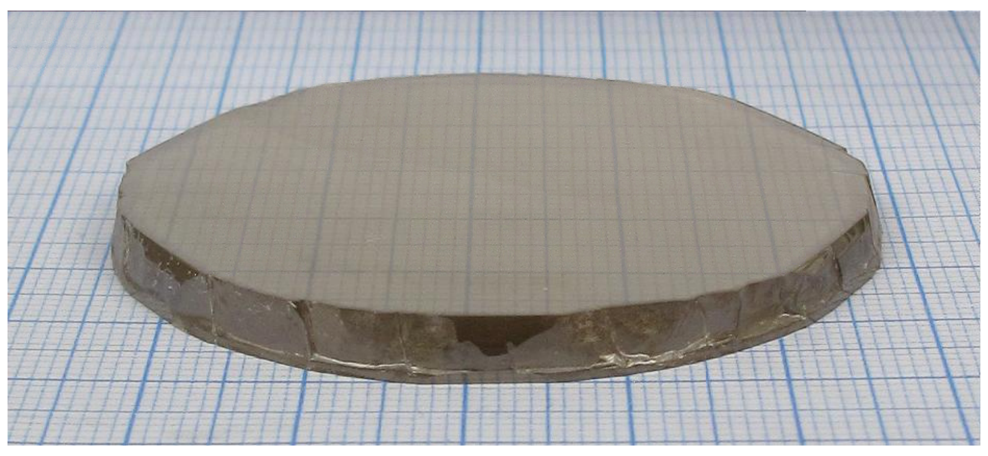


Fig.2. Ammonothermal-GaN crystal grown in one crystallization run: 6-mm-thick and with a 2.1-inch diameter; grid 1 mm

Scheme of basic ammonothermal system

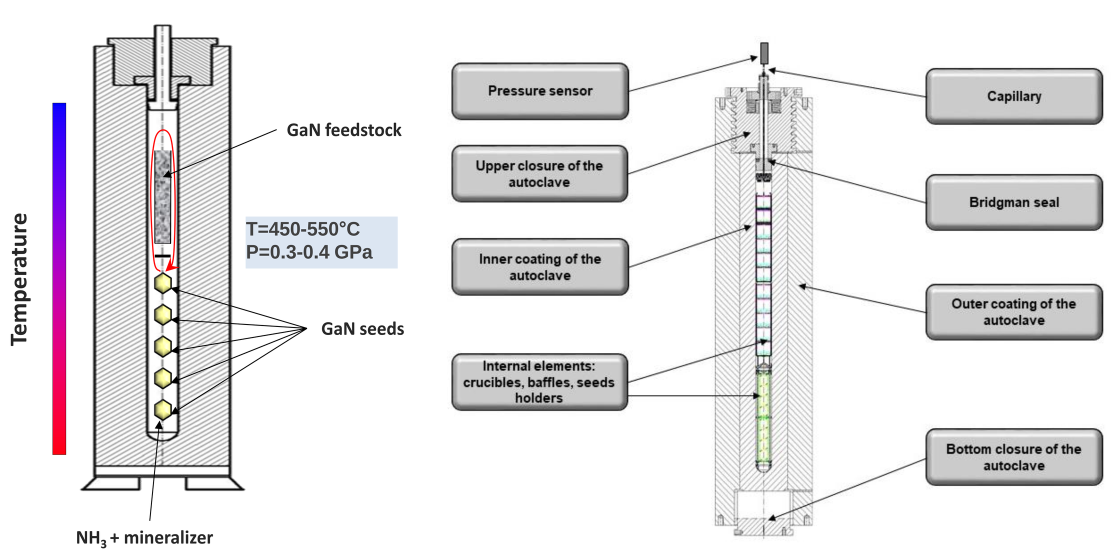
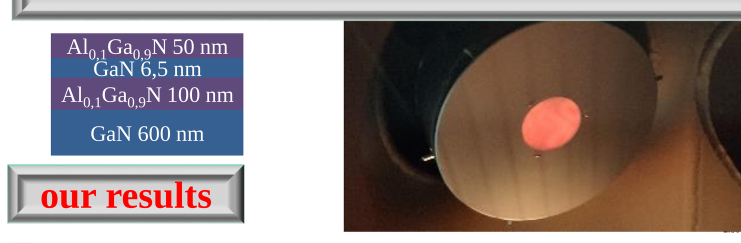


Fig. 3. a) Scheme of basic ammonothermal process and cross-section of autoclave divided into dissolution zone (with feedstock) and crystallization zone (with GaN seeds); red arrow symbolizes the convective mass transport in the temperature gradient; b) scheme of a typical ammonothermal autoclave used at IHPP PAS (Institute of High Pressure Physics of Polish Academy of Sciences); the main elements are marked; all parts are made of high quality steel and high purity metals; crucibles with feedstock are in the upper zone of the autoclave; native seeds on special holders in the lower zone; the zones are divided by baffles.

as a substrates we used GaN highly doped with manganese!

HIGH QUALITY STRUCTURE GROWN BY AMMONIA MBE/ SQW GaN/AlGaN example



our results

Dedicated 1-inch molyblock (3 inch heater)

Preliminary results

2x2 μm² rms 0.17 nm | 5x5 μm² rms 0.16 nm | 10x10 μm² rms 0.17 nm

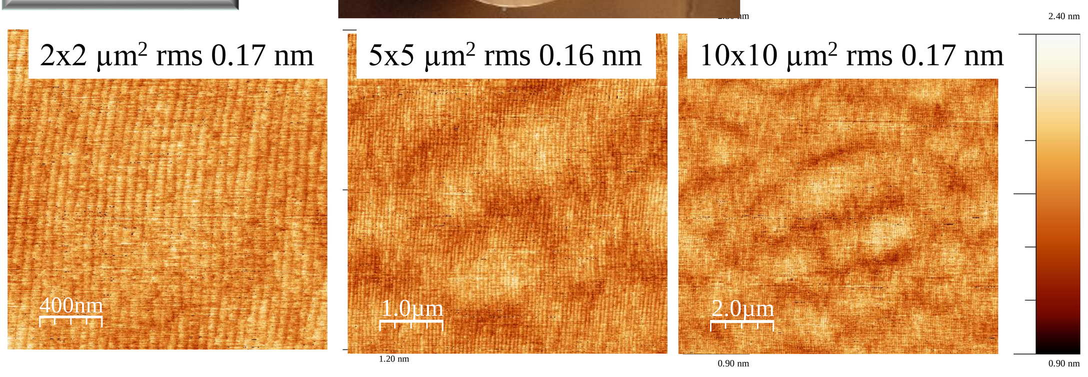
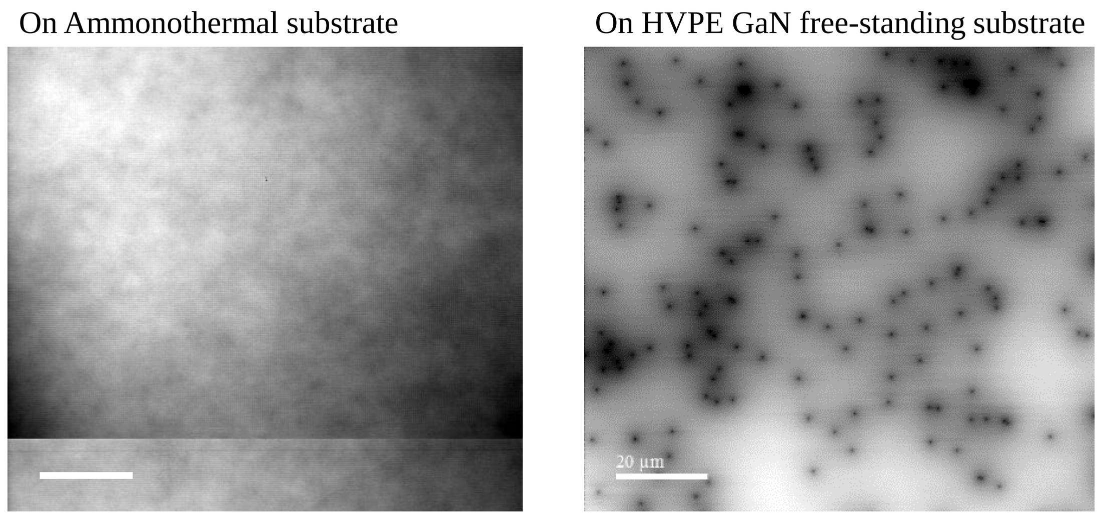


Fig. 4. Atomic force microscopy (AFM) results for 6nm single quantum well GaN/AlGaN grown by the molecular-beam epitaxy on the ammonothermal substrates. In all measured magnifications RMS is constant and atomic steps are clearly visible.

COMPARISON PANCHROMATIC / SQW GaN/AlGaN example

On Ammonothermal substrate | On HVPE GaN free-standing substrate



Dark spot density < 10^4 cm^{-2} | Dark spot density = $1{,}7 \times 10^6$ cm^{-2}

Fig. 5. Comparison of cathodoluminescence imaging measurements, for layers grown on the ammonothermal substrate (density of dark spots below 10^4 cm^{-2}) and layers grown on HVPE (Halide Vapor Phase Epitaxy) free-standing substrate (Dark spot density = $1{,}7 \times 10^6$ cm^{-2}).

our results

SQW GaN/AlGaN example / low temperature PL

PL linewidth (low exc. power) = 8.9 meV

Strong quantum confined Stark effect (large QW width)

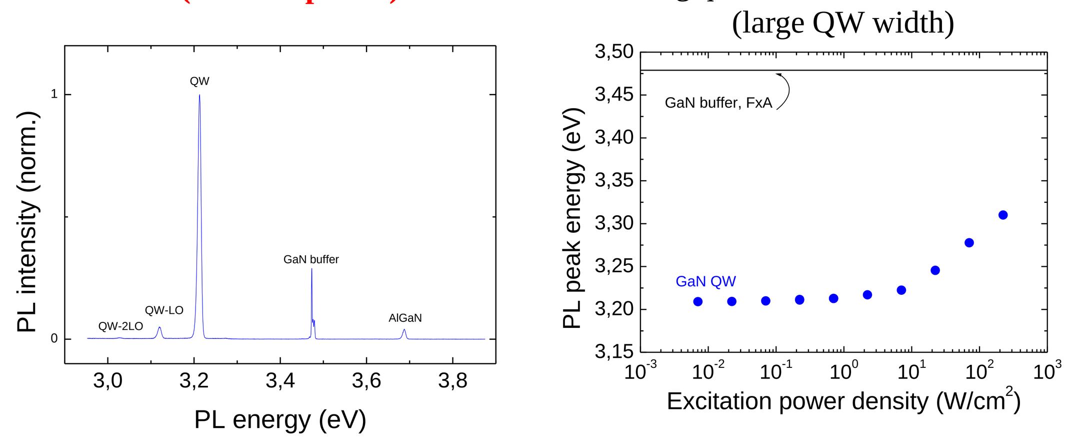
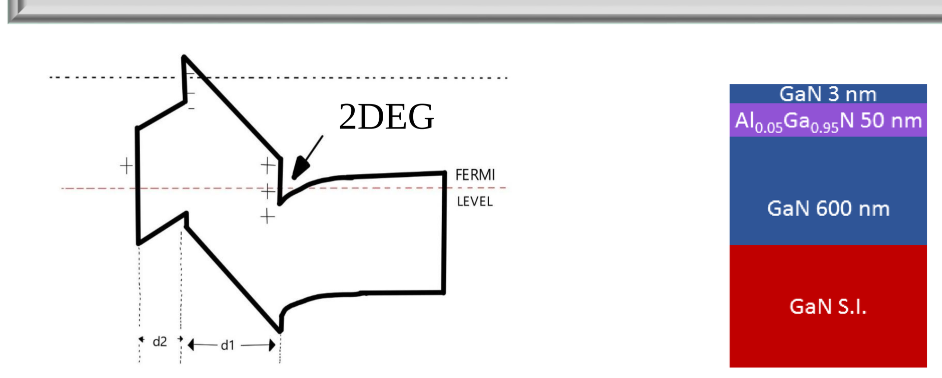


Fig. 6. Results of photoluminescence measurements for a single 6.5 nm quantum well grown on the ammonothermal substrate. Despite a strong built-in electric field (quantum confined Stark effect), full width at half maximum of emission related to the quantum well is very low 8.9 meV.

our results

Polarization- induced 2D electron gas in nitrides

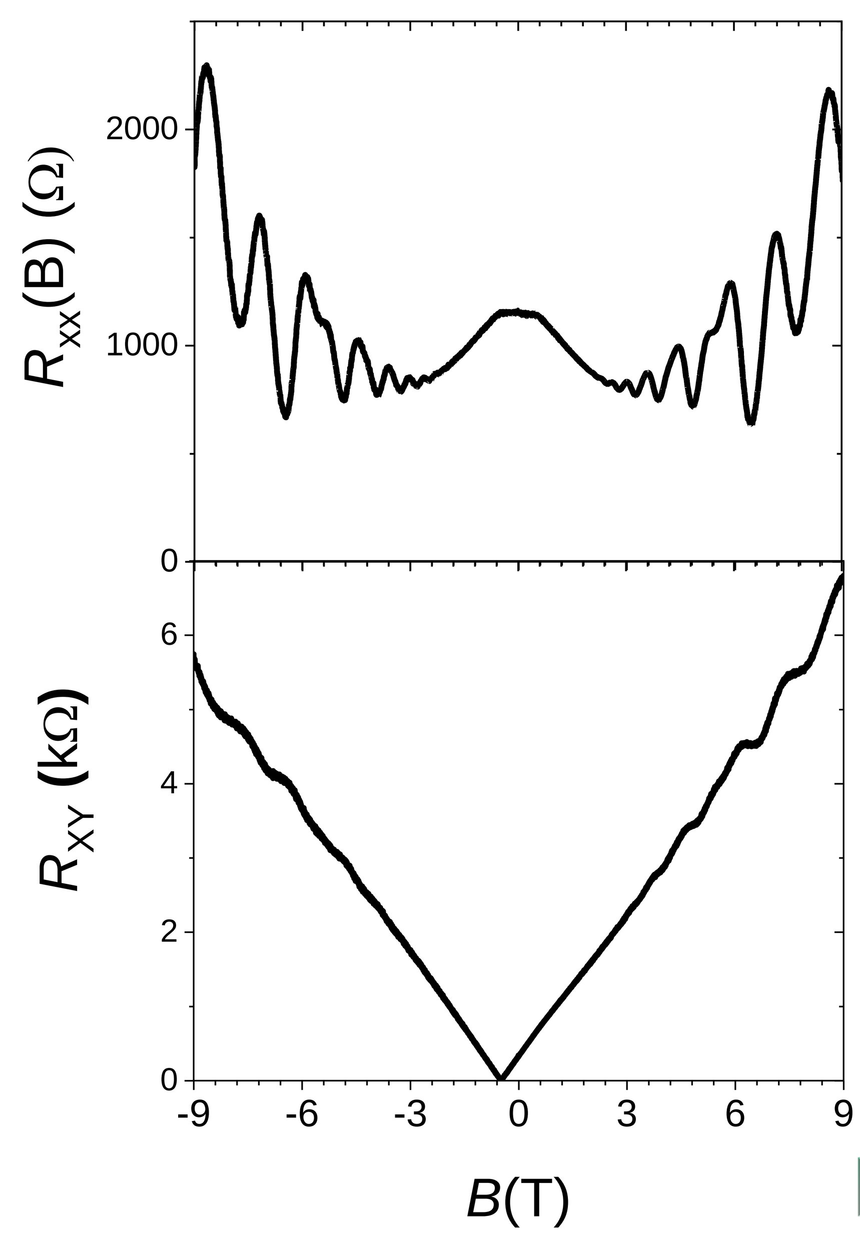


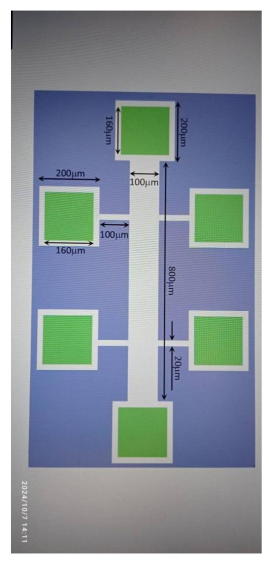
To achieve very high 2DEG mobility in AlGaN/GaN systems, you need:

- High-quality epitaxial growth with minimal defects and impurities. (**High quality substrates, Ammonia MBE)**
- A smooth, abrupt GaN/AlGaN interface with optimized barrier thickness and aluminum content. (**low aluminum concentration)**
- Careful control of scattering mechanisms (impurities, roughness, phonons). (**low temperature measurements)**
- Proper strain and thermal management to reduce defect densities and phonon scattering. (**low aluminum concertation, high quality substrates)**

our results

GaN/AlGaN 2DEGs IN THE QUANTUM REGIME

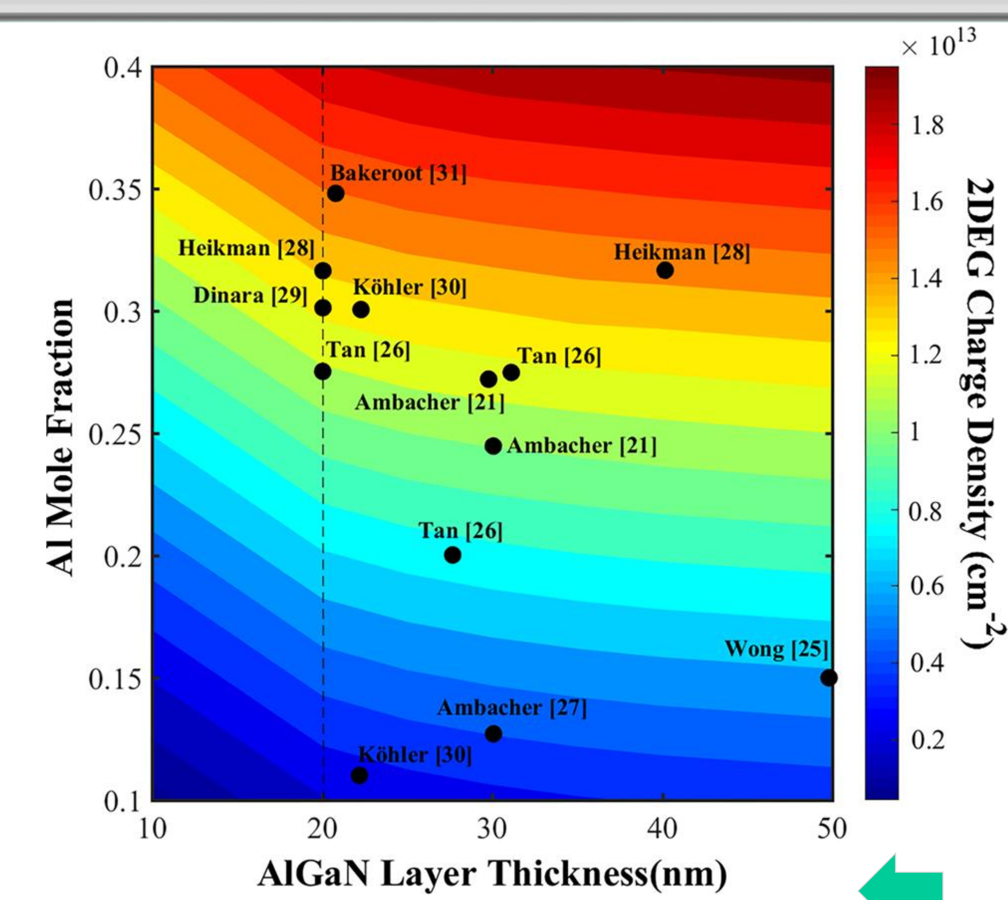




our results

Magetotransport studies at T=3K indicate presence of 2DEG in the structure (Quantum Hall effect). Values of magnetic field where plateaus are seen give information about concentration of 2DEG $B_n = h\, n_{2D} / e\, n$ and resistance shows mobility of the carriers $\mu = (n_{2D} e \rho)^{-1}$: $n_{2D} = 9.4\ 10^{11}$ cm^{-2}, μ=25000 cm²/Vs Qualitative analysis of results proofs the existence of the parasitic channel of conductance (paralel conductivity).

What should be the next step….



Manfra results (167.000 cm²/V*s)

Our results (25.000 cm²/V*s)

Fig. 8. Contour plot of 2DEG charge density for GaN HEMT as a function of barrier layer thickness (d) and Al mole fraction in the barrier layer. Experimental data indicated by black (After Analytical Model for Two-Dimensional Electron Gas Charge Density in Recessed-Gate GaN High-Electron-Mobility Transistors by Samaneh Sharbati et al.)

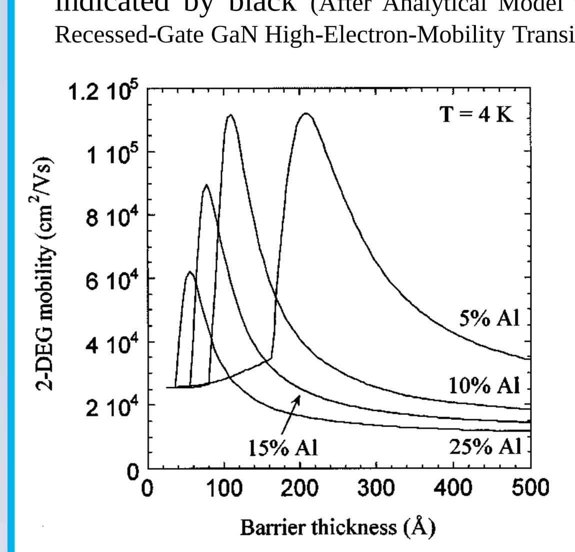
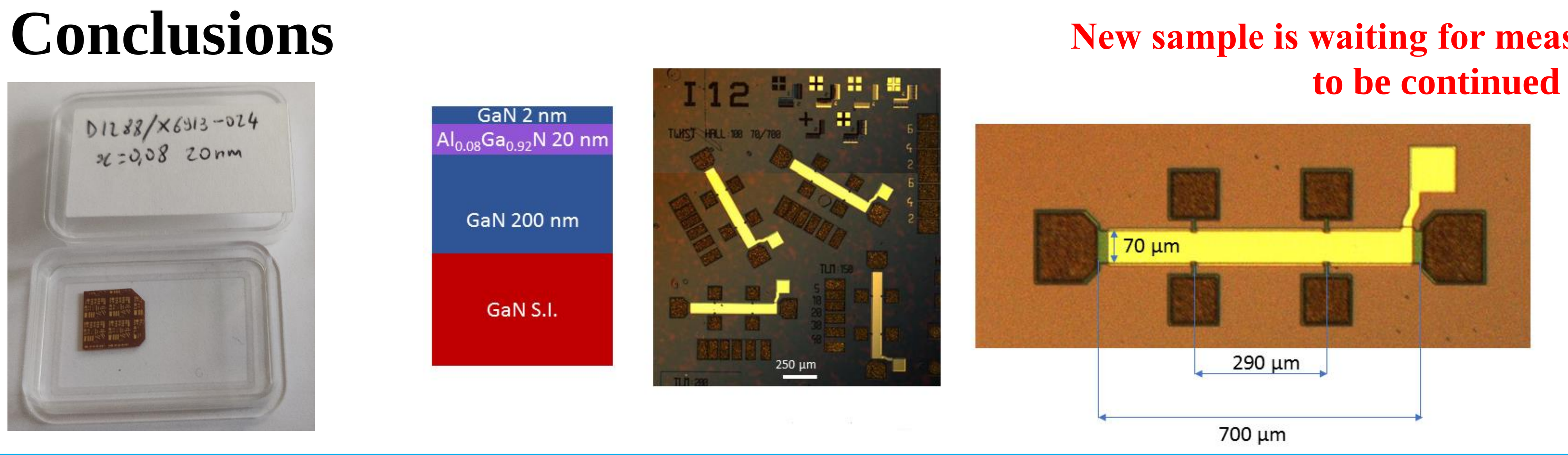


Fig. 9 Low temperature 2DEG mobilities as a function of barrier thickness for four different AlGaN/GaN heterostructures with different Al barier compositions.. (After Effect of polarization fields on transport properties in AlGaN/GaN Heterostructures by L. Hsu and W. Walukiewicz.)

We should lowered the AlGaN barrier thickness keeping low concertation of aluminum.

Conclusions

New sample is waiting for measurements …... to be continued



our results

References

1. M. A. Khan, J. N. Kuznia, J. M. Van Hove, N. Pan, and J. Carter, "Observation of a two-dimensional electron gas in low pressure metal organic chemical vapor deposited GaN-AlGaN heterojunctions," Appl. Phys. Lett. 60, 3027 (1992).
2. Yoon Jang Chung, A. Gupta, K. W. Baldwin, K. W. West, M. Shayegan, and L. N. Pfeiffer Understanding limits to mobility in ultrahigh-mobility GaAs two-dimensional electron systems: 100 million cm2/Vs and beyond Phys. Rev. B 106, 075134 (2022)
3. J. Falson, Y. Kozuka, M. Uchida, J.H. Smet, T. Arima, A. Tsukazaki & M. Kawasaki "*MgZnO/ZnO heterostructures with electron mobility exceeding 1 × 106 cm2/Vs"* Scientific Reports 6, 26598 (2016)
4. M. J. Manfra, K. W. Baldwin, A. M. Sergent, K. W. West, R. J. Molnar and J. Caissie *Electron mobility exceeding 160 000 cm2/Vs in AlGaN / GaN heterostructures grown by molecular-beam epitaxy* Applied Physics Letters 85 p5394 (2004)
5. S. Sharbati, · I. Gharibshahian,· T. Ebel, · A. A. Orouji, · W.-T. Franke "*Analytical Model for Two-Dimensional Electron Gas Charge Density in Recessed-Gate GaN High-Electron-Mobility Transistors* " Journal of Electronic Materials (2021) 50:3923–3929
6. L. Hsu; W. Walukiewicz *"Effect of polarization fields on transport properties in AlGaN/GaN heterostructures"* J. Appl. Phys. 89, 1783–1789 (2001)

Acknowledgment

This work was supported by the Polish National Science Centre within the OPUS Project No. 2020/37/B/ST8/03446