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Application of laser module with driver based on avalanche S-diode for light-emitting diode structure characterization

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***Abstract*—This work presents results of experiments on electrical pumping of laser diode by driver based on avalanche S-diode. Nine-fold increase of pulse power of semiconductor commercial InGaN/GaN laser diode at pulse duration 15-20 ns and frequency 90 kHz was achieved. Proposed laser module was used in set of tools for light-emitting diode structures characterization as a pumping source for photoluminescence measurements. Finally comparative test measurements of quantum efficiency of conventional light-emitting structures were conducted using electroluminescence and photoluminescence regimes. Measurements have shown promising results for developed laser module for light-emitting diode structures characterization.**

Keywords—avalanche pulse S-diode; semiconductor laser diode; light-emitting diode; photoluminescence; quantum efficiency

I. INTRODUCTION

An avalanche pulse S-diode is a semiconductor device of microwave electronics, on the reverse branch of the current-voltage characteristic of which the negative differential resistance (NDR) section is observed [1]–[3]. It is used as a threshold element in circuits of exciting nonsinusoidal location antennas and pulse pumping of high-power light-emitting diodes, lasers, and Gunn-effect diodes [2], [3]. The typical switching times of the S-diode from the closed to open state vary from 0.05 to 0.50 ns, and the threshold voltages from 50 to 1000 V.

This work is devoted to research and development of laser module in which electrical pumping of commercial laser diode is realized on avalanche pulse S-diode. Also the application of such module for characterization of semiconductor structures for light-emitting diodes (LEDs) is presented.

The most common technique of LED structures characterization is photoluminescence (PL) measurements. In this technique LED structures are pumped by laser radiation with aim to measure the PL external quantum efficiency of LED. Such measurements were carried out for high-efficiency structures for ultraviolet, blue, and green diodes based on InGaN/GaN multiple quantum wells (MQWs) (currently, above LEDs are used in modern outdoor and indoor lighting devices). In this regard different lasers were used: Ti:sapphire [4], Nd:YAG [5], Xe-Cl [6], Alexandrite [7] and Helium–cadmium lasers [8]. As usual, the dependence of PL quantum efficiency on the intensity of excitation is the same as the dependence of quantum efficiency on the current density at the electroluminescence regime. It is represented as a curve with maximum after which decline of quantum efficiency (so called efficiency droop) is observed. The analysis have shown that for the high-efficiency LEDs the required optical power density in PL measurements corresponds to the efficiency droop and must be as high as 10^2 kW/cm^2. Just about this value corresponds to rated forward current density of InGaN/GaN LEDs under electrical excitation regime (1-10 A/cm^2) [9]. In this work we will show that such optical power can be achieved for the semiconductor laser diodes by using pulse pumping and focusing of the laser spot.

It is well known that using of pulse pumping regime with short pulse durations permits to enhance an optical power of semiconductor lasers significantly. Usually this task is solved by application of drivers which are based on avalanche transistors. This work presents results of experimental study of original device (avalanche pulse S-diode) in a circuit for the pumping of commercial semiconductor laser.

II. EXPERIMENT

An avalanche S-diode is the semiconductor device which operates at the reverse bias at the negative differential resistance section of current-voltage characteristic. The device is based on *n*-GaAs doped with deep acceptor centers [1], [10]–[12]. It switches under microplasma impact ionization regime due to inhomogeneous distribution of impurity [13], [14]. This process causes relatively poor stability of S-diode, i.e. large jitter. However, it was shown that even in oscillator circuit the instability of switch (deviation range) can be reduced to hundreds picoseconds [15]. The switch voltage depends on gradient of impurity in space charge region and thickness of diode base [1], [12]. In this experiment we used low-power S-diode with switch voltage equal to 90 V (maximum pulse current is 10 A).

The driver circuit was designed as a piker with a delay line. Circuit diagram of driver is shown in Fig. 1.

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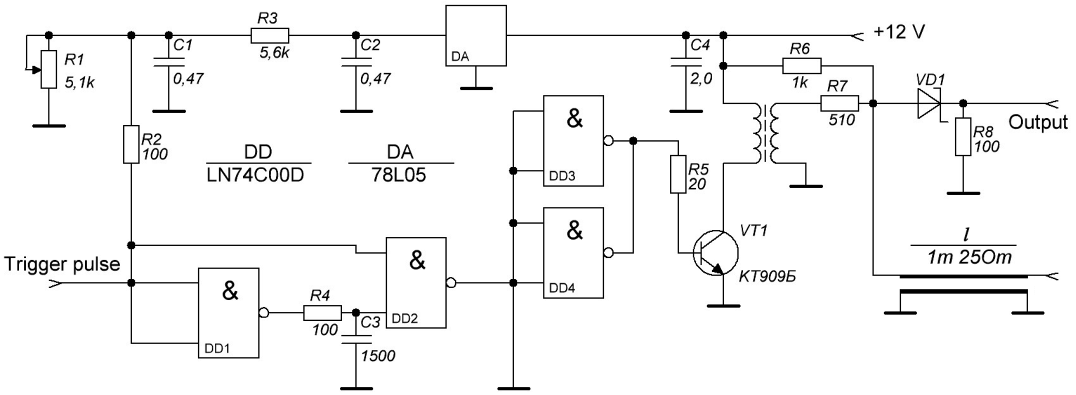

Fig. 1. The scheme of driver based on avalanche S-diode.

As a load the InGaN/GaN laser diode (LD) with a wavelength 405 nm was used. According to datasheet the maximum optical power of LD is 250-450 mW (LD Nichia NDV4642VFR). To measure the form of electrical and optical pulses we used LeCroy104Xs oscilloscope (bandwidth - 1 GHz) and silicon photodiode (pin-diode) with response time 2 ns.

PL experiments were carried out for commercial blue LED-structure grown by MOVPE on the [0001] patterned sapphire substrate. An active n-type region of the structure consisted of the $In_{0.15}Ga_{0.85}N/GaN$ MQWs and barriers with the thicknesses 2.5 and 15 nm, respectively. The thickness of the p-$Al_{0.15}Ga_{0.85}N$ barrier layer was about 30 nm. From this structure, planar light-emitting diodes with ohmic contacts and the resistance less than 10^{-2} $\Omega \cdot cm^2$ were made. The area of LED is 1 mm^2.

Photoluminescence was excited by a pulsed YAG-laser with an average power of 35 mW (0.2-1 kHz, duration – 10 ns, 355 nm) and developed laser module (0.2-90 kHz, duration – 15-20 ns). To enhance the power density of laser radiation we used focusing by quartz lens (minimum diameter of laser spot on a sample was about 100 mkm). The dependence of PL quantum efficiency on the optical power was measured at room temperature. Optical power was changed by neutral glass filters. The photoluminescence spectra were measured with an Ocean Optics spectrometer.

To compare the PL and electroluminescence (EL) regimes, we measured the dependence of the external quantum efficiency η on the current at the room temperature using a Keithley 2636A SourceMeter, and a LeCroy104Xs oscilloscope. To prevent overheating at high current densities we used pulse regime (duration – 30 µs, frequency – 50 Hz).

III. RESULTS

At the Fig. 2 pulse shapes of electrical and optical pulses are shown. We found that falling edge of optical pulse is about 8-10 ns and it is the same for different length of delay line *l*, Fig. 1. As shown in Fig. 3 the reduction of delay line length leads to sharp decrease of optical pulse amplitude, and for 2 ns duration the optical generation is not observed. Evidently the strong power dependence in nanosecond range can be explained by capacitance recharging of LD and charge carrier life time in active region of LD.

For pulse durations t < 15 ns we observed nine-fold increase of pulse power as compared with datasheet maximum power of LD. Experiments had shown that at pulse duration 15-20 ns and frequency 90 kHz stable pulse generation observed without catastrophic degradation of laser diode.

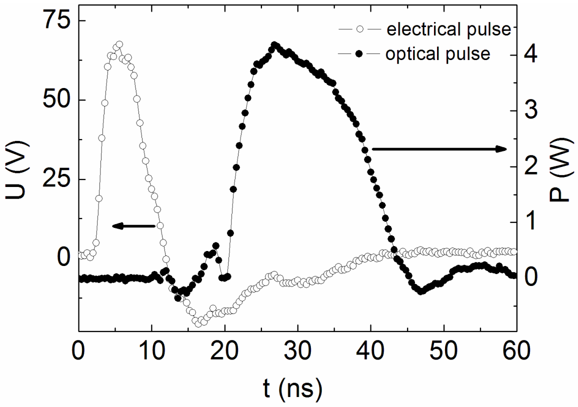

Fig. 2. The shape of electrical (left) and optical (right) pulses.

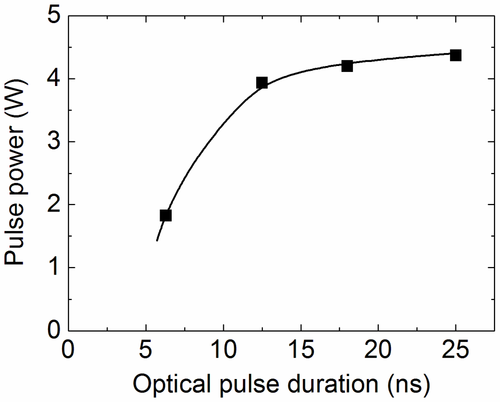

Fig. 3. Dependence of optical power on pulse duration.

Let us discuss results on characterization of InGaN/GaN LED structures by using laser module with driver based on avalanche S-diode. As mention above, we measured PL and EL spectra using three type of excitation (405 nm laser module, 355 nm YAG laser, and electron injection regime). Normalized electroluminescence and photoluminescence spectra are presented in fig. 4 and fig. 5. Experiments are shown that the change in the optical pumping mode (405 or 355 nm) gives no difference in photoluminescence spectra.

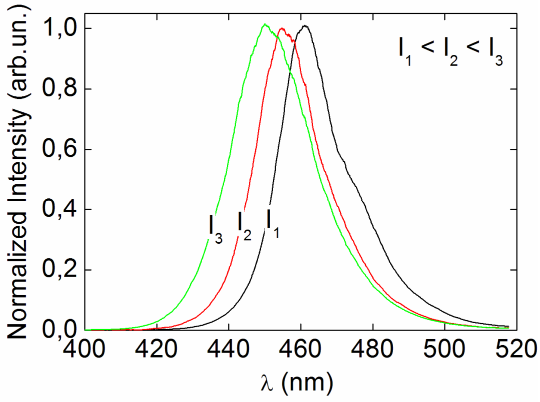

Fig. 4. Normalized electroluminescence spectra for different current.

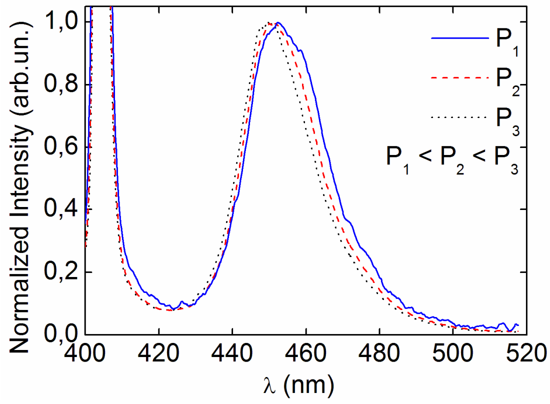

Fig. 5. Normalized photoluminescence spectra for different pumping optical power.

However the shapes of luminescence spectra for electro- and photoluminescence regimes are very different. We observed red shift of wavelength under pumping mode change from photo- to electroluminescence. The shift is equal to 10-12 nm what can be explained by scatter of quantum wells properties in different structure samples, e.g. due to InN composition inhomogeneous. Another reason of wavelength shift appearance is the peculiar conditions of carrier injection at different pumping modes. It is well known that electrical pumping is accompanied by tunneling of carriers through energy states of defects in injection barriers. Such a process leads to a lowering of the open voltage in InGaN/GaN light-emitting diodes. Obviously this effect leads to a lowering of photon emission energy what is equivalent to observed wavelength shift.

To compare EL and PL results the experimental dependences were plotted in coordinates $\eta = \eta(n_{\text{inj}})$, were η was calculated in arbitrary units from optical power P as P/n_{inj}. The value n_{inj} represents the number of injected carriers per second per unit area (injection rate). In the case of electrical pumping this value was calculated as

$$n_{inj} = \frac{I}{e \cdot S} \tag{1}$$

where I – current, e – electron charge, and S – area of LED.

In the case of optical pumping the calculation of n_{inj} is difficult because of amount of reflected and absorbed radiation in *p*-layer must be considered. Moreover for accurate determination of n_{inj} the diffusion and recombination processes of nonequilibrium carriers in *p*-layer should be involved. Therefore to simplify the problem we used normalization which based on experimental data for wavelength shifts of luminescence spectra with pumping [16].

For determination of absolute value of quantum efficiency we also normalized experimental data. Normalization was performed by maximum efficiency (η = 100%) which corresponds to lowest temperature [17].

Experimental results for quantum efficiency after normalization are presented on the fig. 6. The highest quantum efficiencies measured at T = 300 K have similar values (~56-65%) for PL and EL regimes.

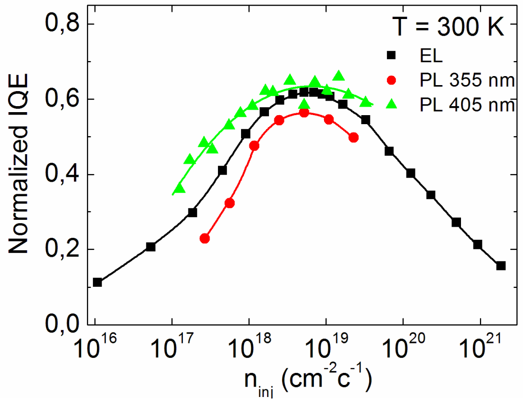

Fig. 6. Dependence of normalized quantum efficiency on flux density of injected carriers.

Moreover the experimental curves have the same form. For EL and PL regimes, the quantum efficiency at room temperature is mainly described by ABC-model:

$$\eta = \frac{B \cdot n^2}{A \cdot n + B \cdot n^2 + C \cdot n^3}, \tag{2}$$

where *A*, *B*, and *C* are the temperature dependent Shockley–Read, radiative, and Auger recombination coefficients, respectively, and $n \sim n_{\mathrm{inj}}$ (for linear recombination regime) is the concentration of non-equilibrium carriers in the MQWs.

The observed similarity of the dependencies $\eta = \eta(n_{\mathrm{inj}})$ for all excitation regimes allows us to conclude that application of laser module with driver based on avalanche S-diode is promising for LED structures characterization. The module can be used for uniformity control of LED wafers in post-growth industry production, such as mapping of PL intensity and peak wavelength, or laboratory measurement of internal quantum efficiency of LED structures.

IV. CONCLUSION

The laser module based on commercial laser diode and driver with pulse avalanche S-diode was developed. The following characteristics of the module were achieved: laser peak wavelength is 405 nm, pulse duration is 15-20 ns, maximum frequency is 90 kHz, and pulse optical power is 4.2 W. The example of module application was presented in this work. The module was used in set of tools for light-emitting diode structures characterization as a pumping source for photoluminescence measurements. The analysis of the results have shown that application of laser module with driver based on avalanche S-diode is promising for LED structures characterization.

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