Magnesium doping of hot-wall MOCVD GaN

Gallium supersaturation enables hole conductivity even without annealing.

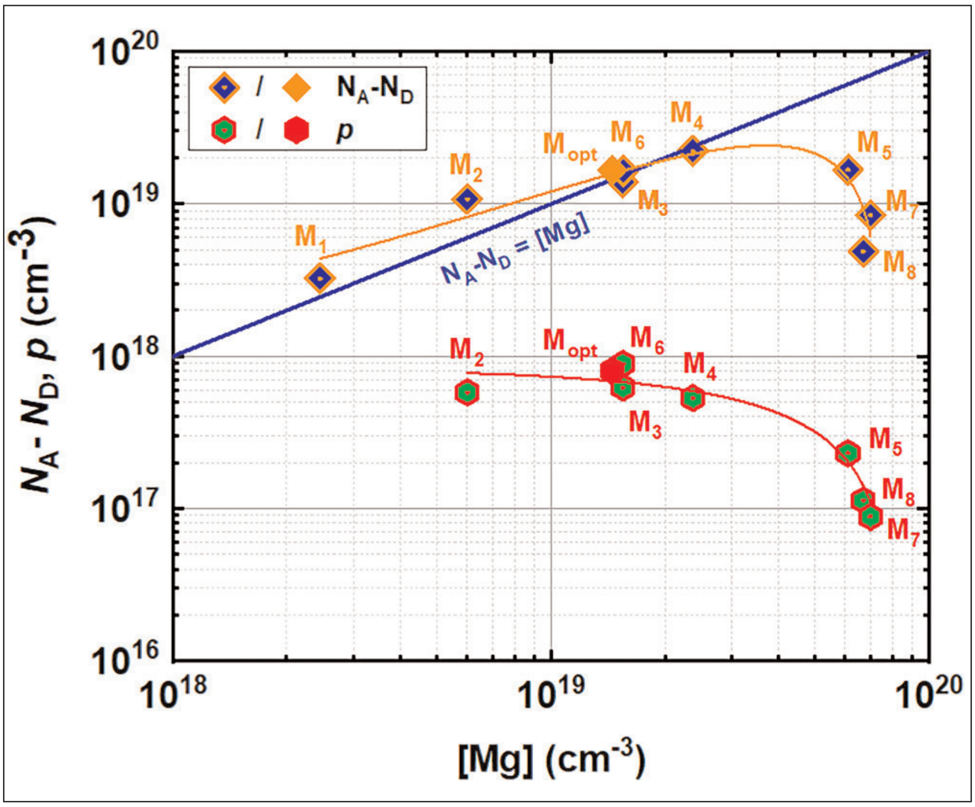

Figure 1. Net acceptor concentration N_A–N_D (from capacitance–voltage measurements) and free-hole concentrations (from Hall analysis) in annealed p-GaN as function of [Mg]. Red and orange curves offer guides to the eye. Blue solid line corresponds to N_A–N_D = $[M_g]$.

Researchers based in Sweden and Iceland report on the growth of p-type magnesium-doped gallium nitride (p-GaN:Mg) using hot-wall metal-organic chemical vapor deposition (MOCVD) [A. Papamichail et al, J. Appl. Phys., v131, p185704, 2022]. The growth technique has been shown to provide "superior III–nitride material quality and high-performance devices," according to the team from Linköping University, University of Iceland, Chalmers University of Technology, Hitachi Energy Sweden, SweGaN AB, and Lund University. The researchers point out that, up to now, there have been no reported studies of the capability of hot-wall MOCVD to deliver high-quality GaN:Mg layers with p-type conductivity.

The optimizing of p-type doped material is a key step toward GaN-based power diodes, vertical transistors, and normally-off high-electron-mobility transistors (HEMTs). The hot-wall MOCVD technique was found to enable p-type GaN even without the usual annealing process used to drive out hydrogen incorporated during the growth process, which passivates the ability of Mg to act as an acceptor.

The samples consisted of 500nm p-GaN grown on (0001) on-axis silicon carbide (SiC) wafers in a horizontal hot-wall MOCVD reactor. The nucleation layer was 50nm aluminium nitride (AlN) grown at 1250°C with a V/III ratio of 1258. The nitrogen component was sourced from ammonia (NH_3, 2l/minute) in nitrogen/hydrogen carrier gas at 100mbar pressure. The group III metals were from trimethyl (TMGa/Al) metal-organic compounds. The magnesium-doping precursor was bis(cyclopentadienyl)magnesium (Cp_2Mg).

Most of the GaN:Mg samples were grown at 1120°C. Variations were made in V/III ratio, growth rate, Cp_2Mg/TMGa ratio, and carrier gas flows. Apart from an unintentionally doped (UID) Ga sample, the Mg concentration ranged from 2.45×10^{18}cm^3 to 1.10×10^{20}cm^3. Activation was accomplished using rapid thermal annealing (RTA) at 900°C in nitrogen.

The team found that Ga supersaturation had a strong effect on Mg incorporated for samples with a given Cp_2Mg/TMGa ratio. The researchers comment: "Our results indicate that Ga supersaturation can be conveniently used as a universal parameter for the optimization of Mg incorporation and C reduction in MOCVD of GaN instead of multiple growth parameters independently used for the same purpose." Carbon (C) tends to form a shallow donor state that reduces the effectiveness of Mg as an acceptor, lowering the free-hole concentration.

After exploring these factors the researchers grew an optimized 550nm GaN:Mg layer on 1μm GaN UID buffer ($M_{opt)}$). The optimized parameters were 1120°C temperature, 100mbar pressure, 906 V/III ratio, 0.6μm/h growth rate, 0.167% Cp2Mg/TMGa, 19l/min H_2, and 9l/min N_2.

The researchers comment: "The free-hole concentration of 8.4x10^{17}/cm^3 and the resistivity of 0.77Ω-cm in the annealed sample are among the best results reported in the literature." The hole mobility was 10cm^2/V-s. The hole density represented a Mg activation rate of 5.25%.

Even without annealing to activate the sample, the free-hole density reached 1.67x10^{16}/cm^3. "Hence, hot-wall MOCVD addresses a practical challenge related to the realization of as-grown p-GaN without the need for ex-situ post-growth annealing for Mg activation," the team writes, adding, "These results provide an intriguing opportunity to exploit the technique for delivering lightly p-type doped material required in device heterostructures, e.g. vertical MOSFETs, and simplifying the device fabrication process."

The growth on a buffer layer also enabled a reduction of screw- and edge-type dislocation densities to 1.6x10^7/cm^2 and 4.3x10^8/cm^2, respectively.

Mg concentrations ([Mg]) beyond 2.4x10^{19}/cm^3 were found to suffer from the generation of pyramidal inversion domains (PIDs) (Figure 2). These structures tend to segregate out Mg atoms, rendering them electrically inactive. ■

https://doi.org/10.1063/5.0089406

Author: Mike Cooke

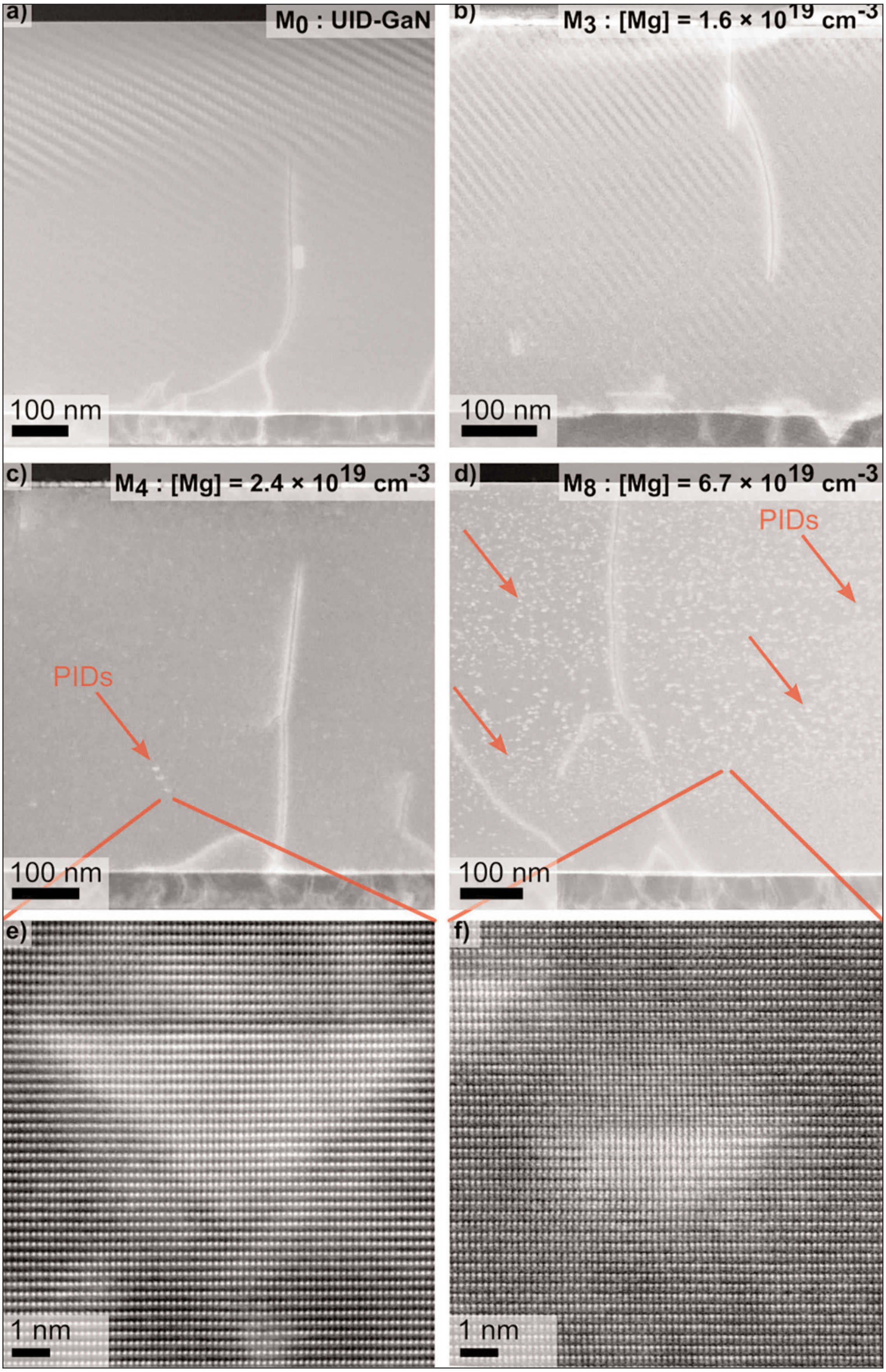

Figure 2. Scanning transmission electron microscope (STEM) images of as-grown GaN:Mg layers with different [Mg]: (a) UID, (b) 1.6x10^{19}/cm^3, (c) 2.4x10^{19}/cm^3, and (d) 6.7x10^{19}/cm^3. Arrows in (c) and (d) highlight some PIDs. Higher-magnification images of PIDs for (c) and (d) shown in (e) and (f), respectively, both in [$1\bar{1}00$] projection.