Conference materials
UDC 621.315.592
DOI: https://doi.org/10.18721/JPM.183.151

Capacitance characterization of GaN/InP multilayer structures

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Abstract. This study investigates defect states in GaN/InP multilayer structures fabricated using plasma-enhanced atomic layer deposition (PEALD) for potential applications in high-efficiency multijunction solar cells. Deep-level transient spectroscopy (DLTS) and admittance spectroscopy were employed to characterize defects in the heterostructures. The DLTS spectra revealed a distinct peak in the temperature range of 230–300 K, corresponding to defect states with activation energies of 0.46–0.58 eV under various bias voltages (from 0 to +2 V and from −1 to 0 V). Admittance spectroscopy confirmed the presence of similar defects, demonstrating voltage-dependent activation energies in the range of 0.36–0.57 eV, which is likely associated with interface states at the GaN/InP interface.

Keywords: multilayer structures, defects, admittance spectroscopy, DLTS

Funding: The work was carried out with the support of the Russian Science Foundation (RSF) under grant No. 24-19-00150, https://rscf.ru/project/24-19-00150.

Citation: Mikhaylov O.P., Baranov A.I., Pozdeev V.A., Uvarov A.V., Maksimova A.A., Vyacheslavova E.A., Gudovskikh A.S., Capacitance characterization of GaN/InP multilayer structures, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 18 (3.1) (2025) 258–262. DOI: https://doi.org/10.18721/JPM.183.151

Материалы конференции
УДК 621.315.592
DOI: https://doi.org/10.18721/JPM.183.151

Исследование емкостных характеристик многослойных структур GaN/InP

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Аннотация. В данной работе изучены дефектные состояния в многослойных структурах GaN/InP, выращенных методами плазмохимического атомно-слоевого осаждения (PEALD), для потенциального применения в высокоэффективных многопереходных солнечных элементах. Для характеризации дефектов в гетероструктурах использовались методы нестационарной спектроскопии глубоких уровней (DLTS) и спектроскопии полной проводимости. Спектры DLTS показали четко выраженный пик в температурном диапазоне 230–300 K, соответствующий дефектным состояниям с энергиями активации

0,46–0,58 эВ при различных напряжениях смещения (от 0 до +2 В и от –1 до 0 В). Спектроскопия полной проводимости подтвердила наличие аналогичных дефектов, продемонстрировав зависимость энергии активации от приложенного напряжения в диапазоне 0,36–0,57 эВ, вероятно, связанных с поверхностными состояниями на границе раздела GaN/InP.

Ключевые слова: многослойные структуры, дефекты, спектроскопия полной проводимости, нестационарная спектроскопия глубоких уровней

Финансирование: Работа была выполнена при поддержке Российского научного фонда (РНФ) в рамках гранта № 24-19-00150, https://rscf.ru/project/24-19-00150.

Ссылка при цитировании: Михайлов О.П., Баранов А.И., Поздеев В.А., Уваров А.В., Максимова А.А., Вячеславова Е.А., Гудовских А.С. Исследование емкостных характеристик многослойных структур GaN/InP // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.1. С. 258–262. DOI: https://doi.org/10.18721/JPM.183.151

Introduction

In the modern world, there is a shift toward renewable energy sources, which has been particularly active since 2020, after which the cost of electricity has significantly increased. Today, single-junction solar cells (SCs) based on an anisotype heterojunction of hydrogenated amorphous and crystalline silicon (a-Si:H/c-Si) demonstrate the most popular in terms of efficiency and economic benefits. However, such structures have practically reached its maximum theoretical efficiency due to fundamental reasons [1]. The most significant limitation on the maximum achievable efficiency of single-junction solar cells is the thermalization loss of charge carriers, where the excess photon energy transferred to the generated charge carriers is dissipated as lattice vibrations. Consequently, researchers have recently been exploring alternative approaches to enhance efficiency, with multi-junction solar cells with active layers of III-V semiconductors in top subcells emerging as a promising solution [2–3]. However, the selection of top-junction materials must satisfy energy balance requirements, where the optimal bandgap should fall within the 1.7–1.8 eV range [4]. Therefore, selecting appropriate materials presents a significant challenge. Additionally, lattice constant mismatch must be considered as it can significantly degrade the quality of the top-junction material [5]. Layers of short-period superlattices of GaN/InP is promising candidate for these challenges since its bandgap can be precise tuned, and strain-induced elastic deformations can be compensated by lattice mismatch. Most studies in this field is devoted to exploration of III-V alloys grown by molecular beam epitaxy (MBE) [6]. For mass production, however, this approach is prohibitively expensive and complex. Therefore, we fabricate these structures using plasma-enhanced chemical deposition (PECVD) as for amorphous silicon. The resulting samples were then characterized for defects using deep-level transient spectroscopy (DLTS) and admittance spectroscopy.

Materials and Methods

InP and GaN layers were deposited using plasma-enhanced atomic layer deposition (PEALD) on *n*-type monocrystalline Si (100) substrates. Prior to deposition, the Si substrates were treated with a 10% HF/H_2O solution to remove the native oxide. The growth program consisted of 5 repetitions of 60-cycle InP (6 nm) and 20-cycle GaN (3 nm) depositions. The deposition process was carried out in an Oxford Plasmalab System 100 PECVD reactor at a pressure of 350 mTorr, temperature of 380 °C, and P = 200 W. Further, DLTS measurements were performed for the obtained structures. DLTS is a capacitance-based method for investigating defect properties in semiconductors, which relies on analyzing capacitance relaxation in response to changes in applied bias voltage. Measurements of capacitance DLTS were performed using an automated installation based on a Boonton-7200B capacitance bridge in the temperature

range of 80–360 K in a Janis VPF-100 nitrogen vacuum cryostat. Admittance spectroscopy measurements were also performed. This technique involves temperature scanning of the sample while continuously measuring its capacitance and conductance at multiple frequencies.

Results and Discussion

In the DLTS spectra in Figure 1, obtained under positive (0 to +2 V) and negative (–1 to 0 V) biases, a characteristic peak is observed in the temperature range of 230–300 K, corresponding to a defect with an activation energy of 0.46–0.58 eV.

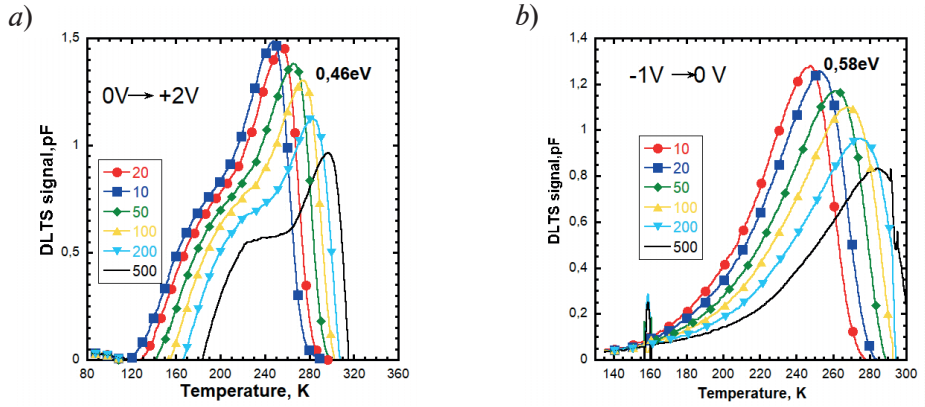

Fig. 1. DLTS signal graphs for the studied samples at (*a*) Vinit = 0 V, Vpulse = +2 V and (*b*) Vinit = –1 V, Vpulse = +1 V for emission rate of 10–500 s^{-1}

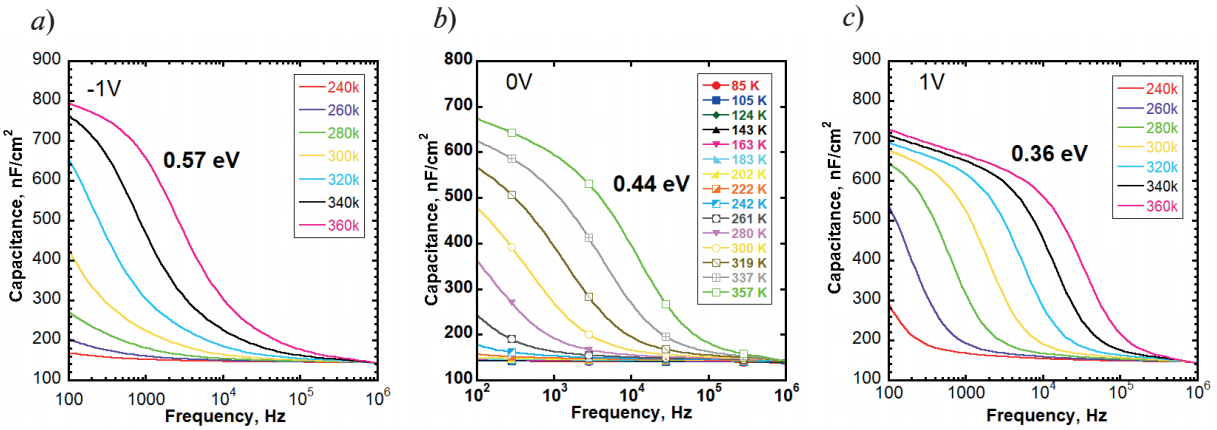

Fig. 2. The C-t plot for the studied sample under different bias voltages

The observed dependence of activation energy on bias voltage in GaN/InP superlattices clearly indicates the presence of interface states at the GaN/InP heterointerface, where the applied bias voltage modifies the potential barrier at the heterojunction through band bending.

Figure 3 shows the band diagram of the studied structure under different applied voltages, obtained using the A-force software. The data used is specified in Table. In Fig. 3, *a*, the applied voltage is 0 V, while Fig. 3, *b* displays the band diagram at –1 V. It is clearly visible that the applied bias voltage leads to band bending and an increase in the activation energy (the distance from the Fermi level to the conduction band, indicated by the arrow on the graph).

Table

Parameters used for obtaining the band diagrams

	InP	GaN	Si
Eg, eV	1.34	3.39	1.12
χ, eV	4.4	4.1	4.05

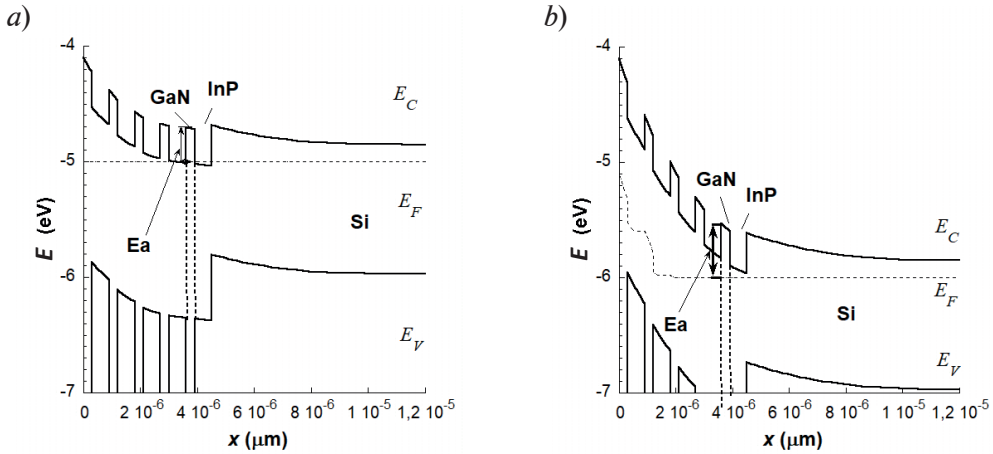

Fig. 3. Schematic view of the simulated band diagram for the GaN/InP superlattice structure at voltages of: 0 V (*a*) and −1 V(*b*)

Conclusion

The observed dependence of defect activation energies (0.36–0.58 eV) on applied bias voltage in GaN/InP heterostructures unequivocally indicates that the primary defect states are localized at the interface, where the activation energy is modulated by external voltage through band bending effects. These results highlight the critical importance of interface engineering, including optimization of growth conditions.

Acknowledgments

The work was supported by the Russian Science Foundation (RSF) under grant No. 24-19-00150, https://rscf.ru/project/24-19-00150/.

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Received 11.08.2025. Approved after reviewing 15.09.2025. Accepted 22.09.2025.