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Optical gain in heavily doped $Al_{0.65}Ga_{0.35}N$:Si structures under continuous pumping

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The optical gain coefficients measured in heavily doped $Al_{0.65}Ga_{0.35}N$:Si structures under continuous pumping with broadband radiation (190–330 nm) at room temperature. The optical gain of $212\,cm^{-1}$ was obtained under $3.2\,mW/cm^2$ of the optical pump power density, which well agrees with the data obtained with pulsed excitation. The measured value for the radiative recombination cross-section under continuous optical excitation is $\sigma \approx 10^{-15}\,cm^2$.

Keywords: heavily doped $Al_xGa_{1-x}N$ structures, optical gain, radiative recombination cross-section.

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Semiconductor laser sources find applications in various fields of science and technology, since they offer a wide range of operating wavelengths, compactness, efficiency, reliability, low cost, and ease of use. $Al_{0.65}Ga_{0.35}N:Si/AlN/Al_2O_3$ heterostructures hold promise as materials for active media of devices emitting in the visible and ultraviolet (UV) spectral range [1,2]. Layers of $Al_xGa_{1-x}N$ ($x > 0.5$) doped heavily with silicon to density $n_{Si} \geqslant 10^{20}\,cm^{-3}$ are characterized by a broad luminescence spectrum ($\lambda = 350-700\,nm$) and high quantum efficiency $\eta = 0.14-0.8$ [3,4], which should help construct sources of coherent and incoherent radiation ranging from blue light to the near infrared in a single emitting sample. The authors of [3,4] have investigated the mechanisms of optical gain, measured the absolute gain, and obtained tunable stimulated emission in the $Al_{0.74}Ga_{0.26}N$:Si heterostructure in an experiment with an external optical cavity under optical pumping by pulsed radiation with wavelength $\lambda = 266\,nm$. Efficient radiation sources operating in the continuous mode at room temperature are required in various practical applications. In view of this, experimental studies of optical gain in heavily doped $Al_xGa_{1-x}N$:Si heterostructures under continuous optical pumping are of great interest.

The aim of the present study is to measure the parameters of optical gain for broadband radiation in a heavily doped $Al_{0.65}Ga_{0.35}N$:Si heterostructure under continuous optical excitation.

Layers of $Al_{0.65}Ga_{0.35}N$:Si $1.2\,\mu m$ in thickness were grown by molecular-beam epitaxy on 0.43-mm-thick sapphire substrates [4], which were coated with 350-nm-thick buffer AlN layers deposited in advance. Doping was performed in a flow of SiH_4 to silicon density $n_{Si} \approx 2 \cdot 10^{20}\,cm^{-3}$. The studied samples have a smooth surface with root-mean-square roughness RMS $< 5\,nm$. Radiation of a DDS-30 deuterium arc lamp (DAL) with a discharge current of 250 mA was used for optical pumping. Emission spectra were measured with a diffraction spectrometer with a resolution of 0.5 nm. A quartz light guide with a core diameter of 1 mm was used to couple radiation to the spectrometer. The absolute pump power was measured with a Thorlabs S401C sensor. All measurements were performed at room temperature.

Two optical arrangements (longitudinal and transverse) were used to measure the optical gain. In the longitudinal arrangement (Fig. 1, *a*), the intensities of probe radiation transmitted through the $Al_{0.65}Ga_{0.35}N:Si/AlN/Al_2O_3$ heterostructure were measured under continuous UV pumping from a deuterium lamp $I(\lambda)$ and without pumping $I_0(\lambda)$. A broadband incandescent lamp served as a source of probe radiation. An SZS-23 light filter was used to limit the spectrum of this lamp to the 300–700 nm range. DAL radiation was focused onto the heterostructure surface by a spherical quartz lens with a focal length of 5 cm into a spot 2 mm in diameter. Radiation from the incandescent lamp transmitted through the heterostructure was focused into the core of the light guide, which was positioned at a distance of 11 cm from the structure in order to prevent the penetration of scattered visible radiation and luminescence into it. Integral gain k_{int} and wavelength dependences of gain $k(\lambda)$ were determined using the following equations:

$$S/S_0 = \exp(k_{int}l), \qquad I(\lambda)/I_0(\lambda) = \exp(k(\lambda)l), \qquad (1)$$

where l is the length of the excited region in the layer and S and S_0 are the intensities of incandescent lamp radiation integrated over the spectrum in experiments performed with and without pump radiation, respectively.

In the transverse arrangement (Fig. 1, *b*), the method of measuring the dependence of emission intensity $I(\lambda_0, L)$

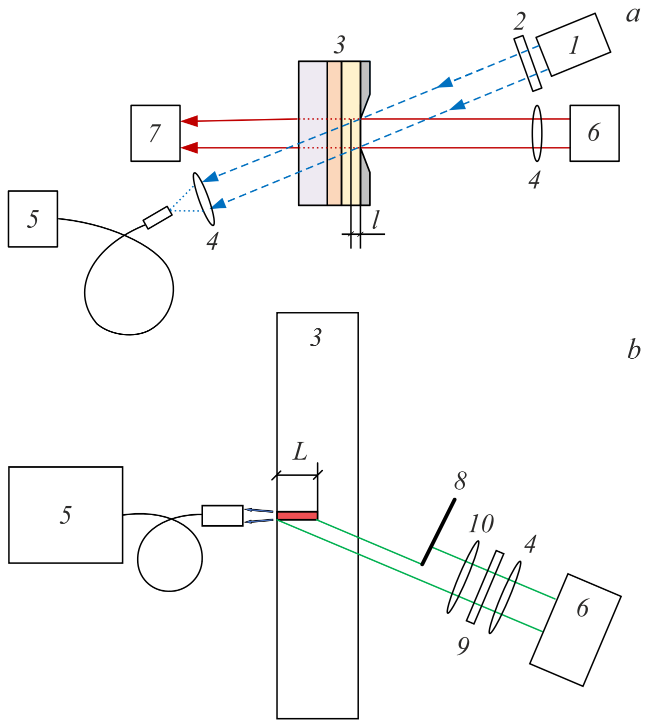

Figure 1. Experimental optical arrangements: *a* — longitudinal; *b* — transverse. *1* — Incandescent lamp, *2* — SZS-23 light filter, *3* — $Al_{0.65}Ga_{0.35}N$:Si heterostructure, *4* — spherical quartz lens, *5* — spectrometer, *6* — deuterium lamp, *7* — pump power meter, *8* — shutter, *9* — UFS-5 light filter, and *10* — cylindrical quartz lens.

from the end face of the layer on gain region length L [5] was used to determine gain $k(\lambda_0)$ at the maximum of the emission spectrum with $\lambda_0 = 507.6\,\text{nm}$:

$$I(\lambda_0, L) = \left(I_s s/k(\lambda_0)\right)\left[\exp\left(k(\lambda_0)L\right) - 1\right], \qquad (2)$$

where I_s is the spontaneous emission power density and s is the cross-sectional area of the excited region.

Figure 2, *a* shows the UV spectrum of DAL radiation within the 190−366 nm range (dependence *1*) with a total radiation power of 154 μW. In the longitudinal measurement arrangement (Fig. 1, *a*), the transmission spectrum of the studied $Al_{0.65}Ga_{0.35}N$:Si structure (dependence *3*) may be used to calculate absorbed power $P_{abs} \approx 97\,\mu\text{W}$, which corresponds to power density $W_1 \approx 3.2\,\text{mW/cm}^2$.

The power absorbed by the structure in the transverse arrangement (Fig. 1, *b*) is $P_{abs} \approx 8.5\,\mu\text{W}$. The radiation beam focused by spherical and cylindrical lenses onto the structure surface and shaped by a slit was $10 \times 0.8\,\text{mm}$ with absorbed power density $W_2 \approx 0.17\,\text{mW/cm}^2$.

The greater part of the pump radiation spectrum falls within the range of interband transitions of the structure, where the absorption coefficient is $(1.0{-}1.5) \cdot 10^5\,\text{cm}^{-1}$ [6]. This corresponds to excitation depth $l \approx 100\,\text{nm}$. Figure 2, *b* shows two averaged spectra of probe radiation that passed through the structure under study in experiments performed with and without pump radiation. Having processed 30 experimental curves with the use of equations (1), we obtained absolute values of gain $k_{int} = 235 \pm 40\,\text{cm}^{-1}$ and $k(\lambda) = 212 \pm 35\,\text{cm}^{-1}$, which remain unchanged within the measurement accuracy in the 500−650 nm spectral range. Owing to the smallness of the signal-to-noise ratio, the gain values were not determined at the edges of the emission spectrum. Figure 3 shows the results of measurement of variation of intensity $I(\lambda_0)$ with length L of the excited region under transverse pumping of the active medium. Gain $k(\lambda_0) = 6.2\,\text{cm}^{-1}$ was determined by interpolating these experimental data with the use of equations (2). The significant difference between $k(\lambda)$ and $k(\lambda_0)$ $(k(\lambda)/k(\lambda_0) \approx 34)$ is attributable to several factors. The first factor is the difference in absorbed pump power densities $W_1/W_2 \approx 14$ due to the high divergence of DAL pump radiation, which makes it impossible to focus it into a small excited region. The second one has to do with the fact that, as was demonstrated in [7,8], the method of determination of gain from the results of measurements of dependences of the emission intensity on length of the gain region is not always correct, since leaky modes (radiation escaping from the excited region to the passive part of the sample under study) are neglected in it. This may lead to underestimation of gain.

Let us compare the gain values determined under continuous pumping with similar values obtained under pulsed excitation [4]. In the latter case, with gain $k(\lambda) = 212\,\text{cm}^{-1}$, the calculated density of absorbed photons is $N_p \approx 2.1 \cdot 10^{17}\,\text{cm}^{-3}$ [4]. The density of absorbed photons in the continuous excitation mode is given by

$$N_{st} = (W_1\tau)/(E_i l) \approx (3.9 \cdot 10^{-20}\tau)\,\text{cm}^{-3},$$

where $E_i = 8.3 \cdot 10^{-19}\,\text{J}$ is the average energy of pump photons with a maximum at $\lambda = 240\,\text{nm}$ and τ is the time of slow luminescence intensity decay.

It was demonstrated experimentally (see [3,4]) that non-stationary radiative recombination is characterized by fast ($\sim 10\,\text{ns}$) and slow (on the order of hundreds of microseconds) time decay processes; the latter is characterized by a hyperbolic function that contributes approximately 85% of the overall recombination.

Since the time dependence of emission intensity decay is proportional to the density of photons inducing radiative recombination, the value of τ may be determined from the approximation of experimental data for the decay time by hyperbolic function $I(t) = C/(t + t_m)$, where $I(t)$ is the time decay of luminescence intensity and C and t_m are the decay curve parameters [3]. The results of calculation of the ratio between the area under the luminescence intensity decay curve bounded at $\tau \approx 540\,\mu\text{s}$ and the total area under this curve reveal that 90% of all pump photons absorbed in the structure pass into radiative recombination. The densities of photons N_p and N_{st} absorbed under pulsed and continuous pumping become equal at $\tau \approx 540\,\mu\text{s}$. The obtained value of decay time τ verifies

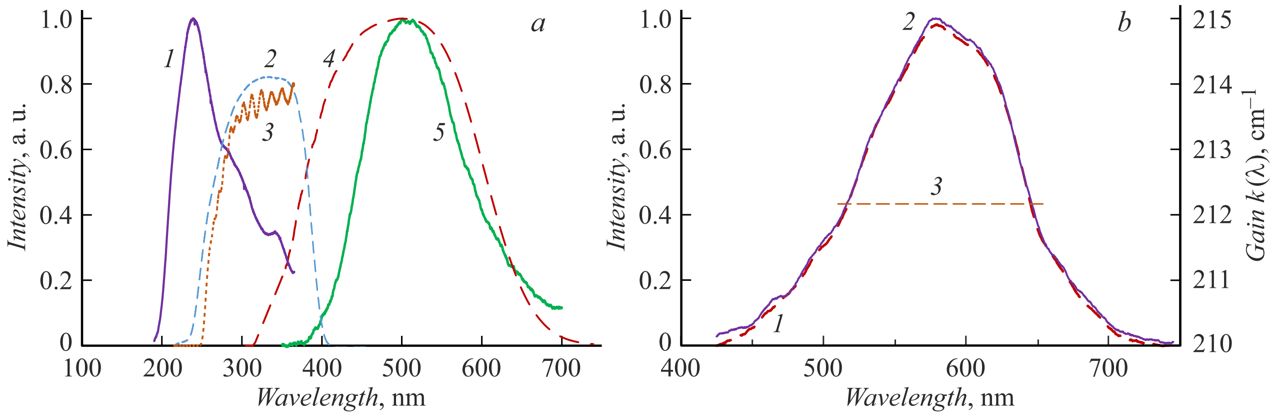

Figure 2. Spectral dependences. *a*) *1* — deuterium lamp spectrum, *2* — transmission spectrum of the UFS-5 light filter, *3* — transmission spectrum of the $Al_{0.65}Ga_{0.35}N$:Si heterostructure, *4* — transmission spectrum of the SZS-23 light filter, and *5* — emission spectrum of the $Al_{0.65}Ga_{0.35}N$:Si structure; *b*) *1* — spectrum of probe radiation, *2* — spectrum of amplified radiation, and *3* — gain $k(\lambda)$.

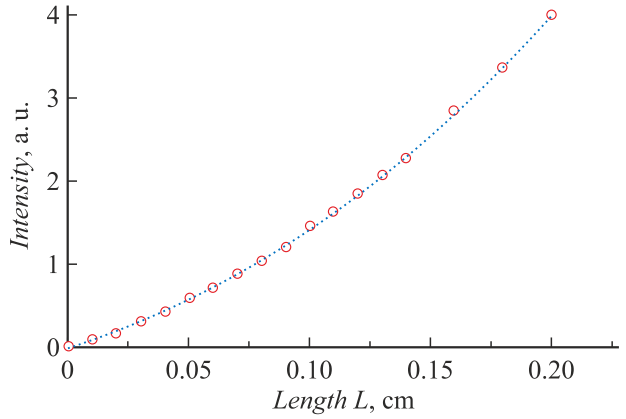

Figure 3. Dependence of the emission intensity on gain region length L. Circles represent experimental data, while the dotted curve is the result of approximation by equations (2).

this conclusion for the continuous excitation mode as well. Equations $\sigma = k(\lambda)/N_{st}$ allows one to determine the radiative recombination cross section, which is equal to $\sigma \approx 10^{-15}\,\mathrm{cm}^2$ and matches the corresponding value for the pulsed mode [4]. Thus, optical gain measurements in heavily doped AlGaN:Si layers demonstrated that the values of gain and large radiative recombination cross sections determined in continuous and pulsed modes are matching. This makes it possible to generate stimulated emission within a wide visible range with high efficiency under continuous optical excitation. The four-level optical excitation and radiative relaxation laser arrangement [4], which requires low pump powers to achieve threshold gain, is an important positive aspect of the studied structures.

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Conflict of interest

The authors declare that they have no conflict of interest.

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