JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. **18** No 4, 04031(7pp) (2026)

ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том **18** № 4, 04031(7cc) (2026)

OPEN ACCESS

REGULAR ARTICLE

Research of Dynamic Characteristics of LEDs by the Small Disturbance Method

V.A. Andriychuk* ✉, L.M. Kostyk, Y.O. Filiuk, M.S. Nakonechnyi, Y.M. Osadtsa

Ternopil Ivan Puluj National Technical University, 46005 Ternopil, Ukraine

(Received 29 May 2026; revised manuscript received 14 August 2026; published online 21 August 2026)

The introduction of LED light sources, which has led to significant energy savings, requires energy-saving power sources. The main attention of LED driver developers is paid to the search for pulsed sources, the work of which is based on the results of studies of dynamic processes occurring in the LED structure itself. To study the influence of current pulses on the electrophysical parameters of LEDs, the small perturbation method was used in this work. The results of measurements of the differential resistance and capacitance of LEDs for various stationary states are presented. They are the main quantities that control transient processes in electrical circuits and play an important role in the development of pulsed power sources. It is shown that the increase and decrease of the injection current and the light flux are well described by an exponential dependence, and the time constant of the kinetics of the light flux is much greater than the current, which is associated with the lifetime of the donor-acceptor pairs. It was established that at a forward bias voltage of ≥ 2.65 V and a pulse frequency of 1 kHz, the reactive component associated with the capacitance of the LED disappears in the relaxation current, which makes it an active energy consumer. Based on the results of the study of the kinetics of the light flux, the maximum pulse frequency of the LED driver was determined to be 100 kHz.

Keywords: LEDs, InGaN-GaN, Current-voltage characteristics, Dynamic characteristics, Diffuse and negative capacitance, Small disturbance.

DOI: 10.21272/jnep.18(4).04031 PACS number: 78.60.Fi

1. INTRODUCTION

To study the influence of current pulses on the electrophysical parameters of the diode, this work uses the small perturbation method, which has found application in theoretical physics, namely in quantum mechanics when finding solutions to the Schrödinger equation [1]. Its use in electrical engineering is focused on studying the dynamic characteristics of the system, when it is fixed in a stationary state, and by applying a small perturbation, measurements of its parameters are made. The perturbing signal does not affect the stationary state, which allows measurements to be made at different points of the *I-V* characteristic. A small perturbation can be a rectangular current or voltage pulse, the fronts of which are analyzed in the time range, or a small oscillatory perturbation with a certain angular frequency ω with a change in the frequency range.

The small perturbation method allows measuring the differential resistance and capacitance of LEDs for different steady states. In [2], a method for measuring and calculating the electrical characteristics of quantum dot-based micro-LEDs under the action of a small AC direct voltage is considered. The authors calculate the differential resistance and capacitance from the circuit impedance. The presented results show the existence of negative capacitance at low frequencies and high voltages.

The method of small perturbations associated with the stationary state in measuring the lifetime of charge carrier recombination in halides perovskite devices was used in [3]. It was noted that the lifetime is affected by various additional device properties, such as multiple trapping effects and capacitive charging. An equivalent circuit was proposed and used to interpret the results.

In [4], a small-signal method is proposed for determining the carrier lifetime in solar cells. It is shown that intensity modulated photovoltage spectroscopy in the frequency domain of lifetime measurement does not describe the recombination dynamics, but is limited by the differential resistance of the diode and its capacitance.

In [5], for measuring the differential carrier lifetime in InGaN -based LEDs, the small perturbation was the optical excitation signal of the recombination centers. The results obtained based on the dynamics of the electrical and optical perturbations were very close, which indicates the possibility of using different perturbation signals.

In [6], an analytical model was proposed for interpreting the steady-state response and the response to small disturbances in both the time and frequency domains.

The purpose of this work was to theoretically substantiate the use of the small perturbation method in measuring the dynamic characteristics of LEDs and studying their behavior when changing the forward bias voltage, and to analyze electrophysical processes in the structure of LEDs when applying current pulses.

* Correspondence e-mail: andriychukva31410@gmail.com

Cite this article as: V.A. Andriychuk et al., *J. Nano- Electron. Phys.* 18 No 31, 04031 (2026) https://doi.org/10.21272/jnep.18(4).04031

2. THEORETICAL JUSTIFICATION OF THE SMALL PERTURBATION METHOD

At a given voltage V forward bias current will flow through the diode according to the Shockley equation:

$$I = I_S\left(e^{\frac{V}{mV_T}} - 1\right), \quad (1)$$

where I_S is the saturation current at a negative voltage on the diode V; $V_T = kT\ / q$ – thermal voltage, which at 300K is 26 mV; m – the ideality coefficient of the LED.

In such a steady state, the carrier concentration in the heterojunction shells according to Boltzmann statistics will be equal to:

$$N_C = N_s e^{\frac{V}{mV_T}}, \quad (2)$$

where N_c is the total carrier concentration in the shell region; N_s – carrier concentration at reverse voltage.

If a constant bias is applied to the LED, thus creating a homogeneous steady state, and then a small variable perturbation is applied $V_c = V_{c0} + v_c e^{j\omega t}$, then variable components are added to the steady state for all parameters:

$$I = I_0 + ie^{j\omega t}, N_c = N_{c0} + n_c e^{j\omega t}, N_w = N_{w0} + n_w e^{j\omega t}. \quad (3)$$

In this situation, the change in carrier density in the active region of the heterojunction:

$$\frac{dn}{dt} = G - R(n) - \frac{C_d}{qd}\frac{dV_c}{dt}, \quad (4)$$

here: G is the carrier injection rate, $R(n)$ is the rate of their recombination.

The last term of equation (4) takes into account the capacitive charge that appears in the active region when the heterojunction is forward biased and carriers are injected. This capacitance is associated with the diffusion of carriers in the active region, and in the literature it is called diffuse [2, 7]. Since we determine it at a specific point of the *I-V* characteristic by the weak perturbation method, it acts as a differential parameter of the LED. Thus, in the steady state $R(n) = G$ The alternating injection current caused by a small disturbance will be determined by the differential parameters of the operating point of the *I-V* characteristic, namely the differential resistance and differential capacitance. Let us consider the process of its decay after the step pulse of the disturbance voltage $G = 0$ is stopped:

$$\frac{dn(t)}{dt} = -R(n)\cdot n(t). \quad (5)$$

After integrating this expression, we get:

$$n(t) = n_0 e^{-Rt} = n_0 e^{-\frac{t}{\tau}}, \quad (6)$$

where $\tau = 1/R(n)$.

Whatever the function $R(n)$, which describes the rate of recombination of carriers, their decay will follow an exponential dependence. Constant decay, which is equal to the lifetime of carriers injected by a small perturbation at a selected point of the I-V characteristic, will be determined by:

$$\tau = \left(\frac{\partial R(n)}{\partial n}\right)^{-1}. \quad (7)$$

We will use the widely used empirical ABC model of recombination processes [5,7], in which the recombination rate is equal to:

$$R(n) = An + Bn^2 + Cn^3, \quad (8)$$

where A *is the* Shockley-Read-Hall recombination coefficient associated with defects in the crystal structure and, accordingly, with local energy levels in the band gap; B *is* radiative recombination coefficient; C is the coefficient associated with Auger recombination.

At such a low injection level, we will not take into account Auger recombination processes.

Differentiate equation (8) with respect to n:

$$\frac{\partial R(n)}{\partial n} = A + 2Bn. \quad (9)$$

Considering that the recombination time constant τ is inversely proportional to the rate of recombination processes, from equations (7) and (9) we obtain:

$$\frac{1}{\tau} = \left(\frac{1}{\tau_{br}} + \frac{1}{\tau_r}\right), \quad (10)$$

where τbr and τ_r are the lifetimes of non-radiative and radiative recombination, respectively.

For a small amplitude of the forward bias disturbance voltage, equation (4) can be written as:

$$\left(\frac{\partial n}{\partial v} + \frac{C_d}{qd}\right)\frac{dv}{dt} = \frac{\partial R}{\partial n}\frac{\partial n}{\partial v}v. \quad (11)$$

Multiplying by (qd) we get:

$$\left(qd\frac{\partial n}{\partial v} + C_d\right)\frac{dv}{dt} = -\frac{1}{\tau}qd\frac{\partial n}{\partial v}v. \quad (12)$$

The expression $qd\frac{\partial n}{\partial v}$ has the dimension F/cm^2, so it can be denoted by C_b and considered as a capacitance associated with the accumulation of charges at defect levels through which non-radiative recombination occurs. By its physical nature, it is very close to the barrier capacitance. Thus, equation (12) can be written:

$$\left(C_b + C_d\right)\frac{dv}{dt} = -\frac{1}{\tau}C_b v$$
$$\left(1 + \frac{C_d}{C_b}\right)\frac{dv}{dt} = -\frac{1}{\tau}v \quad (13)$$

After solving this differential equation, we obtain:

$$v = v_0 e^{-\frac{t}{\tau_{eff}}}, \quad (14)$$

Where $$\tau_{eff} = \left(1 + \frac{C_d}{C_b}\right)\tau. \quad (15)$$

Thus, the equivalent circuit of an LED at a given forward bias voltage is V and a small sinusoidal disturbance $v(t)$ can be represented as in the form of a two-terminal (a b) (Fig. 1). This electrical model of the LED is represented by a parallel link consisting of resistance R_d, which is determined by the resistance of the active region of the heterojunction, and parallel-connected capacitors C_d, and C_b, the capacitances of which determine the capacitance of the heterojunction. Resistance R_s is connected in series to them, which includes the volume resistance of the *p*- and *n-type* barrier semiconductors.

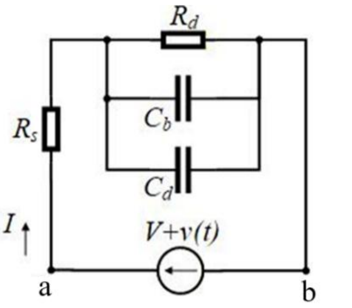

Fig. 1 – Diagram of an electrical circuit with a LED in the form of a bipolar junction

3. EXPERIMENTAL METHODOLOGY

For experimental measurements, commercially available C503B BAN CY0C0461 blue LEDs manufactured by CREE, made on the basis of InGaN-GaN compounds, were used. To power the LED in the constant bias mode with an applied sinusoidal or rectangular signal with a frequency of 1-10 kHz and an amplitude of 50 mV, a SIGLENT SDG 1050 generator was used. To power the LED with a power of 1 W, a LW-K3010D DC source and a pulse transformer with a transformation ratio of 1:1 was used, connected in series with the LED. A sinusoidal or rectangular signal from the generator was applied to its primary winding. The change in current in the circuit was determined by the voltage drop across the series-connected resistance R, which, together with the internal resistance of the source, did not exceed 60 Ohm.

The current-voltage characteristics of LEDs were measured in two modes - static and dynamic. During static measurement, voltage was applied to the LED from a LW-K3010D DC source. Measurements of current and voltage parameters were performed using a UNI-T UT8803E digital multimeter. For measurements of the *I-V* characteristics in dynamic mode, a Siglent SDG 1050 generator and a Siglent SDS 1072CML+ oscilloscope, which operated in X/Y mode, were used. Operation in dynamic mode allowed minimizing the change in LED temperature and neglecting the effect of self-heating.

Measurements of the differential resistance and capacitance of the diode were performed at a given bias voltage with the supply of an alternating voltage of sinusoidal or rectangular shape with an amplitude of 50 mV. The value of the differential resistance was determined from the ratio of the amplitude values $R_d = v_m/i_m$. Such measurements were carried out for different points of the *I-V* characteristic.

To measure the capacitance of the LED, a bridge circuit was used, in one of which an LED was connected, and in the other – a reference capacitor with a parallel resistance. In the diagonal of the bridge, a SIGLENT SDG 1050 generator or a DC source with a pulse transformer connected in series and an electronic microammeter UNI-T UT8804E were included. The results of the experiments were recorded on a personal computer.

4. RESEARCH RESULTS AND THEIR DISCUSSION

Experimental studies of the dynamic characteristics of LEDs were started with a static *I-V* characteristics and a low injection level. Fig. 2. shows the current-voltage characteristic of C503B BAN CY0C0461 type LED.

The *I-V* characteristic was approximated by an exponential dependence $I(V) = e^{(A+BV+CV^2+DV^3)}$ with numerical values of the coefficients: $A = 1987.50$, $B = -2573.43$, $C = 1091.90$, $D = -152.67$, which is depicted in Fig. 2 by a solid line. From this dependence, an analytical expression for the differential resistance was obtained:

$$R_d = \frac{dV}{dI} = \frac{e^{-(A+BV+CV^2+DV^3)}}{B+2CV\ +3DV^2}\,. \tag{16}$$

In Fig. 3, the line shows its dependence on the forward bias voltage. The experimental results are represented by square markers.

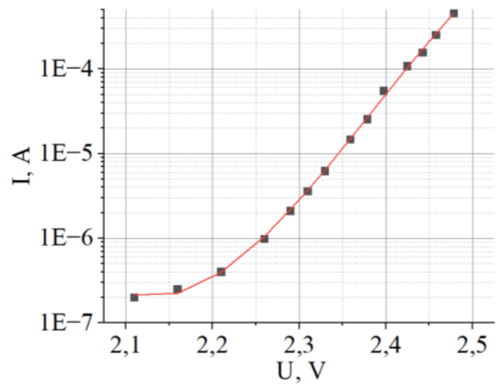

Fig. 2 – Volt-Ampere characteristic

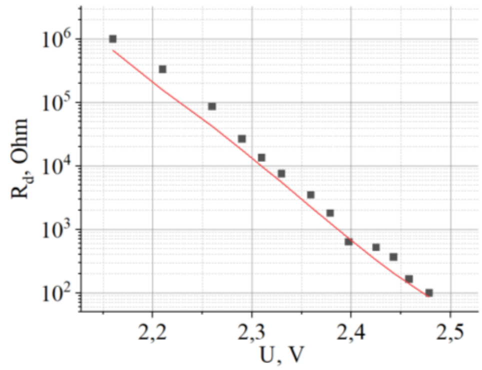

Fig. 3 – Dependence differential time R_d, from the forward bias voltage U

Experimental measurements of the capacitive characteristics of the diode were possible up to a forward bias voltage of 2.42 V and a wave disturbance with an amplitude of 50 mV and a frequency of 1 kHz. Further increase in voltage greatly reduced the Q factor of the circuit and made it impossible to distinguish the useful signal from the noise background. The measured experimental results are shown in Fig. 4 by square markers and in Table 1.

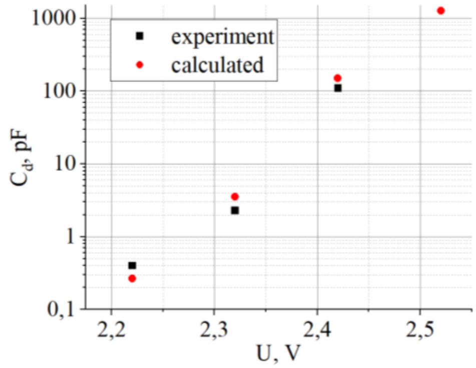

Fig. 4 – Dependence of the LED capacitance C_d, from the forward bias voltage U

The influence of forward bias voltage on the kinetics of the small perturbation current was studied. Fig. 5 shows the relative change in $i/i_0 = f(t)$ of the leading (a) and trailing (b) fronts of the LED current pulse and their logarithmic dependences $\ln(i/i_0) = f(t)$ (c) and (d) at different values of forward bias voltage. The linear nature of the logarithmic dependence indicates an exponential law of current change. The time constants of current change at different forward bias voltages which are given in Table 1, were determined from the angle of their inclination to the time axis.

Table 1 – The time constants of current change at different forward bias voltages

V, V	R_d, Ohm	τ, ns	C_d, pF	
			Experimental	Calculated
2.25-2.22	86160	30	0.4	0.3
2.30-2.32	20100	50	2.3	3.5
2.40-2.42	635	80	110	150
2.50	100	100		1270

From the graphs of Fig. 5 it is seen that with increasing voltage the slope of the dependence $\ln(i/i_0) = f(t)$ decreases and at a voltage ≥ 2.65 V it approaches zero. This indicates that the reactive component in the complex resistance of the diode disappears. The capacitance of the diode ceases to participate in the kinetics of the current. It is either shunted by a small resistance R_d, or compensated by a negative capacitance, the appearance of which is considered in the works [2, 7, 8].

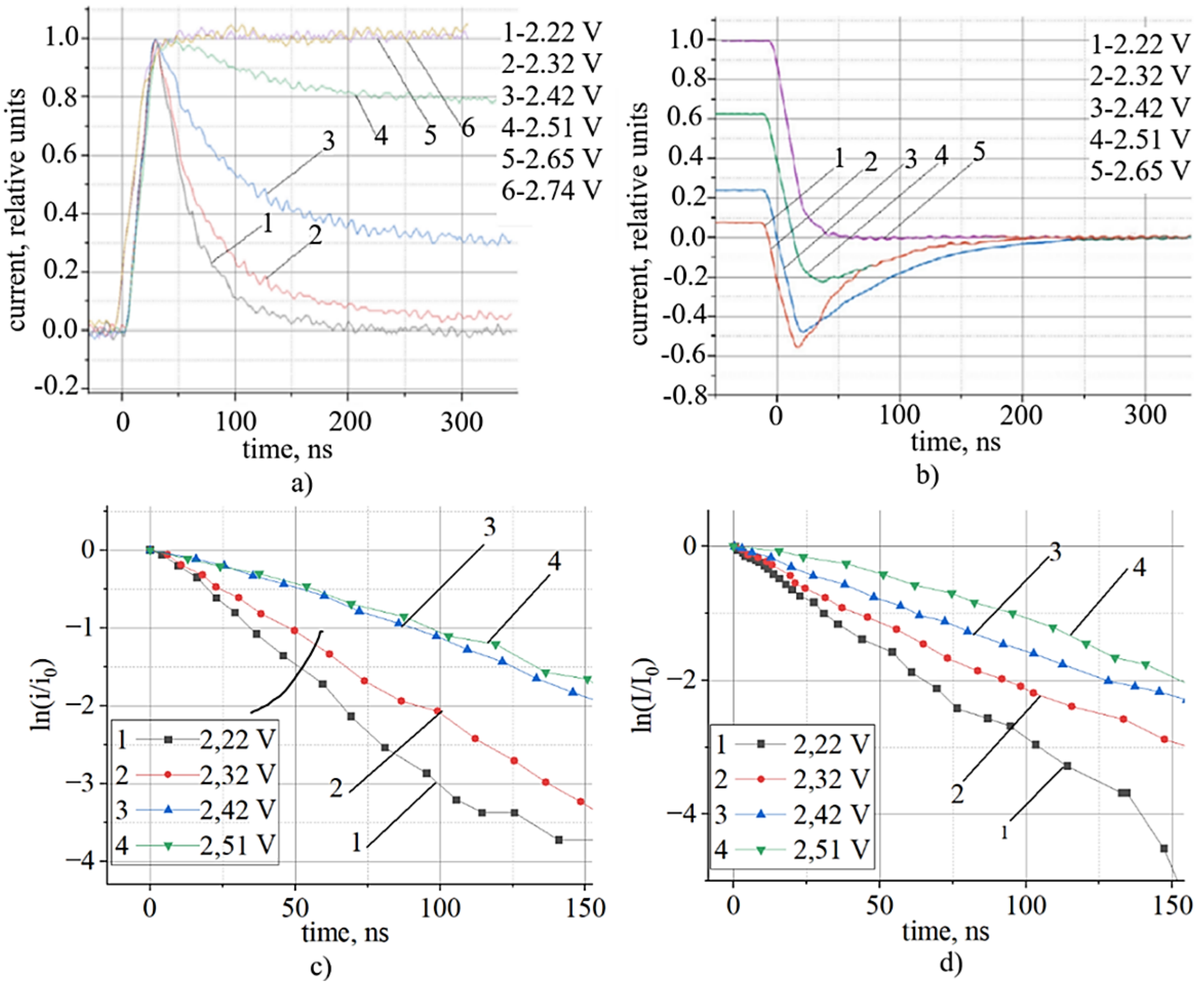

Fig. 5 – Relative change in the leading (a) and trailing (b) edges of the LED current pulse and their logarithmic dependence (c) and (d) at different forward bias voltages

According to the results of studies of transient processes in electrical circuits with DC, the time constant of current kinetics can be determined by the formula $\tau = R_d \cdot C_d$, where R_d and C_d – differential resistance and capacitance of the LED [9]. The calculation of the LED capacitance at different values of the forward bias voltage was carried out as $C_d = \tau / R_d$. The calculation results are given in Table 1 and Fig. 4. Up to a voltage of 2.42 V, the experimental and calculated results are very close. With increasing voltage, the LED capacitance increases and at a voltage of 2.50 V reaches a value of 1000 pF.

Time parameters were also measured. changes in the luminous flux caused by small-disturbance current pulses at different values of forward bias voltage. In Fig. 6 (a) and (b) shows the oscillograms of the increase and decrease of the light flux, and (c) and (d) – their logarithmic dependences. From these graphs, time constants were determined, which are given in Table 2.

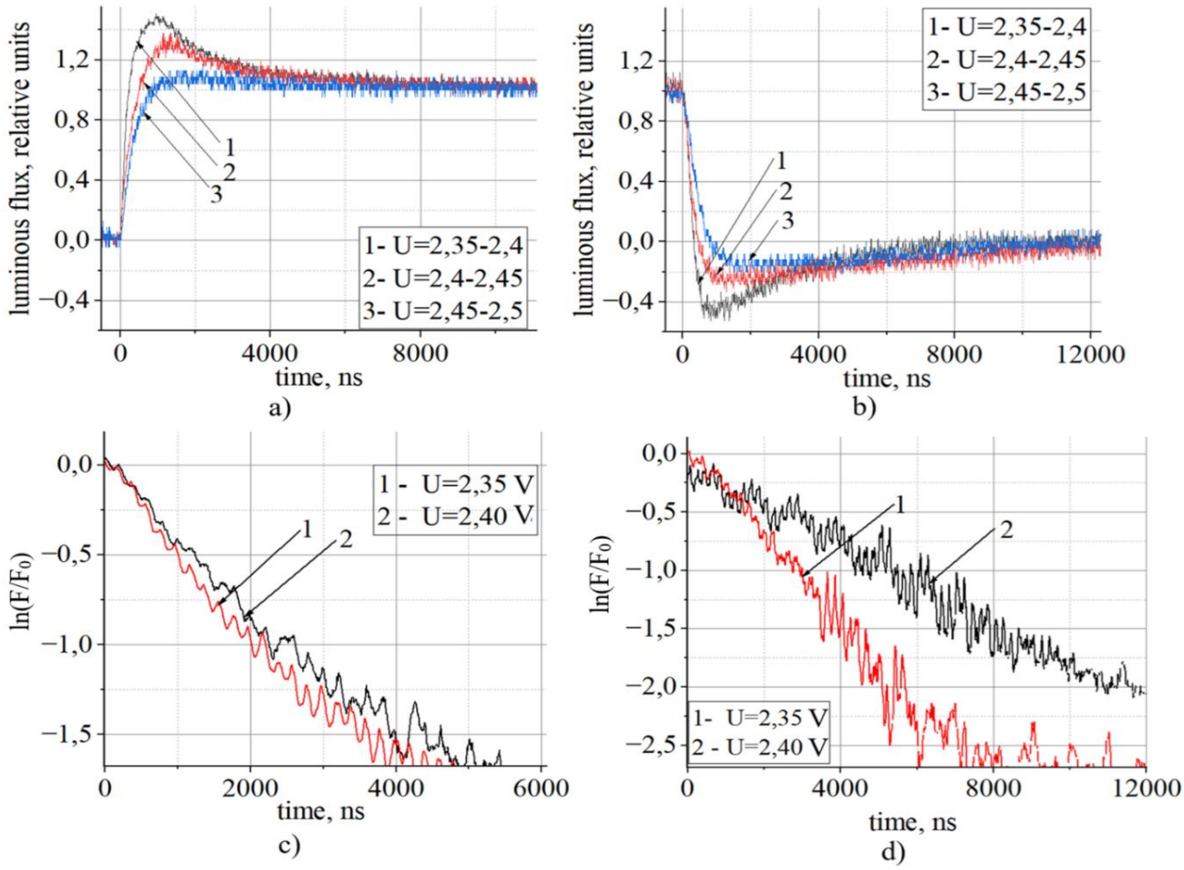

Fig. 6 – Relative change leading (a) and trailing (b) front of the impulses luminous flux, and their logarithmic dependence (c) and (d) at different forward bias voltages

Table 2 – Time constants

High-voltage	Time constant, ns	
	Front line	Rear front
2.35	900	2570
2.40	1000	2700
2.45	2800	5800

Compared to current, the time constant of the luminous flux is much larger. As with current, at voltage ≥ 2.65V the slope of the dependence $\ln(F/F_0) = f(t)$ becomes close to zero.

Fig. 7 shows the oscillogram of the current pulse (channel 2) and voltage (channel 1) of the small disturbance at a forward bias voltage of 2.65 V and a pulse frequency of 1 kHz. It can be seen from the oscillogram that the kinetic parameters of the injection current pulse are very close to the voltage parameters of the small disturbance signal. This is also observed at higher voltages of direct displacement.

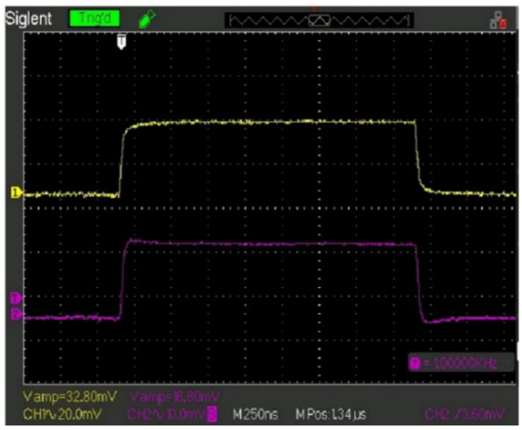

Fig. 7 – Oscillograms of the voltage pulse (channel 1) and current (channel 2) of small disturbance, at a forward bias voltage of 2.65 V

Thus, starting from a forward bias voltage of 2.65 V, the LED behaves as an active resistive element. The reactive components of the LED disappear. Considering that the diffuse capacitance can change its sign to the opposite at a certain forward bias voltage [2, 7, 8], it can be assumed that at $U = 2.65$ B, for the LED C503B BAN CY0C0461 such a transition occurs. At a given voltage, the impedance of the diode is determined by the resistance of the heterojunction R_d and the resistance of the boundary regions R_s.

Based on the experimental results obtained, we will consider the electrophysical processes that occur in the structure of the LED. At the moment of applying a step voltage of small perturbation, the concentration of minority carriers in the active region near the junction boundary increases sharply, while at a small distance from the boundary it remains balanced for a given forward bias voltage. The concentration gradient in the active region is maximum, and a large diffusion current passes through the diode. This is visible in the current pulse of the leading edge (Fig. 5). As the minority charge carriers spread into the depth of the active region, the gradient of their concentration decreases and the current through the junction decreases, heading towards a steady value, which is determined by the forward bias voltage and the voltage of the weak perturbation pulse. According to the equivalent circuit (Fig. 1), the current decrease corresponds to the capacitive nature of the transition process in the diode, which is associated with the charge C_d and C_b capacitances, which can be attributed to diffuse and barrier, respectively. The time to establish equilibrium will be determined by the time constant $\tau = (C_d + C_b)\,R_d$ of the small-disturbance pulse current. Considering that at a forward bias voltage $C_b << C_d$, τ will be determined by the value of the diffuse capacitance and the lifetime of the carriers injected into the active region. Since the value of the diffuse capacitance increases with increasing injection current, τ also increases (Table 2).

Simultaneously with the described process, changes in the resistance of the active region occur. At the moment of pulse application, its resistance is maximum, but as the charge carriers spread into the depth, its resistance will decrease, causing an increase in current. The decrease in the differential resistance R_d, which follows from Fig. 3, reduces the Q factor of the equivalent circuit of the diode. At a forward bias voltage $U \geq 2.65$ V, the differential resistance R_d decreases so much that the current through the diode will be determined only its value, and the voltage across the capacitor is the voltage drop across it.

Now let's consider the moment of cessation of the supply of a rectangular pulse of small disturbance.In this case, the voltage at the heterojunction will decrease abruptly due to the injected minority charge carriers that have accumulated in the active region. The magnitude of the charge depends on the injection level and the lifetime of the carriers. This will lead to a sharp drop in the current (Fig. 5b). Over time, the excess charge in the active region will decrease due to both the extraction of minority carriers into the base region and their recombination. In this case, the current will gradually increase until it reaches a stationary value. The duration of the transient process depends on the magnitude of the accumulated charge, which is determined by the value of the current of the perturbation pulse, the extraction rate of the injected carriers, and the duration of their lifetime.

The time constant of the rise and fall of the luminous flux is much larger than that of the current. Here it is worth paying attention to the nature of the blue glow in GaN doped with Mg, when the magnesium concentration exceeds 10^{18} cm^{-3}. The authors [10] explain the blue glow with a maximum at 2.8 eV by electron transitions from a deep donor (approximately 0.7 eV below the conduction band) to a shallow Mg acceptor, the energy level of which is located 0.2 eV above the top of the valence band. That is, by the recombination of donor -acceptor pairs, the lifetime of which is determined by the extinction constant of the LED glow (Table 2).

5. CONCLUSIONS

Theoretical justification for using a small perturbation imposed on a steady state to measure the dynamic characteristics of a semiconductor is given.

The dynamic resistance and capacitance of the LED were measured for different points of the *I-V* characteristic and their dependence on the forward bias voltage was presented.

It is shown that when a step signal of small disturbance is applied, the decrease in the injection current and luminous flux is described by an exponential dependence, and their time constant is determined.

The time constant of the light flux dynamics is much greater than the current, which is associated with the lifetime of donor -acceptor pairs, the recombination of which explains the blue glow of the studied LEDs. This parameter determines the maximum frequency of the pulsed LED power supply, which is 100 kHz.

It is established that at a forward bias voltage ≥ 2.65 V and a pulse frequency of 1 kHz. in the dynamics of current change, the reactive component associated with the capacitance of the LED disappears. This may be caused by the appearance of a negative component and a decrease in the quality factor of the parallel equivalent circuit of the LED.

REFERENCES

1. I.O. Vakarchuk, *Quantum Mechanics. 4th Ed.* (L.: Ivan Franko National University of Lviv: 2012).
2. Keming Ma, Zixian Wei, Shi Zhang, Zhiyuan Cao, Lei Wang, Chien-Ju Chen, Meng-Chyi Wu, H.Y. Fu, Yi Luo, Lai Wang, Yuhan Dong, *International Conference on Optoelectronic and Microelectronic Technology and Application* **11617**, 911 (2020) https://doi.org/10.1117/12.2585520.
3. J. Bisquert, *J. Phys. Chem. Lett.* **13**, 7320 (2022) https://doi.org/10.1021/acs.jpclett.2c01776.
4. Z.S. Wang, F. Ebadi, B. Carlsen, W.C. Choy, W. Tress, *Small Meth.* **4**, No 9, 2000290 (2020) https://doi.org/10.1002/smtd.202000290.
5. I. Reklaitis, F. Nippert, R. Kudžma, T. Malinauskas, S. Karpov, I. Pietzonka, A. Hoffmann, *J. Appl. Phys.* **121** No 3, 035701 (2017) https://doi.org/10.1063/1.4973903.
6. P. Ragonese, C. Maurizio, B. Kalinic, T. Kirchartz, S. Ravishankar, *Adv. Energy Mater.* **15** No 37, e01101 (2025) https://doi.org/10.1002/aenm.202501101.

7. E.F. Schubert, *Light-Emitting Diodes* (Ed. by Fred Schubert) (Cambridge University Press: 2018).
8. E.M. Bourim, J.I. Han, *Electron. Mater. Lett.* **12** No 1, 67 (2016) https://doi.org/10.1007/s13391-015-5281-9.
9. V.A. Andriychuk, L.M. Kostyk, Ya.O. Filuk, M.S. Nakonechny, *Tech. Electrodynam*. 2, 87 (2024) https://doi.org/10.15407/techned2024.02.087.
10. U. Kaufmann, M. Kunzer, M. Maier, H. Obloh, A. Ramakrishnan, B. Santic, P. Schlotter, *Appl. Phys. Lett.* **72** No 11, 1326 (1998) https://doi.org/10.1063/1.120983.

Дослідження динамічних характеристик світлодіодів методом малого збурення

Володимир Андрійчук, Любов Костик, Ярослав Філюк, Мирослав Наконечний, Ярослав Осадца

Тернопільський національний технічний університет імені Івана Пулюя, 46005 Тернопіль, Україна

Впровадження світлодіодних джерел світла, яке привело до відчутної економії енергоресурсів, вимагає енергоощадних джерел живлення. Основна увага розробників світлодіодних драйверів звернута на пошук імпульсних джерел, робота яких базується на результатах досліджень динамічних процесів, що протікають в самій структурі СД. Для дослідження впливу імпульсів струму на електрофізичні параметри СД в даній роботі використано метод малих збурень. Представлені результати вимірювань диференціального опору та ємності СД для різних стаціонарних станів. Вони є основними величинами, які контролюють перехідні процеси в електричних колах та відіграють важливу роль при розробці імпульсних джерел живлення. Показано, що наростання і спадання струму інжекції та світлового потоку добре описується експоненціальною залежністю, а постійна часу кінетики світлового потоку набагато більша від струму, що пов’язано із часом життя донорно-акцепторних пар. Встановлено що при напрузі прямого зміщення $\geq$2,65 В та частоті імпульсів 1 кГц в релаксації струму зникає реактивна складова, пов’язана з ємністю СД, що робить його активним споживачем енергії. За результатами дослідження кінетики світлового потоку визначено максимальну частоту імпульсів драйвера СД 100 кГц.

Ключові слова: Світлодіоди, InGaN-GaN, Вольт-амперні характеристики, Динамічні характеристики, Дифузна і негативна ємність, Мале збурення.