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SEMICONDUCTOR QUANTUM GENERATOR BASED ON GALLIUM ARSENIDE WITH A PLANE RESONATOR

Introduction. By the present time, works have been published in which the generation of optical radiation in various semiconductor materials under excitation by a beam of accelerated electrons has been reported. In all these works, the optical radiation was observed in a plane perpendicular to the direction of the electron beam. An analogous resonator geometry has also been used in optical excitation of semiconductors.

Increasing the total generation power by increasing the dimensions of the resonator is known to be limited by losses, which in semiconductor lasers are due predominantly to absorption of light by free carriers and to scattering by optical inhomogeneities of the crystal. If these, as well as other types of losses, are characterized by the absorption coefficient χ, then the total generation power at the output of a laser with a Fabry–Perot resonator can be written in the following form:

$$P = j\eta SL\frac{1-e^{-\chi L}}{\chi L}\,\frac{1-R}{1-Re^{-\chi L}}, \qquad (1)$$

where j is the pump power per unit volume of the resonator; η is the internal efficiency, i.e., the ratio of the power of the induced radiation per unit volume of the active region to the pump power; R is the coefficient of reflection of light from the resonator mirrors; S is the area of the mirrors; L is the distance between them.

As is seen from (1), with increasing L (with a simultaneous increase in the total excitation power), the output power of the generator tends to a certain limit

$$P_{\max} = j\eta S(1-R)/\chi. \qquad (2)$$

This means that the total external efficiency of the generator falls rapidly. Obtaining greater total power by increasing j is limited by thermal effects in the crystal, since η is always less than unity.

Increasing the volume of the active region by increasing the energy of the electrons and, correspondingly, increasing their penetration depth into the crystal is also limited by the threshold for the occurrence of radiation defects in the lattice. For gallium arsenide this threshold is ~ 230 keV ([1]), which corresponds to a depth of the excited region of ~ 0.1 mm.

Thus, taking relation (2) into account, the size of the active region proves to be limited, and increasing the total power of optical-radiation generation in a semiconductor laser with the "ordinary" resonator geometry encounters a whole series of difficulties of a fundamental nature.

However, the fact that gain coefficients $\gamma \gg \chi$ can be realized comparatively easily in semiconductors makes it possible to dispense with the use of "long" resonators and to obtain generation in a syste-

···which we shall conventionally call "emitting mirrors" ([2]). In the present work, generation is reported in a system with a plane resonator, in which the mirror area $S \gg L^2$.

Experimental results

The experimental arrangement is shown in Fig. 1.

A sample of n-type gallium arsenide with a concentration of uncontrolled impurities $2 \cdot 10^{16}$ cm^{-3} and a mobility of 5200 cm^2/V $\cdot$ s at 300°K was made in the form of a plane-parallel plate 100 μ thick and several millimeters in diameter. Both surfaces of the plate were polished and formed an optical resonator. The sample holder was fastened inside a metal Dewar vessel, into which liquid nitrogen or water was poured ($T \sim 300$°K).

For excitation of the crystal, an electron beam with an energy of ~ 150 keV was used, formed by Pierce optics. After deflection by a magnetic field through 90°, the electrons were focused onto the sample by a short-focus magnetic lens. Turning the beam through 90° made it possible to record the radiation emerging from the gallium arsenide plate normal to its surface irradiated by electrons. The duration of the electron-current pulse at the sample was $150 \cdot 10^{-9}$ s, and the repetition frequency was 10 Hz. The maximum electron-current density at the sample reached 10 A/cm^2. To suppress generation along the surface irradiated by electrons, a metal mesh was placed in front of the crystal.

Fig. 1. Experimental arrangement. 1 –electron gun; 2 –focusing coils; 3 –deflecting electromagnet; 4 –sample; 5 –sample holder; 6 –Dewar vessel; 7 –vacuum window.

Fig. 2. a –spectral distribution of the intensity of spontaneous (1) and stimulated (2) radiation of GaAs at 300°K; b –one of the spectrograms of stimulated

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Figure 1: Fig. 1. Experimental arrangement. 1 —electron gun; 2 —focusing coils; 3 —deflecting electromagnet; 4 —sample; 5 —sample holder; 6 —Dewar vessel; 7 —vacuum window

Fig. 2

Figure 2: Fig. 2

radiation.

Figure 2 shows the generation spectrum in the sample at a temperature of 300°K. The distance between individual maxima corresponds to the modes of a Fabry-Perot resonator for $L = 100\ \mu$. Generation arose at a current density of 5 A/cm^2. As can be seen from Fig. 2, the photon energy corresponding to the maximum in the generation spectrum is 0.045 eV less than the forbidden-band width $E_0 = 1.430$ eV at a temperature of 300°K.

Apparently, as in the case of injection lasers, transitions from the tails of the density of states play an important role in the present case as well ([3,4]).

To determine the losses in the inactive region and to estimate the maximum gain coefficient at the lasing wavelength, the transmission spectra of a gallium arsenide plate were measured in the same geometry as in the lasing regime. Figure 3 shows the dependence of the absorption coefficient on wavelength, obtained from an analysis of the transmission spectra.

Discussion of the Results

As is known, for lasing to arise in a Fabry—Perot type resonator the gain coefficient must exceed a certain minimum value $\gamma_{\min}$, determined by the self-excitation condition:

$$\gamma_{\min} = -\ln R_1 R_2 / 2L_1 + \chi + (L_2/L_1)k, \tag{3}$$

where R_1 and R_2 are the reflection coefficients of the mirrors; χ and k are the loss coefficients, respectively, in the active region of length L_1 and in the inactive region of length L_2.

Substituting into (3) $\chi = 5$ cm^{-1} ([5]), $k = 40$ cm^{-1} (Fig. 3), $R_1 = R_2 = 0.3$ (Fresnel reflection), $L_1 = 40\ \mu$ and $L_2 = 60\ \mu$, we obtain $\gamma_{\min} \simeq 350$ cm^{-1}.

Fig. 3. Dependence of the absorption coefficient on the energy of the incident photon for the GaAs sample used in the present experiments.

As is known, the expression for the gain coefficient in the lasing regime can be written in the form:

$$\gamma = F(E_0 - \hbar\omega)(f_e + f_h - 1), \tag{4}$$

where f_e and f_h are the distribution functions of electrons and holes, and $F(E_0 - \hbar\omega)$ is the dependence of the absorption coefficient on the quantum energy. The expression in parentheses can never be greater than 1. Thus, $F(E_0 - \hbar\omega)$ gives an estimate of the maximum possible value of γ. On the other hand, in absorption

$$k = F(E_0 - \hbar\omega)(1 - f_e). \tag{5}$$

At a temperature of 300°K and an impurity concentration of $\sim 10^{16}$ cm^{-3}, one may assume that electron degeneracy in the impurity band does not occur and $f_e \ll 1$. In this case the gain coefficient in the lasing regime cannot (in absolute value) exceed the absorption coefficient measured at low intensity of the transmitted light, i.e., the values shown in Fig. 3.

However, the estimates made above of the minimum gain coefficient required for lasing exceed by almost an order of magnitude the value of the absorption coefficient at the lasing wavelength measured experimentally. Such a contradiction is far beyond the experimental errors and may be associated with narrowing of the band gap of the excited crystal. As an elementary calculation shows, heating of the crystal by the electron beam gives a decrease in the band-gap width of $8 \cdot 10^{-3}$ eV, whereas to explain the above contradiction this decrease must be no less than $2 \cdot 10^{-2}$ eV.

Such a decrease in the band-gap width may be due to effects of screening of the crystal field by free carriers and to interaction of the carriers with one another. An exact calculation of these effects is a very difficult theoretical problem. At present, calculations of the interaction energy have been carried out in the limiting cases of strong degeneracy ($T \to 0,\ 1/n \to 0$) and absence of degeneracy ([6,7]), which in our case apparently are a poor approximation.

However, for order-of-magnitude estimates one can obtain the following expression for the dependence of the band-gap width on the concentration of free-

free carriers:

$$\Delta E \sim -\frac{E_0}{1 + r_{\text{scr}}^2/r_0^2} - \frac{e^2}{\varepsilon_0 r_{\text{scr}}} - \frac{2e^2 n^{1/3}}{\varepsilon_0}, \tag{6}$$

where E_0 is the band gap of the unexcited crystal; r_0 is the lattice constant; e is the electron charge; ε_0 is the dielectric constant of the unexcited crystal; r_{scr} is the radius of screening of the static field;

$$r_{\text{scr}}^2 = \frac{\varepsilon_0}{4\pi e^2}\left(\frac{\partial n}{\partial \mu_n} + \frac{\partial p}{\partial \mu_p}\right)^{-1}; \tag{7}$$

n, p are the concentrations of electrons and holes, respectively; μ_n, μ_p are the quasi-Fermi levels of the electrons and holes, respectively.

The first term in formula (6) corresponds to the effect of screening of the crystal field and was obtained by us in the weak-coupling approximation for the electrons in the crystal and with the approximation of the dielectric constant of the excited crystal by the expression ([8,9])

$$\varepsilon(k,\omega)\big|_{\omega\to 0} = \varepsilon_0(1 + 1/k^2 r_{\text{scr}}^2), \tag{8}$$

where k is the wave vector of the Fourier component of the crystal field. (In the case of interest to us one should put $k = k_{\min} = 1/r$.)

The second and third terms in formula (6) correspond to the interaction energy of the free carriers, which in this case are treated as a free electron-hole plasma ([7,8]).

For GaAs (the ratios of the effective masses of the carriers to the mass of a free electron are 0.06 for electrons and 0.44 for holes, $\varepsilon_0 = 11.5$, $r_0 = 5.6$ Å), at $T = 300^\circ$ K, formula (6) gives that when the carrier concentration changes from $n = 2 \cdot 10^{16}$ cm^{-3}, $p = 0$, to $n = p = 10^{18}$ cm^{-3} (the concentration at which $\mu_n + \mu_p = E_0$), the change in the band gap is $\Delta E = (0.04 + 0.03 + 0.02) = 9 \cdot 10^{-2}$ eV.

The estimate obtained for the dependence of the band gap on the concentration of free carriers does not claim quantitative agreement with experiment; however, it shows that this effect may be substantial.

An increase in the wavelength of the maximum of the recombination radiation with increasing concentration of free carriers was observed in ([10]) and was attributed to exchange interaction, which is valid only in the case of strong degeneracy.

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Note: Figure translations are in progress. See original paper for figures.