Physics of the Solid State, 2025, Vol. 67, No. 12

08

Optical and photoelectric properties of multilayer GaN|InP structures formed by plasma chemical atomic layer deposition

© E.Ya. Yarchuk[1,2], A.V. Uvarov[2], A.A. Maksimova[1,2], A.S. Gudovskikh[2]

[1] St. Petersburg State Electrotechnical University „LETI“,
St. Petersburg, Russia
[2] St. Petersburg Academic University named after J.I. Alferov, Russian Academy of Sciences,
St. Petersburg, Russia

E-mail: ernst_yarchuk@mail.ru

Received April 30, 2025
Revised September 8, 2025
Accepted November 11, 2025

The results of a study of the possibility of using lattice-matched multilayer GaN|InP compositions with a silicon substrate to form an upper transition by plasmochemical atomic layer deposition are presented. Temperature dependences of dark conductivity and photoconductivity were obtained during studies, which made it possible to evaluate the photoelectric properties of films based on GaN|InP superlattices, as well as individual InP and GaN layers. The values of photoconductivity activation energies for GaN|InP structures in the range 0.17−0.25 eV and for individual InP and GaN layers — 0.1 and 0.4 eV, respectively, are obtained.

Keywords: solar energy, indium phosphide, gallium nitride, photoconductivity, activation energy.

DOI: 10.61011/PSS.2025.12.63098.8024k-25

1. Introduction

With the increasing demand for renewable energy sources, solar energy is becoming one of the main areas of modern science. The desire to increase the efficiency of converting solar radiation into electric current stimulates the development of materials with optimal photovoltaic characteristics and their combination in the creation of solar cells.

At the same time, the complexity of introducing solar cells into various functional structures is increasing: increased demands are placed on the strength, durability and economic efficiency of materials. Although classical silicon solar cells remain technologically mature and commercially available, their practical efficiency limit is only about 26 % [1].

The possibility of using lattice-matched multilayer GaN|InP compositions with a silicon substrate to form the upper junction of tandem solar cells is studied in this paper.

2. Experiment

The use of binary compounds of gallium nitride and indium phosphide with oppositely different crystal lattice constants relative to the silicon substrate makes it possible to compensate for elastic stresses. This approach has been successfully applied to control the absorption edge of one of the transitions of tandem structures [2]. Variation of the thickness of the InP quantum wells will allow achieving the required effective band gap width for the upper transition (1.7−1.8 eV) [3]. To form short-period GaN|InP superlattices with sharp interfaces and low background doping, plasma chemical atomic layer deposition was applied at a temperature of 380°C. GaN and InP layers were formed using this method on quartz substrates to study the optical and electrical properties. In the multi-layered GaN|InP structures, the thickness of the GaN and InP layers ranged from 0.3 to 3 nm and from 0.6 to 6 nm [4], respectively, see the table below.

The structural properties were studied using Raman spectroscopy using an EnSpectr R532 spectrometer with a laser operating at a wavelength of 532 nm. The obtained Raman spectra are shown in Figure 1.

With the growth of GaN|InP superlattices on quartz, the crystal structure of InP layers, varying from 0.6 to 6 nm, is preserved, as evidenced by Raman spectra. Clear lines of the TO and LO InP modes are observed in the Raman spectra. In this case, the position of the peaks of

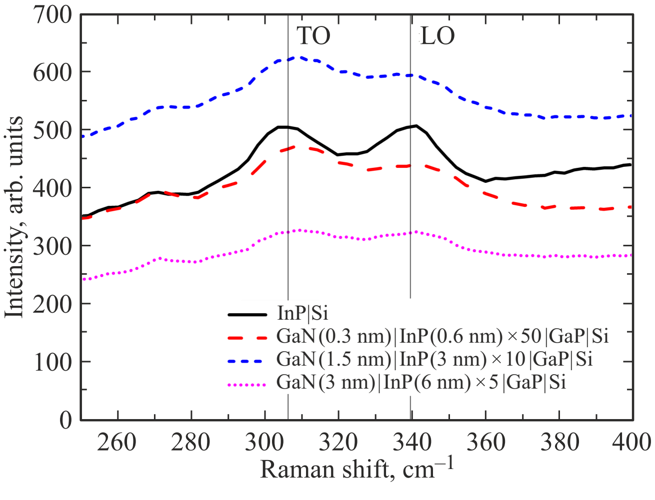

Figure 1. Raman spectra.

Relation of layer thicknesses and activation energy

Structure	E_a for σ_{ph}, eV	E_a for σ_d, eV
InP (60 nm) | Si	0.1	0.15
GaN (60 nm) | Si	0.4	0.5
GaN (0.3 nm) | InP (0.6 nm) ×50 cycles	0.17	0.42
GaN (1.5 nm) | InP (3 nm) ×10 cycles	0.22	0.54
GaN (3 nm) | InP (6 nm) ×5 cycles	0.25	0.45

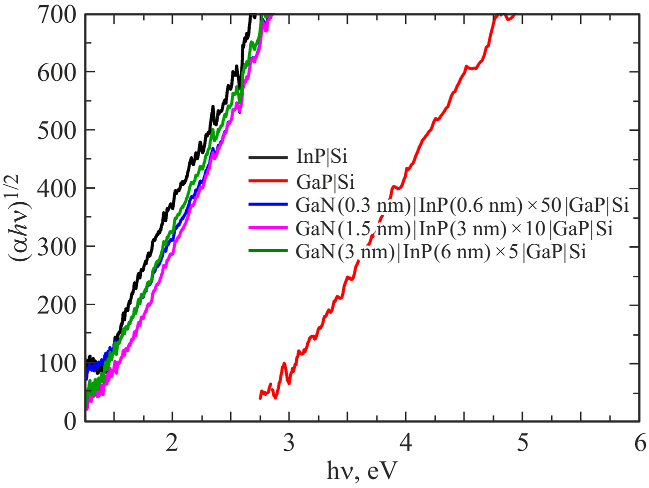

Figure 2. Determination of the absorption edge for the studied samples.

the TO and LO InP modes shifts to the short-wavelength region with a decrease in the thickness of the InP layers. The characteristic peak of GaN E_2 (567–568 cm^{-1}) is not observed in the Raman spectra of GaN|InP superlattices. However, this peak is not observed for a separate GaN layer, which, according to X-ray diffractometry, has a polycrystalline wurtzite structure.

The optical properties of the layers were studied by measuring the transmission and reflection spectra of layers deposited on quartz substrates in the wavelength range 400–1200 nm, and the absorption coefficient spectra were determined. From the absorption coefficient spectra, the absorption edge was determined using the Tautz method [5] for straight-band semiconductors, which corresponds to the energies of 1.3–1.35 eV for GaN|InP superlattices, Figure 2.

To study the photovoltaic properties on the surface of InP and GaN layers, as well as multilayer GaN|InP structures, silver contacts were applied by thermal vacuum spraying through a free mask.

3. Results and their discussion

In the course of the study, the temperature dependences of the specific photoconductivity and the specific dark conductivity were obtained using data on the thickness of the layers, the geometry of the electrodes and the distance between them, Figure 3. This made it possible to evaluate the photoelectric properties of the films based on these structures. The photoconductivity was measured when illuminated by a halogen lamp. It should be noted that for multilayer GaN|InP structures, the number of periods increases with decreasing layer thicknesses, so that the total thickness of GaN and InP remains approximately the same.

The dark conductivity of GaN|InP structures, as well as polycrystalline InP and GaN layers, demonstrates an exponential dependence on the reverse temperature. The obtained values of the activation energies (E_a) of photoconductivity (σ_{ph}) and dark conductivity (σ_d are shown in the table.

The GaN layers have the highest activation energy when illuminated by 0.4 eV. For multilayer GaN|InP structures, the activation energy under illumination is significantly lower than that of the dark one, and its value decreases with decreasing thicknesses of the GaN and InP layers from 0.25 to 0.17 eV. For individual InP layers, the lowest activation energy is observed at 0.1 eV illumination. In the absence of illumination, similar values are observed for all structures with GaN layers, while the InP structure exhibits significantly lower activation energy, only slightly higher than it has when illuminated. The absolute values of photoconductivity of polycrystalline wide-band GaN layers are significantly lower compared to InP layers, and multilayer GaN|InP structures occupy an intermediate value. Moreover, there is a non-monotonic dependence of the conductivity on the thickness of the GaN|InP layers, which was reproduced by repeated measurements on structures with different contact configurations. Structures with a minimum thickness of GaN|InP (0.3|0.6 nm) have the highest conductivity. With an increase in the thickness of the GaN|InP layers to 1.5|3 nm, a sharp decrease in conductivity is observed, and with a further increase in the thickness of the GaN|InP layers to 3/6 nm, the conductivity increases again. A similar dependence on the thickness of the GaN|InP layers is demonstrated by the specific dark conductivity of multilayer structures, Figure 3, *b*.

All this suggests that an increase in the dark and photoconductivity of GaN|InP structures is associated with an increase in mobility. Microcrystalline InP layers have a sufficiently high mobility value [6], which leads to high values of conductivity. If multilayer GaN|InP structures are considered as a set of independent layers, it can be assumed that for structures with relatively thick layers

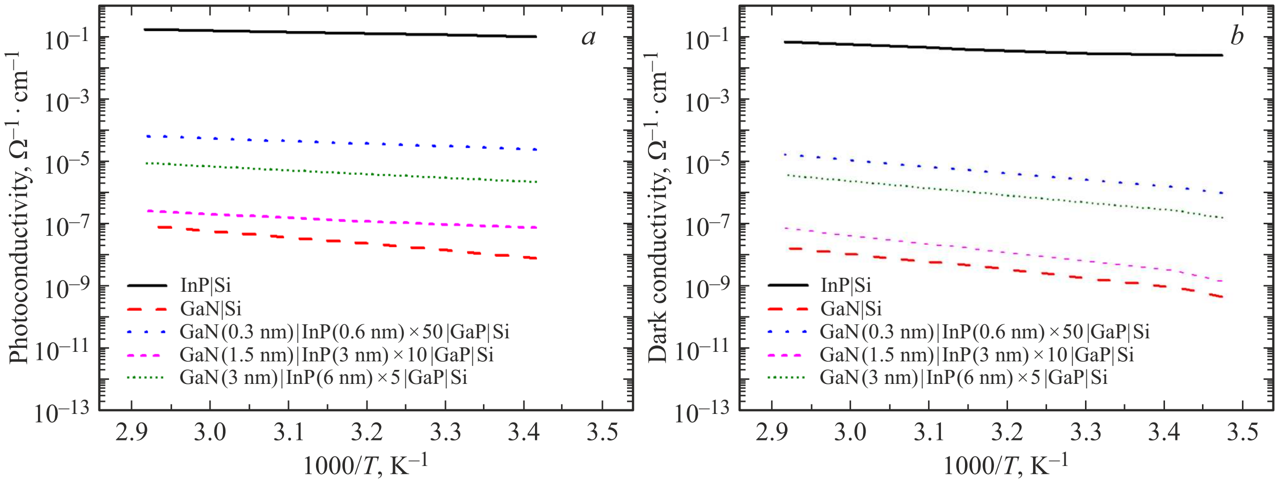

Figure 3. *a*) Specific photoconductivity and *b*) specific dark conductivity of the studied samples.

of GaN (1.5–3 nm) and InP (3–6 nm), carrier transport occurs through nanocrystalline InP layers. The size of InP nanocrystals in a multilayer structure, determined by the period of the superlattice, decreases with decreasing period. For InP layers with a smaller nanocrystal size, lower mobility values are expected due to the increasing influence of grain boundaries. Thus, the observed decrease in dark and photoconductivity with a change in the layer thickness InP from 6 to 3 nm may be due to the increasing influence of grain boundaries.

However, the structure with 0.3|0.6 nm thick GaN|InP layers exhibits greater dark and photoconductivity. This fact suggests that the structural properties of this structure are significantly changing. Such a superlattice can no longer be considered as a set of independent GaN and InP layers, but as a polycrystalline structure for which crystalline properties are preserved in the vertical direction. Preliminary studies using X-ray diffractometry confirm this assumption. For the GaN|InP structure with thicknesses of 0.3|0.6 nm grown on a silicon substrate, a preferential orientation is observed, in contrast to structures with a long period. Presumably, as the thickness of the GaN layers increases, its amorphization occurs, and in this case the superlattice is an alternating set of InP nanocrystalline layers separated by amorphous GaN layers. Transport is determined only by nanocrystalline InP layers, as described above. In the case of very thin barrier layers of GaN (0.3 nm), the GaN|InP superlattice is a layer homogeneous in structural properties. Obviously, further analysis requires more detailed studies of the structural properties using transmission electron microscopy (TEM). We only note that the preliminary TEM results for structures grown on a silicon substrate confirm the assumptions made.

4. Conclusion

It is shown that for GaN|InP superlattices, the photoelectric properties have a clear dependence on the thickness of the periodic layers. If the thickness of the layers decreases below the critical value, a significant increase in photoconductivity is possible. The change in photovoltaic properties is apparently related to a change in the structural properties of the GaN barrier layers. This fact must be taken into account when further developing the technology for forming GaN|InP superlattices.

Funding

The research was carried out at the expense of a grant from the Russian Science Foundation No.24-19-00150.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] M.A. Green, Y. Hishikawa, E.D. Dunlop, D.H. Levi, J. Hohl-Ebinger, M. Yoshita, A.W.Y. Ho-Baillie. Progr. Photovoltaics: Res. Appl. **27**, *1*, 3 (2019). https://doi.org/10.1002/pip.3102

[2] N.J. Ekins-Daukes, J. Adams, I.M. Ballard, K.W.J. Barnham, B. Browne, J.P. Connolly, T. Tibbits, G. Hill, J.S. Roberts. Proc. SPIE 7211, Physics and Simulation of Optoelectronic Devices XVII, 72110L (24 February 2009). https://doi.org/10.1117/12.816946

[3] A.I. Baranov, A.V. Uvarov, A.A. Maksimova, E.A. Vyacheslavova, N.A. Kalyuzhnyy, S.A. Mintairov, R.A. Salii, G.E. Yakovlev, V.I. Zubkov, A.S. Gudovskikh. Tech. Phys. Lett. **49**, *3*, 52 (2023)

[4] A.I. Baranov, J.P. Kleider, A.S. Gudovskikh, A. Darga, E.V. Nikitina, A.Yu. Egorov. J. Phys.: Conf. Ser. **741**, 012077 (2016). https://doi.org/10.1088/1742-6596/741/1/012077

[5] J. Tauc, R. Grigorovici, A. Vancu. Physica Status Solidi b **15**, *2*, 627 (1966). https://doi.org/10.1002/pssb.19660150224

[6] A.S. Gudovskikh, A.V. Uvarov, A.I. Baranov, E.A. Vyacheslavova, A.A. Maksimova, D.A. Kirilenko. FTP **57**, *6*, 406 (2023). https://doi.org/10.61011/FTP.2023.06.56466.22k

Translated by A.Akhtyamov