Polarization-engineered high mobility of two-dimensional hole gas in GaN

P-channel heterostructure field-effect transistor with 10^8 on/off ratio shows great potential for complementary logic in harsh environments.

Researchers in Germany have developed two-dimensional hole gas (2DHG) gallium nitride (GaN) channel structures with record mobility [B Reuters et al, J. Phys. D: Appl. Phys., vol47, p175103, 2014]. Mobility for 2DHGs in GaN is usually around 10cm^2/V-s. Two-dimensional electron gas (2DEG) mobility is much higher, at around 1000cm^2/V-s.

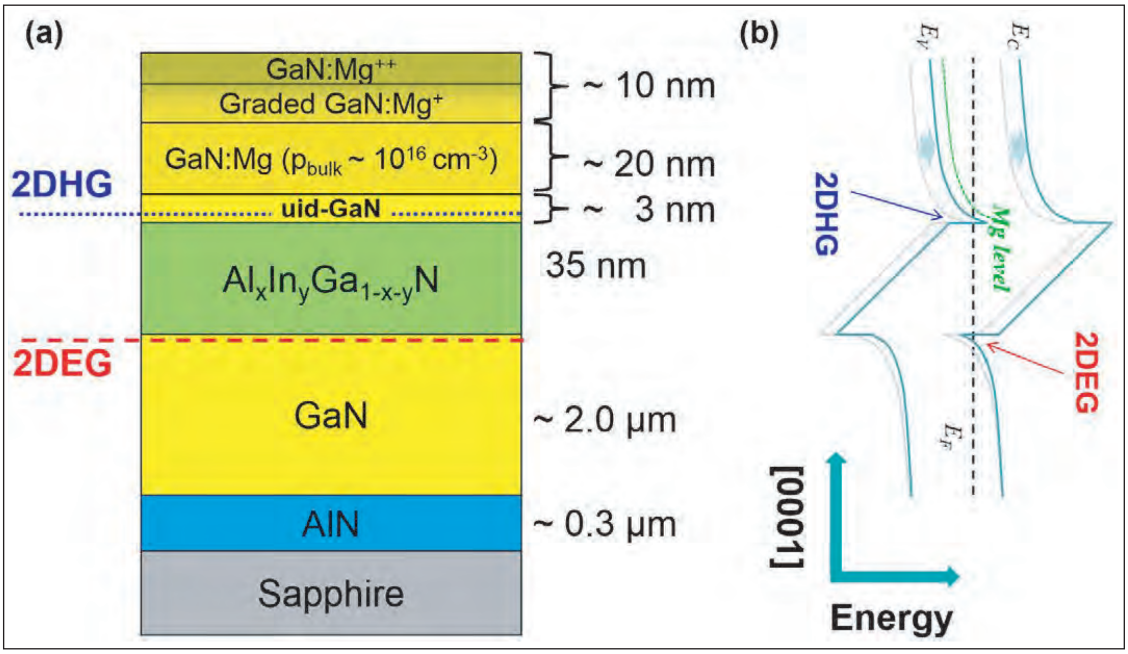

Figure 1. (a) Schematic of nitride semiconductor stack grown by MOVPE. (b) Corresponding schematic of band structure.

The research by RWTH Aachen University, Forschungszentrum Jülich GmbH, Jülich Aachen Research Alliance (JARA)-Fundamentals of Future Information Technologies, and Aixtron SE resulted in one sample with a 2DHG mobility as high as 43cm^2/V-s.

The researchers also produced p-type heterostructure field-effect transistors (p-HFET). Some of these devices demonstrated depletion-mode (normally on) operation. Other devices worked in enhancement mode, giving normally-off behavior that is desired for low power consumption.

Producing p-type hole conductivity in nitride semiconductors is inhibited by background impurities such as silicon or oxygen that act as donors in GaN, meaning that unintentionally doped material is n-type.

The researchers in Germany used an aluminium indium gallium nitride (AlInGaN) back-barrier and magnesium doped bulk p-GaN above the unintentionally doped channel layer. By varying the composition of the back-barrier, different polarization fields could be set up, allowing 2DHGs with different properties to be realized. The upper p-GaN layers were designed to compensate for the typical n-type behavior of the unintentionally doped (uid) GaN channel layer.

The epitaxial structures (Figure 1) were grown on 2-inch c-plane sapphire in an Aixtron horizontal-flow metal-organic vapor phase epitaxy reactor. The surface temperature and growth rate were carefully controlled using spectroscopic measurements over the wavelength range 276–775nm from a LayTec tool, in combination with true-temperature pyrometer data.

Five samples were produced with various AlInGaN compositions for the back-barrier. The composition variation was created through different growth temperatures and trimethyl-Al/Ga precursor flow ratios. The aim was to achieve different spontaneous and piezoelectric (strain-dependent) polarizations, giving control over the contrast with GaN (Table 1).

The more heavily doped p^{++}-GaN surface layer was aimed at ohmic contact formation. The magnesium acceptors were activated with a 20-minute 700°C anneal process in nitrogen.

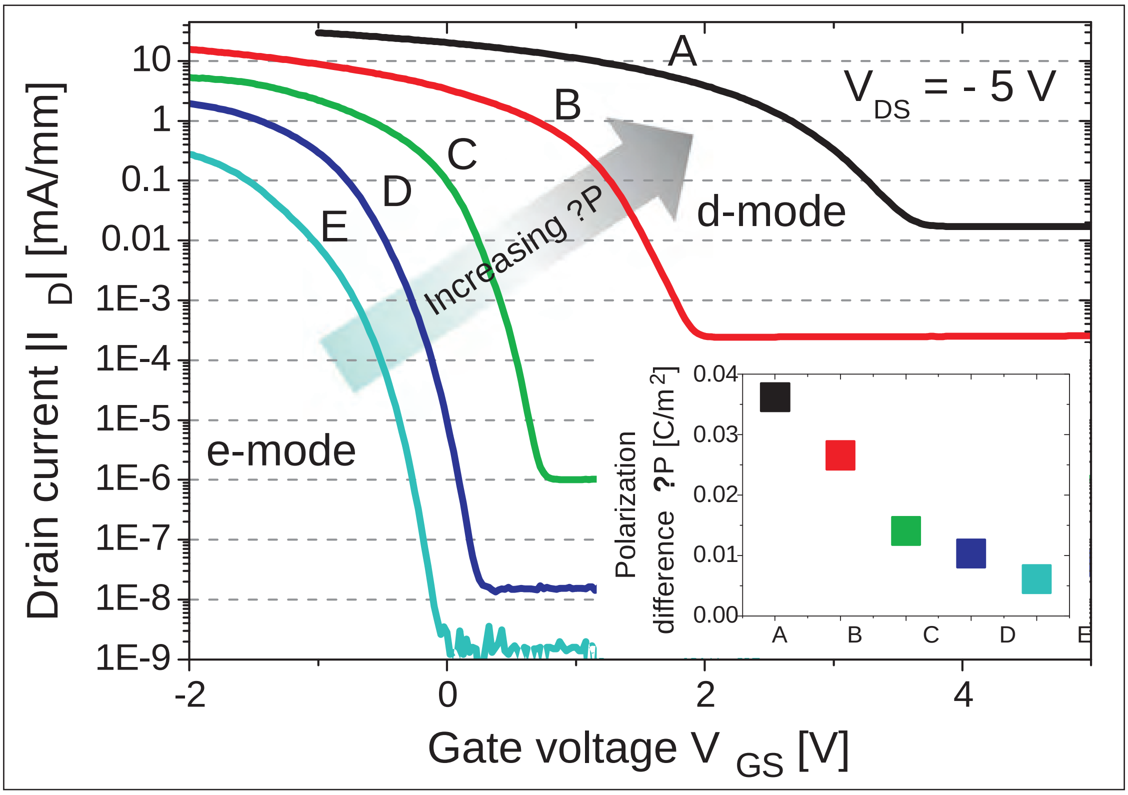

Figure 2. Absolute drain current versus gate voltage. Threshold voltage shifts from negative values (enhancement-mode) to positive values (depletion-mode) with increasing ΔP. Inset: calculated ΔP values for each sample.

Test structures, including a heterostructure field-effect transistor (HFET), were produced with annealed nickel/gold ohmic contacts, molybdenum Schottky gates, and gate and access region recessing through the surface p^{++}-GaN and graded p^{+}-GaN layers with a digital etch process. The gate recessing reduced gate leakage by about four orders of magnitude, according to the researchers.

Hall measurements gave 2DHG densities of between 2x10^{13}/cm^2 and 6x10^{11}/cm^2. A record hole mobility of 43cm^2/V-s was achieved for sample C at 1.3x10^{12}/cm^2 carrier density. However, sample C also suffered from a wider spread of results compared to the other samples. Overall, sample C had a median mobility of 30cm^2/V-s and 2.2x10^{12}/cm^2 carrier density.

HFETs with 1µm gate length and 7nm recess were fabricated. Sample A produced HFETs with depletion-mode/normally-on behavior.

The drain current reached more than 40mA/mm for a negative gate potential of –3V and drain bias 10V. A positive gate potential of 3.5V gave an off-current of 0.01mA/mm, resulting in an on/off ratio of more than 1000. Higher drain currents of more than 100mA/mm have been achieved in 2DHG HFETs, but these devices have only achieved on/off ratios of around one order of magnitude.

The peak transconductance was 9mS/mm. Frequency measurements resulted in a cut-off frequency (f_T) of 206MHz and maximum oscillation (f_{max}) of 640MHz.

Enhancement-mode performance was achieved using sample E with a low polarization difference (Figure 2). The maximum drain current and peak transconductance at 5V drain bias were 0.7mA/mm and 0.2mS/mm. These low values were offset by an even greater reduction in off-current, giving an on/off ratio 10^8, "the best value ever published for p-channel transistors," according to the researchers.

The researchers say that the on/off performance of the enhancement-mode transistor shows "great potential of these devices for applications like complementary III-nitride logics for harsh environments". ■

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Table 1. Sample identification with, respectively, growth surface temperature, precursor Al-to-Ga molar gas phase ratio, compositions determined by Rutherford backscattering spectrometry (RBS) and high-resolution x-ray diffraction (HRXRD), spontaneous and piezoelectric polarization, and polarization difference with GaN.

Sample	T_S(°C)	TMAl/TMGa ratio	Al (%)	In (%)	Ga (%)	$-P_{sp}$ (C/m^2)	$-P_{pz}$ (C/m^2)	ΔP (C/m^2)
A	820	2.4	54	4	52	0.058	0.012	0.036
B	815	1.2	42	3	55	0.052	0.009	0.027
C	807	0.6	25	2	73	0.044	0.004	0.014
D	798	0.4	20	2	78	0.041	0.003	0.010
E	793	0.2	14	2	84	0.039	0.001	0.006