# IDENTIFICATION OF ELECTRICALLY ACTIVE DEFECTS IN MODERN STRUCTURES BASED ON GALLIUM NITRIDE

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**Abstract:** *A compound semiconductor Gallium Nitride (GaN) is an ideal for high power and high-frequency applications since it is suitable to create the well-known two-dimensional gas. Nevertheless, even a minor concentration of electrically active defects is capable to decrease the quality of such semiconductors. An essential task in the continuous evolution of semiconductor structures based on modern compounds is the identification and detection of defect states. This contribution discusses the nature of defect states and describes the principles of the most frequently used defect characterisation method. A better understanding of the presence and the origin of defect states is a technical must, which is utilised to optimise and ensure a high-quality technological and fabrication process.*

**Keywords:** gallium nitride GaN, high electron mobility transistor HEMT, defect characterisation in semiconductors, high frequency and high-power structures.

## INTRODUCTION

In 1956 John Bardeen, Walter Houser Brattain a William Bradford Shockley were awarded the Nobel price of physics for the invention of the 20$^{th}$ century, the transistor [1]. That time nobody could forecast that this invention [2] will change the technical advances of our society to a level, that is capable to redefine the borders between fiction and reality. More intensive development in fields like electronics, micro and nanoelectronics and photonics made possible the debut of Silicon as the “king” of semiconductors. Todays need for higher quality, performance and effectivity with lower costs pushed Silicon to its physical borders, therefore new and new compounds are investigated as suitable replacements for example in the T = 200°C functional temperatures [3]. For instance, in case of a simple example such as mobile phones charged with 4.6 A and 20V, the current silicon technology does not allow the miniaturization in such a scale as needed; therefore new compounds for the new generation of switching structures need to be investigated [4, 5, 6]. GaN a wide bandgap, two-component semiconductor, and its desirable properties make this material a suitable candidate for high frequency and high-power applications (Fig. 1) [7]. Real benefits of GaN become visible in applications such as converters for electrical automobiles, portable batteries, and 5G networks. Improving efficiency of power electronic devices is crucial to reduce switching losses and lower the $CO_2$ emission. The world's total net electricity consumption as well as electricity generation is increasing day by day. It is predicted that it will double between years 2003 and 2030, from 14,781 billion kilowatt hours to 30,116 billion kilowatt hours, which is an average increase rate of 2.7% annually [8]. Electronic devices on GaN basis have the potential to reduce energy losses from 10% to 25% [9], therefore more effective as the silicon based ones. Another positive side of GaN is low or no dependency on high working temperatures and radiation hardness.

Although GaN probably will not entirely replace silicon in common applications, since Silicon is already widely used, technologies understood and mastered with a considerable high fabrication quality and low concentrations of defects.

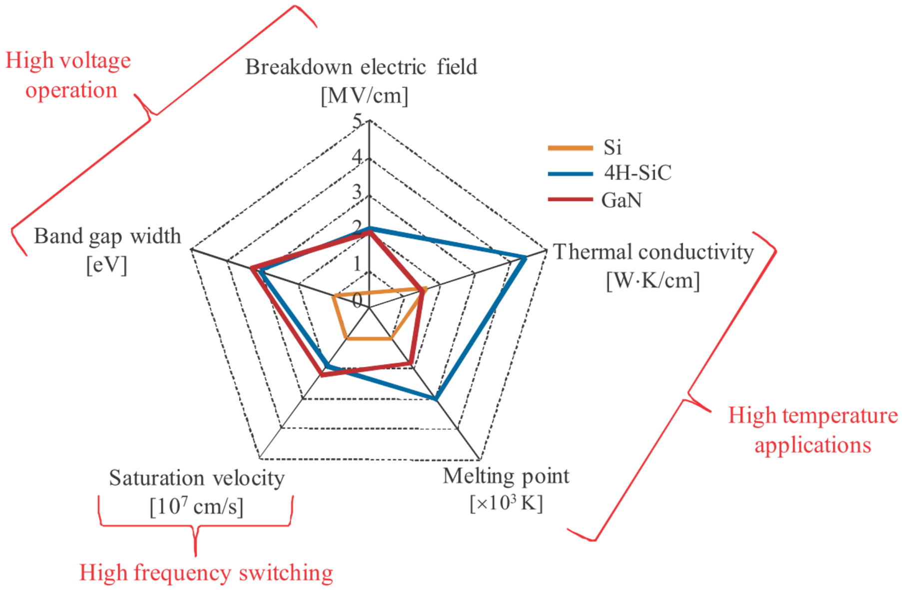


**Fig. 1.** Diagram of GaN, 4H-SiC and Si properties by field of application
Source [10].

The aim of this contribution is to describe defect states of GaN by the most frequently used characterization tool, the Deep Level Transient Spectroscopy method. The article tends to evaluate actual structures developed and fabricated for 5G networks and to discuss possible effects of defect states on this material and application.

## 1. GALLIUM NITRIDE IN THE SEMICONDUCTOR INDUSTRY

The single crystal of gallium nitride first saw the light a day in 1969, when two scientists Maruska and Tietjen in the United States were able to grow it on a sapphire substrate [11]. Despite this first promising result, there was a great disappointment, because scientists were unable to find a suitable method for P-type doping. However, a significant historical breakthrough in the research and development of gallium nitride occurred two decades later in 1989 when a Japanese scientific team headed by Professor Isamu Akasaki of Nagoya University succeeded in producing the first gallium nitride diode with a PN junction. This success was transferred towards the development of a white electroluminescent diode, which is still an essential element of all LCDs.

Nowadays GaN has found applications in almost every area of the semiconductor industry, and without GaN-based elements we cannot imagine devices such as mobile phones, radars, traffic lights, large-screen displays, and others [12]. Despite this significant test, the research of this material is still progressing and all leading research centres tend to better understand this unique material and improve the fabrication quality [13, 14, 15]. Among the worlds recognised workplaces, the Institute of Electronics and Photonics of the FEI STU in Bratislava is also included, an excellent example of this is the visit of Prof. Hiros Amman, Nobel Prize winner for GaN diodes (Fig. 2).

**Fig. 2.** Nobel price winner for blue LED Hirosi Amano (second from left) on his visit at our university (the Institute of Electronics and Photonics), September 19th, 2018.
Source: own

## 2. DEFECTS IN SEMICONDUCTORS

A material defect is a disruption of the ideal regular arrangement of atoms in the semiconductor crystal. In many cases, it is only a non-active structural fault; however, in others it can also have a significant influence on electrical properties. While an ideal semiconductor can be described by energy bands separated by the forbidden gap, the presence of an electrically active defect is able to create an energy level precisely in this gap. These extra levels can capture electrons and hold them for a long period of time, hence defects are often referred to as traps. Typical examples of defect states are admixture atoms, excess atoms in the lattice (interstitials), missing atoms in the crystalline lattice (vacancies), or alignment disorders (dislocations) [16, 17]. A real semiconductor compound can contain traps of various origins, mostly created by unintentional contamination during crystal growth or further processing [18].

In order to understand the generation of defects in semiconductor structures, the diagnostics of semiconductor materials must be an integral part of the research activity. Emphasis is placed mainly on processes that can induce individual defect states and the impact of these on the properties of final semiconductor structures. Due to their properties like automation, availability, sensitivity, non-destructive character, capacitance and current measurement methods are ranked among the most important processes of semiconductor material diagnostics. The principle of the given measurement methods is based on the monitoring of charge changes in the depletion region.

One of the classical methods of characterization is Deep Level Transient Spectroscopy (DLTS) [19]. This method is based on sensing the capacity changes after applying a voltage pulse on the investigated structure. The method follows the relaxation of the system to its original state, which is strongly influenced by the trapping of charges as well as their leakage. The obtained capacitive responses are used to construct Arrhenius dependencies, from which we can determine the basic parameters of traps: activation energy and trapping cross-section. These parameters represent a unique picture of the defect state and can serve as a fingerprint to identify the origin of the defect state.

## 3 TRANSISTORS WITH HIGH ELECTRON MOBILITY

High Electron Mobility Transistors (HEMTs) of the AlGaN/GaN compound has attracted considerable attention, due to its beneficial properties in 5G networks, high power and high frequency applications [18, 20]. This favourable feature is ensured by the presence of the 2 Dimensional Gas 2DEG in the structure, which is formed between the two different bandgap layers, hence at the interface of AlGaN and GaN. 2DEG forms with a high density, over $1\times10^{13}$ $cm^{-2}$, originating from spontaneous and piezoelectric polarization fields as well as from the large conduction band offset, and the electron saturation velocity as high as $2\times10^{7}$ cm/s. The ultimate goal of the actual research is to increase the effectivity of HEMTs in the gigahertz range and at the same time to reduce fabrication costs [21].

One of the important problems of GaN HEMTs is heat dissipation, which is generated by the current flow. The newest substrate suitable for GaN is considered to be silicon carbide SiC, which provides the needed heat transfer and electrical properties. A more advanced investigation showed that the temperature conductivity could be increased by up to 30% by the addition of epitaxially grown isotopic clean SIC layer ($^{28}Si$ + $^{12}C$) isotopes) on the top of the substrate [20]. Nevertheless, heat conduction depends on many other factors such as the presence of defect states such as dislocations in the active region of the transistor [10]. The mismatch between the crystal grid (3.5%) of SiC and GaN also induces mechanical stress that can be compensated, e.g. by an AlN thin layer.

Another issue is the leakage current through the SiC substrate. By this phenomenon, the current flows not int the emitter as it should be, rather through the substrate. This unwanted behaviour can be corrected by additional AlGaN/GaN layers acting as a potential barrier for the leakage current. In addition, this structural setup has beneficial effects on mechanical stress [22].

Reducing production costs is a major challenge in current GaN research. Without finding solutions, mass production and greater commercial application of these structures are not possible. In this respect, it is necessary to replace the expensive SiC semi-insulating substrate with cheaper ones, such as N doped SiC. This material is already widely used in power and LED industries where the thin semi-insulating SiC layer is epitaxially grown [23].

All the above-mentioned technological steps of fabrication are capable of generating electrically active defect states, thereby have a limiting effect on the electrical properties and the quality of the final structures.

## 4 ILLUSTRATION OF DEFECT IDENTIFICATION

To illustrate the identification and measurement of electrically active defect states in GaN three test samples A, B, C are examined. The structures were prepared by MOCVD Metalorganic vapour-phase epitaxy in III-V Lab France. Fig. 3 shows the schematic view of these HEMT samples where the interfaces between AlGaN an GaN, hence the 2DEG is clearly visible. All the structures have minor differences; hence a qualitative comparison should be possible: Structure A as a standard referent structure only newest technological optimization used, while B and C were grown on an N type SiC substrate with a semi-insulating SiC layer on the top. This layer in the case of sample C was an isotopic clean SiC with additional AlGaN/GaN layers included. For all samples ohmic contacts were prepared by TiAlNiAu, and the gate electrode is from NiPtAu to provide a Schottky barrier.

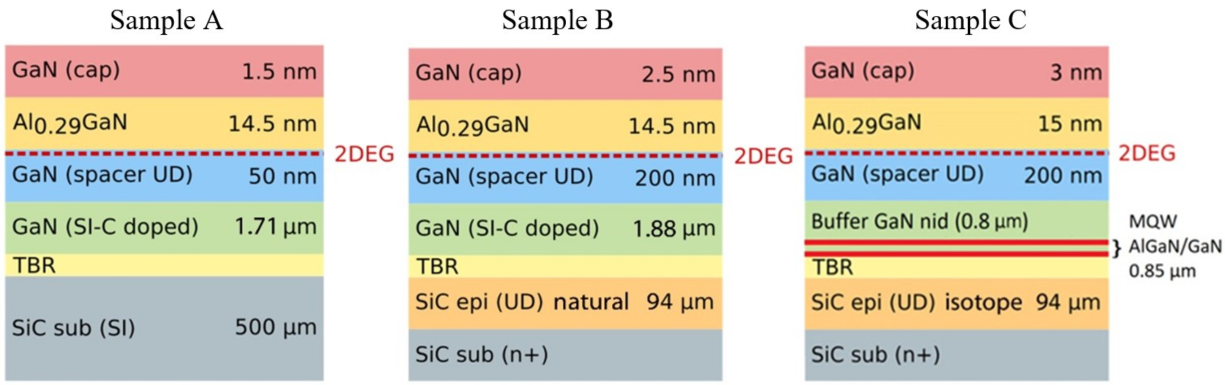


**Fig. 3.** Comparison of investigated HEMT structures.
Source: own

Firs electrical measurements are shown in Fig. 4. C-V and I-V characteristics of all 3 samples showed a quality technological process with low defect concentrations. Reproducibility of these measurements is high even after many cycles of measurements under voltage stress between temperatures 80K to 540K. None of these had effect on electrical properties such as threshold voltage, leakage current, or the quality of the Schottky gate contact that performs the rectifying function. The most visible character of the curves can be observed for sample C where the leakage current was significantly lower. This result can be contributed to the already discussed addition of AlGaN/GaN.

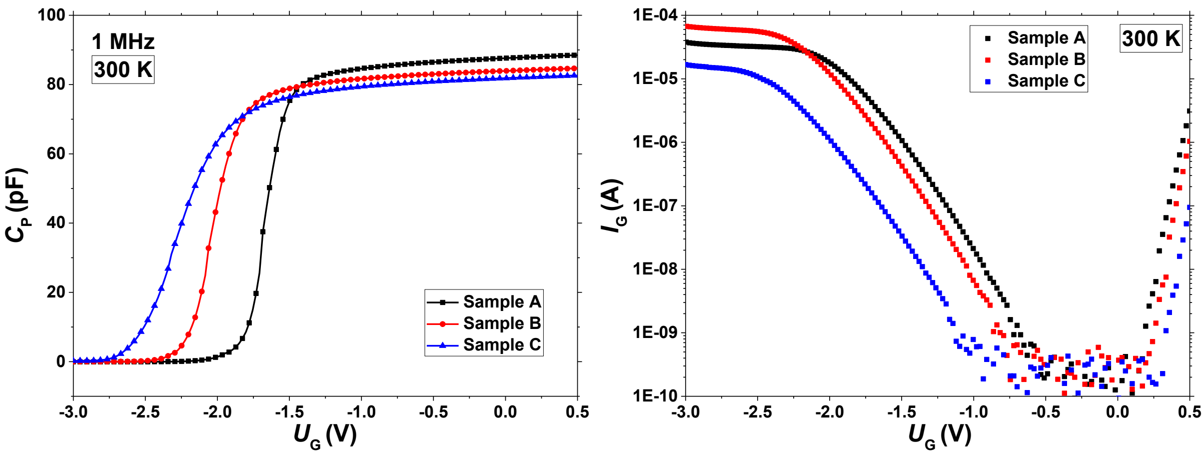


**Fig. 4.** Comparison of C-V a I-V characteristics of GaN/AlGaN/GaN/SiC HEMT structures
Source: own

C-V and I-V characteristics are important to define the input parameters of the DLTS method: reverse voltage $U_R$, filing voltage $U_P$, period width $T_w$, and filling pulse width $t_P$. To be able to evaluate these samples as much as possible, a wide variety and many sets of DLTS measurements were needed to be carried out, to scan the whole sample and retrieve spectra for a reliable evaluation (Fig. 5). Eleven deep energy levels were identified based on Arrhenius curves, which were calculated by the obtained spectra (Fig. 6), and output trap parameters were compared with literature [18, 24, 25].

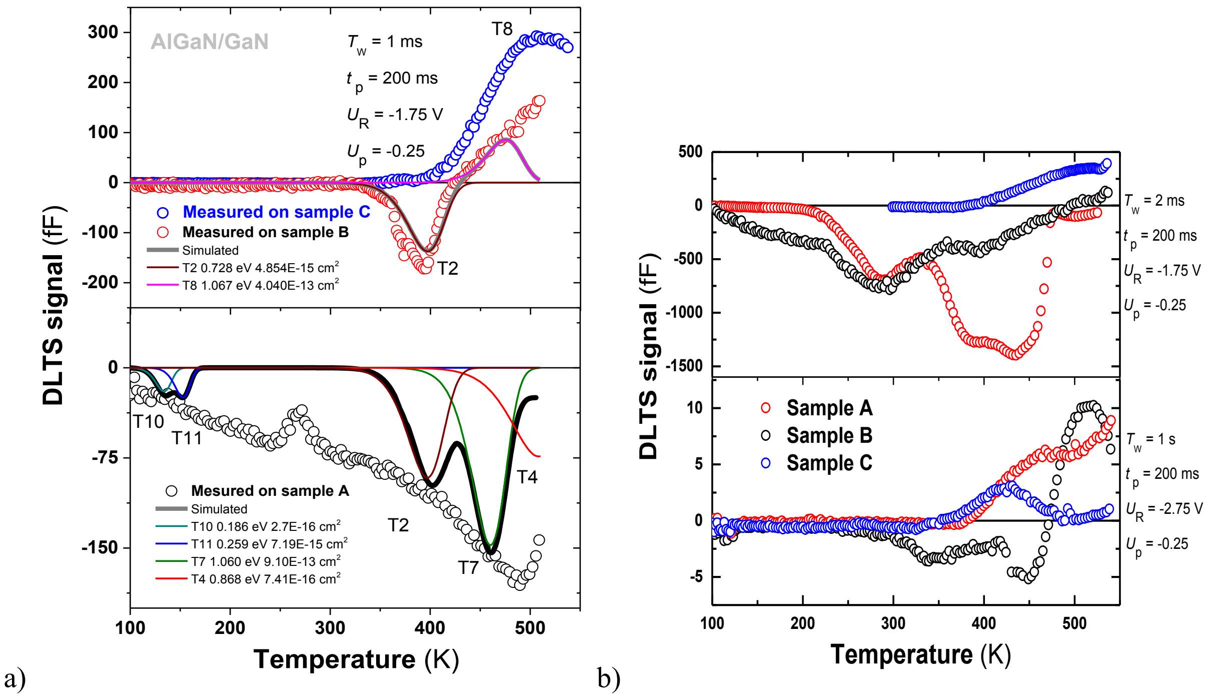


**Fig. 5.** a) DLTS spectrums with simulated defect states A and C, b) DLTS spectrums of A, B and C samples at various measurement conditions (reverse voltage $U_R$, filing voltage $U_P$, period width $T_w$ and filling pulse width $t_P$)
Source: own

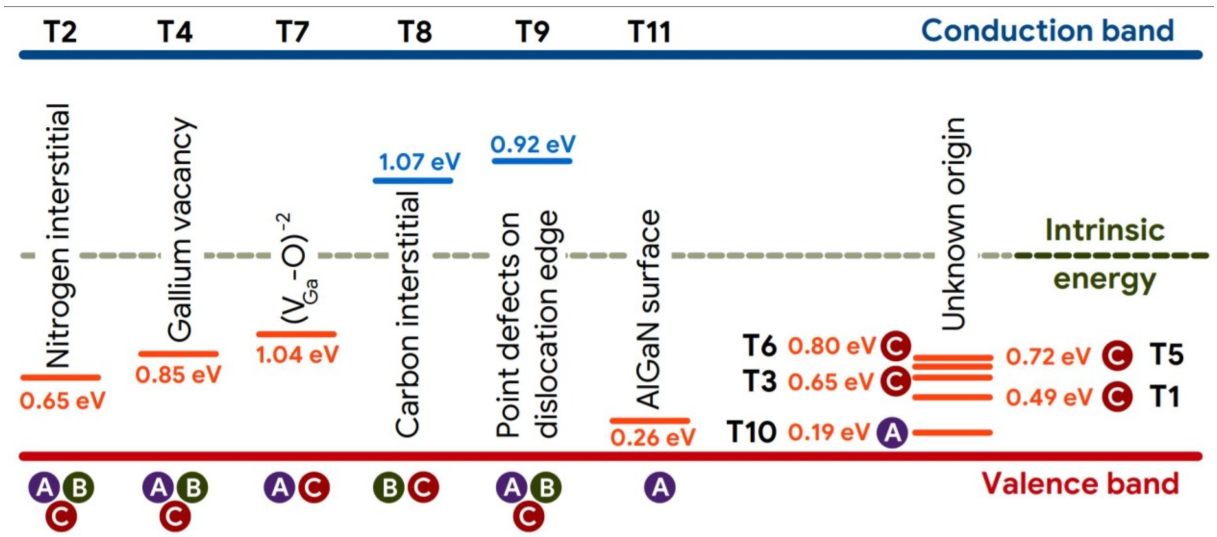


**Fig. 6.** Deep energy levels in GaN/AlGaN/GaN/SiC HEMT structures with activation energies and possible origins.
Source: own

Fig. 5a shows the measured DLTS spectra of samples A and B with defect simulations. Each maximum or spectrum peak indicates the presence of a defect state. Fig. 5b shows the comparison of all samples at matching experimental conditions, while in Fig. 6 all identified defects states were assessed in the band diagram.

As shown, the forbidden gap indicates many deep energy levels. Three of these were found in all samples: nitrogen interstitial (nitrogen atoms outside of the ideal crystal grid), gallium vacancy (gallium atoms are not occupying their ideal state leaving empty locations) and point defects on the edge of dislocation (complex defect state in a form of disarrangement of atoms in the crystal grid). The identified defect states are native, hence they are typical for GaN. The concentration can be reduced by the growth process optimisation.

### 4.1 Assessment of results

The provided samples of GaN/AlGaN/GaN/SiC HEMT structures were evaluated by C-V, I-V and the DLTS method. The results indicated sample C shows the most suitable properties, where the AlGaN/GaN barrier and the isotopic substrate significantly improved the characteristics. Despite such a huge structural change, no significant degradation was identified, and the characteristics stayed intact even after temperature and voltage stress measurements.

## CONCLUSION

Progress of humankind depends on continuous evolution of technology and the improvement of the quality of life. In recent decades, silicon-based structures have improved their efficiency, increased speed and have been miniaturized to their physical limits. However, to advance, new materials that are capable to open new possibilities and solve previously unknown problems need to be investigated. The potential of gallium nitride to save 10 to 25% of energy consumption provides sustainability for years to come, and it is, in fact, the future of electronics. Therefore, it is necessary to raise public awareness of new materials, progressive technologies, and to inspire the young generation to be actively involved in science and research.

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