Demonstration of avalanche capability in polarization-doped vertical GaN pn diodes: study of walkout due to residual carbon concentration

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Abstract—**For the first time, we demonstrate and investigate the avalanche capability in vertical GaN-on-GaN pn diodes with polarization doping. Specifically: (i) we prove that the analyzed devices have avalanche capability, and we describe the dependence of breakdown voltage and leakage on temperature and monochromatic illumination; (ii) we demonstrate the presence of avalanche walkout, i.e. a recoverable increase in breakdown voltage induced by stress in avalanche conditions; (iii) we describe the time-dependence of avalanche walkout as a function of temperature, and demonstrate that walkout is caused by charge trapping due to residual carbon; (iv) we calculate the related activation energy and propose a model able to explain the experimental data. The reported results are of the utmost importance for the improvement in performance of high-voltage avalanche-capable GaN diodes.**

I. INTRODUCTION

Demonstrating vertical GaN-on-GaN diodes with avalanche capability is of fundamental importance for the development of high-voltage devices based on GaN. However, only little is known on the behavior of GaN vertical devices under avalanche conditions. We present **the first comprehensive investigation on this topic**, by demonstrating the avalanche capability of vertical GaN-on-GaN pn diodes with polarization doping and investigating the related physical mechanisms.

II. AVALANCHE BREAKDOWN

The devices under test are vertical pn GaN diodes grown by metal-organic chemical vapor deposition (MOCVD) [1] with a polarization-doped p-side [2] to overcome the low ionization of Mg:GaN (see Fig. 1 for the structure). Such devices show a very low leakage current up to V_{BD}>1300 V, when a sudden current increase takes place. The breakdown voltage has a **positive temperature coefficient** (Fig. 2), supporting the hypothesis that the increase in current is related to avalanche breakdown [3], [4]. The temperature coefficient of 0.5 V/°C (Fig. 3) is compatible with previous reports [3], [4], and consistent with the higher phonon scattering with increasing temperature.

In principle, an abrupt increase in vertical leakage could also be explained by a field-assisted conduction through dislocations, known to generate the leakage in bulk GaN [5]. In this second hypothesis, the positive temperature coefficient would originate from a thermally-assisted electron capture inside the dislocations, limiting the current flow at higher temperature. **In order to confirm the avalanche capability of the devices**, we carried out reverse breakdown measurements under external illumination (Fig. 4). As can be noticed, light is able to reach the active region, since an increase in current in the pre-avalanche region is visible, even when the photon energy is below the energy gap and no band-to-band (365 nm) absorption takes place. This phenomenon may be caused by defect-related absorption or by the Franz-Keldysh effect. Since the absorption coefficient changes with the electric field (e.g. for the curve under 405 nm illumination) and since the spectral dependence is compatible with the high-field absorption tails reported in [6], we conclude that **Franz-Keldysh effect is causing the photon absorption and increased leakage** in this case. By analyzing the high-field region, we notice that the breakdown voltage and the equivalent resistance in the high-current region are not influenced by the external illumination, excluding a possible role of electron trapping and **giving an optical confirmation to the assumption that an avalanche process is present.**

III. BREAKDOWN WALKOUT

The stability of the breakdown voltage is important for high reverse voltage operation. As can be seen in Fig. 5, when the device is operated for a long time in reverse bias mode **a time-dependent mechanism, responsible for the increase in the breakdown voltage of several (30) volts**, takes place. This behavior is **not related to a permanent degradation** of the device, since after some rest time the device slowly returns to its previous current and breakdown voltage levels (Fig. 6 and 7). This process, called **breakdown walkout**, was already demonstrated to be possible and permanent in devices based on the Si [7] and GaAs [8] material system, but recent reports on GaAs pseudomorphic high electron mobility transistors show that it can also be caused by charge trapping [9], in this case at interface states. **Up to now no report on avalanche breakdown walkout is present in the literature for vertical GaN devices.**

Taking into account the significant power dissipated by those devices and by the neighboring ones in a power supply and/or converter, the effect of the operating temperature cannot be neglected. By repeating the reverse-bias stress experiment at different ambient temperatures (Fig. 8), it was possible to demonstrate that **the breakdown walkout process becomes**

stronger and faster at higher temperature, a behavior compatible with the aforementioned charge trapping process. **The activation energy of the walkout process was found to be 0.52 eV**. Deep levels with a similar signature (Fig. 9) were already reported in the past [10]–[13] and related to the presence of carbon at the nitrogen site (C_N) [14]. Typically, C_N defects have higher activation energy (0.8-0.9 eV); in our case, the high electric field (close to the breakdown limit of GaN, >3 MV/cm) may significantly lower this activation energy, due to Poole-Frenkel effect. In the devices under test no intentional carbon doping is present, but a residual concentration (2-6×10^{16} cm^{-3} in the whole structure) was detected by secondary ion mass spectroscopy (SIMS), likely originating from the metal-organic precursors. It is worth noting that the carbon level in these device epitaxial layers can be lowered to be below the detection limit similar to the optimized epitaxial layers employed in our previously reported GaN p-n diodes [4].

IV. ROLE OF RESIDUAL CARBON

In order to identify if a deep level related to the residual carbon is really present in the devices, we developed a new setup for capacitance deep level transient spectroscopy (C-DLTS). In common systems, the maximum voltage that can be applied to the device under test is limited to ±10 V and the maximum filling and measure times are in the order of hundreds of microsecond. The high-voltage nature of the reported diodes requires higher voltages in order to effectively probe their performance in a region affected by high-voltage operation, therefore we increased the maximum voltage to ±40 V. Beyond this limit the leakage is too high and the capacitance measure is not reliable. Additionally, given the depth of carbon-related energy states in the GaN gap, the capture and emission time constants can be relatively long. In most cases this issue is addressed by high-temperature measurements, which are not possible in this case due to the limited reliability of such pre-maturity research samples. For this reason, in our new setup we were able to achieve no maximum limits for the filling and measure phase, which we chose to be 10 s and 1200 s, respectively.

This long measure time is needed to accurately record the capacitance transient of a minority carrier trap at 300 K (Fig. 10). To make sure that the detected transient is not related to surface states or parasitic effects, the figure reports the results of tests carried out at different voltages, i.e. by analyzing different active volumes. The amplitude of the capacitance transient, proportional to the total number of deep levels inside the probed region, increases when a more negative measure voltage is applied. This confirms that **the deep levels generating** the transient are located near the junction and that their position is not limited to a specific layer or interface but **is distributed in the whole volume, compatibly with the hypothesis on the residual point-defect (carbon) concentration**. The results of temperature-dependent measurements are reported in Fig. 11. **By comparing the extrapolated Arrhenius plot with previously published papers (Fig. 12), an excellent agreement with other carbon-related deep level signatures can be noticed.**

Based on the experimental findings, the breakdown walkout process can be modeled as follows. When a strong reverse bias is applied, **hole emission** (i.e. electron capture) from residual carbon takes place, as demonstrated by C-DLTS. The increased (flowing) electron-to-(trapped) electron scattering causes **a reduction in the electron mean free path**, increasing the required applied voltage to start the avalanche multiplication.

V. CONCLUSIONS

In summary, we unambiguously demonstrated, by means of electrical and optical measurements, that high-voltage GaN-based devices with polarization doping exhibit avalanche breakdown. The breakdown voltage is time-dependent, affected by a recoverable walkout mechanism. It is caused by hole emission from residual carbon, as confirmed by temperature-dependent and DLTS measurements. All these phenomena were never reported for GaN before, and their understanding is necessary in order to design reliable and well-performing devices able to exploit the good characteristics of the GaN material system for power and high-voltage operation.

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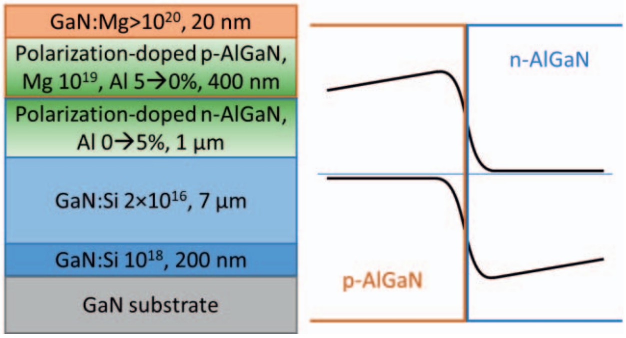

Figure 1. Structure of the devices under test and sketched band diagram.

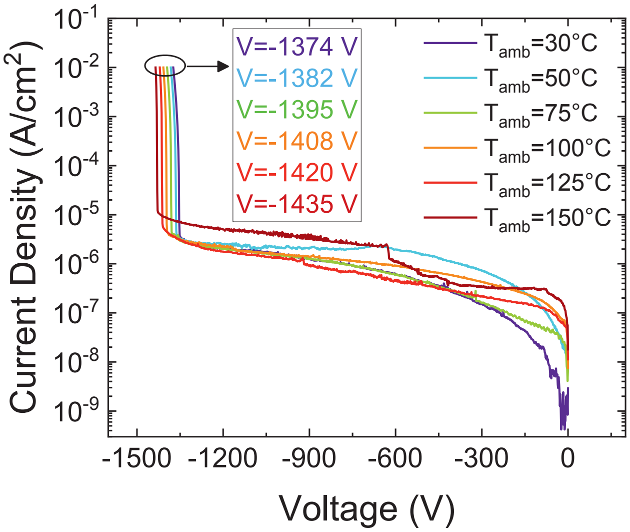

Figure 2. Reverse-bias breakdown measurements at various temperatures. The analyzed devices show avalanche capability, and a positive temperature coefficient is observed

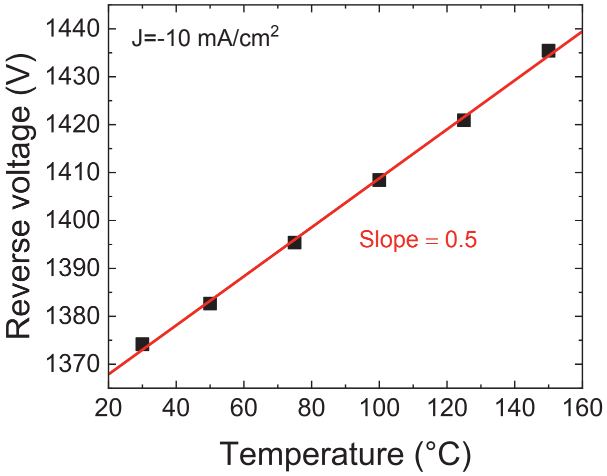

Figure 3. Positive temperature coefficient of the avalanche breakdown: dependence of V_{BD} on temperature.

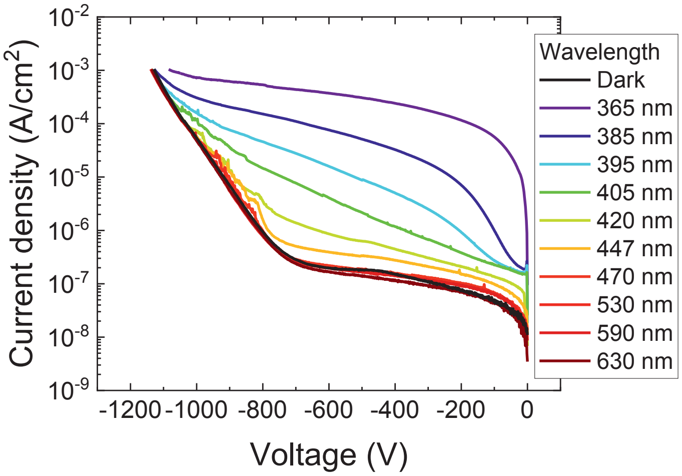

Figure 4. Dependence of reverse current on monochromatic illumination wavelength.

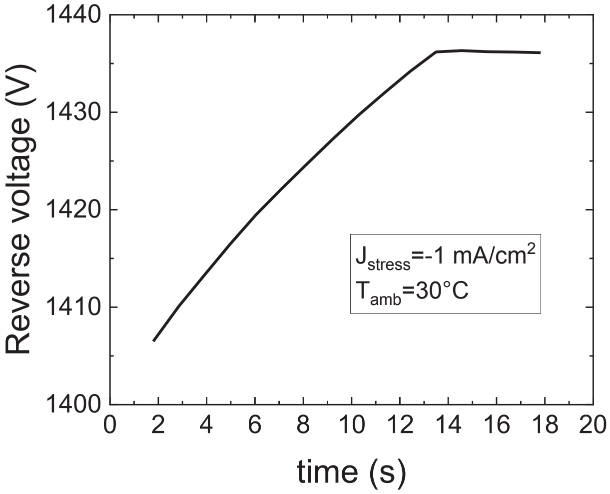

Figure 5. Time-dependent variation of the breakdown voltage during reverse-bias stress at -1 mA/cm^2, 50 °C (i.e. during stress in avalanche regime). A breakdown walkout mechanism is observed, leading to a significant increase in V_{BD}

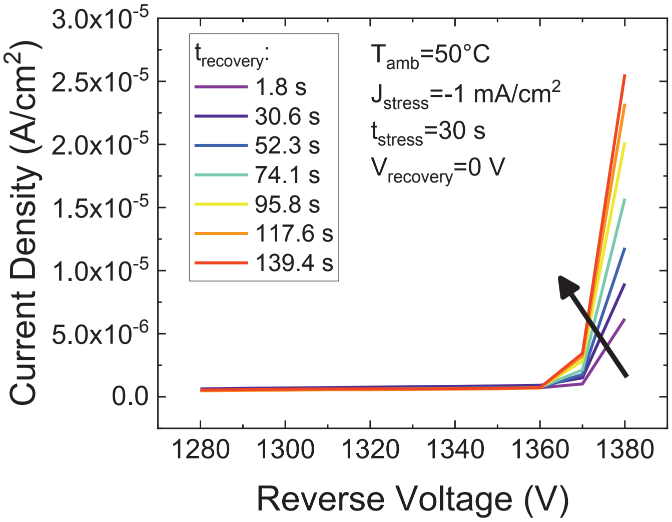

Figure 6. Recovery of the breakdown voltage after reverse-bias stress at -1 mA/cm^2, 50 °C. The observed breakdown walkout is fully recoverable

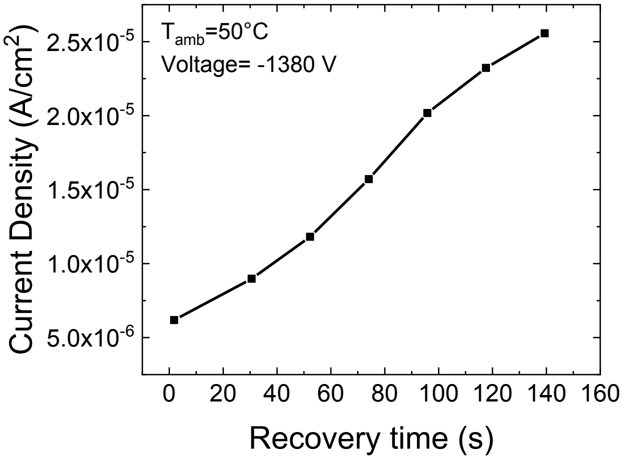

Figure 7. Recovery of the reverse current after reverse-bias stress at -1 mA/cm^2, 50 °C. Breakdown walkout is fully recoverable, with slow de-trapping kinetics

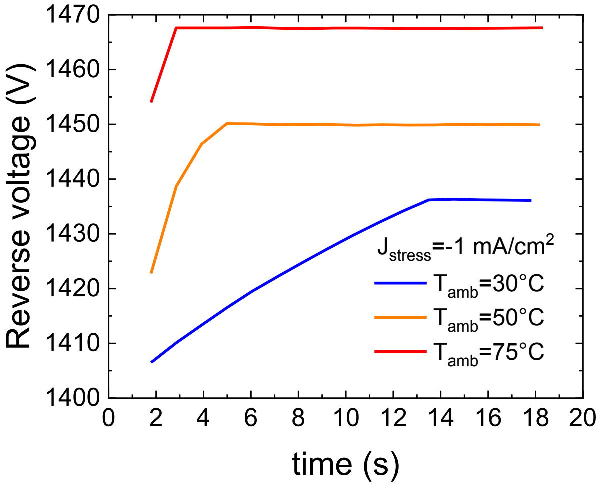

Figure 8. Dependence on temperature of the breakdown walkout process. Increasing temperature leads to a stronger and faster breakdown walkout

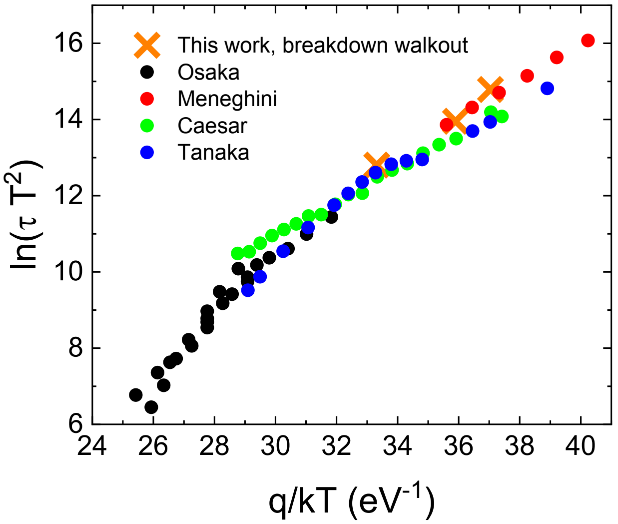

Figure 9. Arrhenius plot of the breakdown walkout process and comparison with deep level signatures from the literature. A correspondence is found with deep-levels related to carbon at nitrogen site

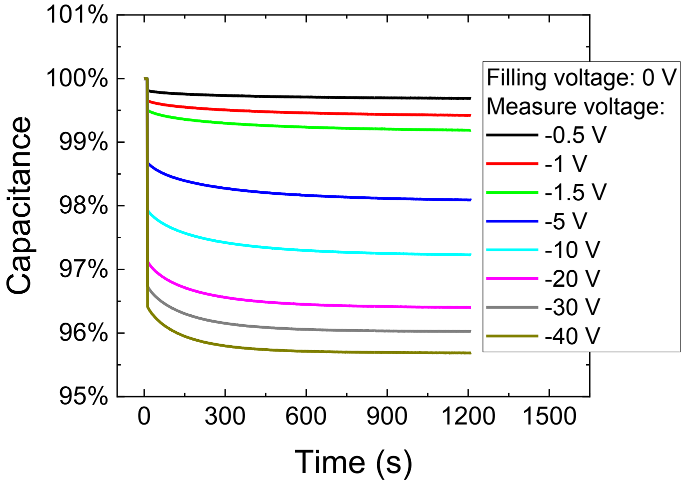

Figure 10. C-DLTS tests at different measure voltage. The results indicate the presence of the deep level in the whole analyzed volume

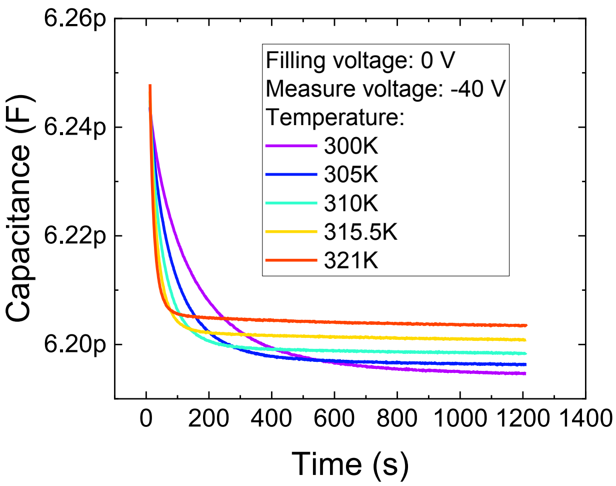

Figure 11. C-DLTS tests at various temperatures. Slow de-trapping processes are dound to take place after exposure to negative bias

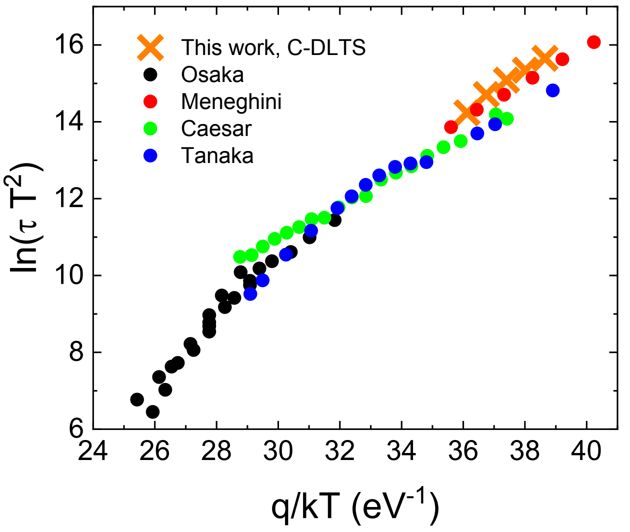

Figure 12. Activation energy of the detected deep level and comparison with deep level signatures from the literature.