

# Fe-doped AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs: Kink-Effect Screening using Yellow Luminescence?

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## ABSTRACT

Yellow luminescence (YL) analysis was investigated as a possible route for the screening of as-grown wafers for kink effect in Fe-doped AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs, i.e., prior to their final fabrication. This is because the kink effect in the output characteristics of Ga<sub>N</sub> HEMTs has previously been suggested to originate from YL-related defect states. In contrast to earlier works, no direct correlation between YL intensity and kink size was observed in the devices studied. This suggests a more complex trapping process to be the underlying mechanism for the kink effect, rather than directly from YL defect states.

## INTRODUCTION

Despite the impressive improvement in the performance of AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs for radar and communication applications, device reliability still poses a present limitation for this technology. In order to identify mechanisms of device failure, multiple lifetime tests and quality checks are typically run on fully processed wafers. Hence, a non-invasive detection method applicable on as-grown wafers prior to device fabrication would be desirable for screening for device wafer quality issues. One intrinsic defect related mechanism is known as the “kink effect”. This is characterized by a sudden drain current increase when the drain-source voltage exceeds a critical value. Although these defects do not affect RF power, they are undesirable since they complicate RF modeling and DC characterization. In Ga<sub>N</sub> HEMTs, the kink effect has been proposed to relate to impact ionization [1], charge trapping [2] or even a combination of both mechanisms [3]. The latter suggested that charge trapping occurs in deep levels of the Ga<sub>N</sub> followed by de-trapping via impact ionization. This work correlated the responsible defect states with yellow luminescence (YL) centers, i.e., defect states that could be optically detected by photoluminescence (PL) at a photon energy of ~2.2 eV. This would offer a potential route to use YL to screen epitaxial layers and to check for wafer quality [9] without the need for full processing and expensive fabrication. Here, we discuss the origin of the kink effect with respect to the impact of Fe doping to test this hypothesis. Fe is known to affect YL states in Ga<sub>N</sub> [4], and this phenomenon is used here to test whether YL could be used as a pre-fabrication “kink-check”.

## EXPERIMENTAL DETAILS

Measurements were performed on AlGa<sub>N</sub>/Ga<sub>N</sub>/SiC HEMTs grown by MOVPE. Ferrocene was used as the Fe source for doping the Ga<sub>N</sub> buffer at a constant level of  $2 \times 10^{18} \text{ cm}^{-3}$ . Based on the surface segregation mechanism of Fe during Ga<sub>N</sub> growth, different doping concentrations at the AlGa<sub>N</sub>/Ga<sub>N</sub> interface, ranging from  $7 \times 10^{15} \text{ cm}^{-3}$  to  $2 \times 10^{17} \text{ cm}^{-3}$ , were achieved by varying the depth in the device layer at which the dopant was switched off [5]. Devices were fabricated using a conventional  $0.25 \mu\text{m}$  T-gate and Ohmic contacts composed of a Ti/Al/Pt/Au stack. The output characteristics of the HEMTs were measured using a Keithley 4200-SCS. The kink size was estimated as the drain current step between the kink starting and end point for different gate-source voltages. PL spectroscopy was employed to quantify the YL signal emitted from the Ga<sub>N</sub> epilayer. A laser beam at  $\lambda = 325 \text{ nm}$  was used for above-GaN-bandgap excitation, while the scattered light was detected with a Renishaw RM spectrometer, probing ~90 nm into the Ga<sub>N</sub> epilayer [6].

## RESULTS AND DISCUSSION

The output characteristics of two representative devices on the wafers with no Fe and with the highest Fe concentration at the AlGa<sub>N</sub>/Ga<sub>N</sub> interface are depicted in Fig. 1. A significant kink in  $I_{\text{DS}}$

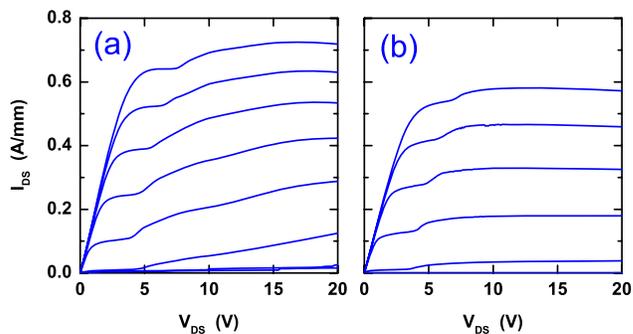


FIGURE 1. OUTPUT CHARACTERISTICS OF REPRESENTATIVE ALGAN/GAN HEMTs WITHOUT FE DOPING (A) AND WITH A FE CONCENTRATION OF  $2 \times 10^{17} \text{ cm}^{-3}$  AT THE ALGAN/GAN INTERFACE (B), AT A SWEEP RATE OF 0.1 V/S. DEVICES HAD A GATE WIDTH OF  $2 \times 50 \mu\text{m}$  AND A SOURCE-DRAIN SPACING OF  $4 \mu\text{m}$ .

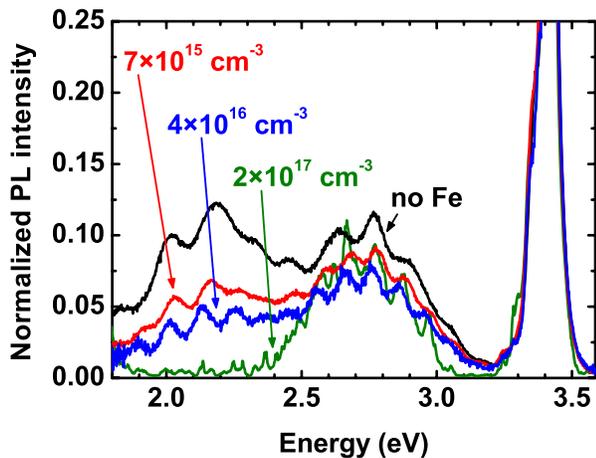


FIGURE 2. PL SPECTRUM OF WAFERS WITH DIFFERENT FE CONCENTRATION AT THE ALGaN/GaN INTERFACE, AS LABELLED IN THE FIGURE. THE PL INTENSITY IS NORMALIZED TO THE GAN BANDEDGE PEAK AT 3.41 eV AFTER BASELINE SUBTRACTION.

appears for both devices when  $V_{DS}$  is varied from 0 to 20 V. This kink arises from a sudden increase in charge under the gate, which is associated with field-induced de-trapping. The generally lower drain current in the device with high doping level results from a shift in pinch-off voltage. This is caused by a higher concentration of acceptor charge under the gate, reducing the 2DEG density and likewise  $I_{DS}$ . The kink in the output characteristics is present at all Fe concentrations at the AlGaN/GaN interface, illustrating that Fe does not suppress the kink effect for the investigated devices.

In order to evaluate the possibility of employing YL for screening for the kink effect, the same set of wafers used for electrical characterization was investigated by PL spectroscopy, as illustrated in Fig. 2. All spectra were normalized to the intensity of the GaN bandedge peak at 3.41 eV. The yellow luminescence centered at  $\sim 2.2$  eV, which can be attributed to a transition between a shallow donor and a deep donor/acceptor level, is strongly affected by the Fe concentration at the AlGaN/GaN interface [7]. The reduction in YL intensity with increasing Fe concentration results from Fe doping reducing the concentration of Ga vacancies ( $V_{Ga}$ ) [4] related to the YL [8]. We note that independent on the level of Fe doping all structures exhibit a blue luminescence band at  $\sim 2.8$  eV, which is often associated with nitrogen vacancies in the GaN epilayer.

A summary of the observations for all wafers studied is presented in Fig. 3. The integrated YL intensity dramatically decreases with higher Fe concentration at the AlGaN/GaN interface, while the relative kink size does not show such a strong dependence. It needs to be emphasized that some reduction in kink size at high Fe doping level is expected, since Fe doping of the GaN buffer enhances the 2DEG confinement, which prevents charge carriers from spreading into the GaN buffer. Therefore, fewer electrons reach kink-related buffer traps located deep in the GaN epilayer, which naturally reduces the kink effect.

If YL defect states were solely responsible for the kink effect, a similar dependence of both phenomena on the Fe concentration would be expected. However, no one-to-one correlation of YL intensity and kink size has been observed. This illustrates that YL defect states are not the sole origin of the kink effect. Nevertheless, trap states in the energy vicinity of YL may still somehow be involved in the kink effect mechanism via a multi-stage trapping process, but

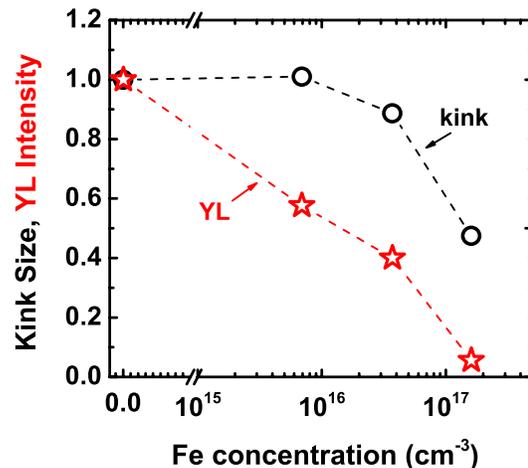


FIGURE 3. KINK SIZE AND INTEGRATED YL INTENSITY FOR DIFFERENT FE CONCENTRATIONS, NORMALIZED TO THE REFERENCE WAFER WITHOUT FE DOPING. THE KINK SIZE WAS AVERAGED OVER DIFFERENT  $V_{GS}$  (0, -1, -2, -3, -4 V).

only as a contributing factor. Considering the lack of strong correlation between kink size and YL intensity, the suggested application of YL analysis as a “kink screening”-method prior to device fabrication does not present an easily workable approach and may lead to false interpretation if not treated with caution.

## CONCLUSION

Yellow luminescence (YL) analysis as a possible route for “kink screening” in GaN epitaxy was investigated with respect to the impact of Fe doping in the GaN epilayer. While the YL intensity decreases drastically with increasing Fe concentration at the AlGaN/GaN interface, the kink size only shows a weak dependence on the level of Fe doping. This suggests a more complex trapping mechanism to result in the kink effect, which is not solely related to YL defect states. Since no direct correlation between YL signal and kink effect could be confirmed, YL analysis does not present a suitable method for “kink screening”, particularly not for Fe-doped GaN epilayers.

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#### ACRONYMS

HEMT: High Electron Mobility Transistor  
MOVPE: metal organic vapor phase epitaxy  
2DEG: two-dimensional electron gas

