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1963

Abstract

Full Text

PHYSICS

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SEMICONDUCTOR QUANTUM GENERATOR ON A p-n JUNCTION IN GaAs

The use of semiconductors as the working material for quantum generators in the optical and infrared ranges was first proposed in 1958 by N. G. Basov, B. M. Vul, and Yu. M. Popov (^{1}). Subsequently, in a paper by N. G. Basov, O. N. Krokhin, and Yu. M. Popov (^{2}), a method was proposed for injecting nonequilibrium current carriers through the p-n junction of degenerate semiconductors in order to create states with negative temperature. The advantage of this method is the possibility of direct conversion of electric current into coherent radiation with a high efficiency. In addition, as was pointed out in (^{2}), under certain conditions such a generator can operate in a continuous regime.

In the work of B. M. Vul et al. (^{3}), recombination radiation was studied at high current densities through a p-n junction in degenerate indium antimonide, when the concentrations of nonequilibrium carriers were sufficient to create an inverted distribution. Radiative recombination upon injection through a p-n junction in gallium arsenide, corresponding to interband transitions, was observed in the work of D. N. Nasledov et al. (^{4}). As one of the possible explanations of the line-narrowing effect of the radiation found in that work, the authors considered the presence of an inverted population. Quite recently, on a p-n junction in GaAs, strong narrowing of the radiation line and generation of coherent light were obtained ($^{5-7}$).

As shown in (^{2}), a state with negative temperature in semiconductors arises when the condition* is fulfilled

$$\mu_e + \mu_p > \Delta, \tag{1}$$

where μ_e and μ_p are the quasi-Fermi levels for electrons and holes, and Δ is the width of the forbidden band. In injection through a p-n junction, condition (1) means that a voltage $V > \Delta/e$ must be applied to the p-n junction in the forward direction. A state with negative temperature arises near the p-n junction in a thin layer of thickness of the order of the diffusion length. At a

Fig. 1. Dependence of the radiation intensity on current density

Figure 1: Fig. 1. Dependence of the radiation intensity on current density

sufficient level of injection, when negative absorption exceeds the active losses, amplification of radiation propagating along the p-n junction arises in the semiconductor. The polished faces of the crystal, situated strictly perpendicular to the p-n junction, form the mirrors of a volume resonator, producing the feedback necessary for generation. The quality factor of the resonator is determined mainly by active absorption, reflection from the polished faces of the sample, and diffraction. The quality factor due to active absorption by free carriers is equal to

$$Q_n = \frac{\varepsilon_0 \omega^3 \tau^2}{4\pi\sigma}, \tag{2}$$

where ε_0 is the dielectric constant, σ is the conductivity, τ is the relaxation time of the current carriers, and ω is the radiation frequency. The quality factor determined by reflection is given by the formula (^{8})

$$Q_0 = \frac{2\pi\varepsilon_0 L}{\lambda(1-R)}, \tag{3}$$

where L is the distance between the polished faces, R is the reflection coefficient, and λ is the radiation wavelength.

For a semiconductor with mobility $3 \cdot 10^3$ cm^2 V^{-1} sec^{-1}, carrier concentration $\sim 10^{18}$ cm^{-3} ($\tau \simeq 0.2 \cdot 10^{-12}$ sec., $\sigma \simeq 0.5 \cdot 10^3$ Ω^{-1} cm^{-1}), $\varepsilon_0 \simeq 10$, $R \simeq 0.3$, having dimensions $L = 5 \cdot 10^{-2}$ cm, the value of the quality factor (2) and (3) for radiation with $\lambda = 0.84$ μ ($\omega \simeq 2 \cdot 10^{15}$) is: $Q_n = 5.9 \cdot 10^5$ and $Q_0 = 5.3 \cdot 10^4$.

The value of the quality factor due to diffraction, in the approximation of geometrical optics, is given by the expression [8]

$$Q_d = \frac{4\pi d^2 \varepsilon_0}{\lambda^2}, \tag{4}$$

where d is the thickness of the field-localization region. For $d = 10^{-3}$ cm, $Q_d = 1.8 \cdot 10^4$. But, as shown in [9], the actual value of Q_d is greater than that given by formula (4) by approximately an order of magnitude.

Fig. 1. Dependence of the radiation intensity on current density

Near the p—n junction the carrier concentration changes appreciably, which leads to a dependence of the dielectric constant on the coordinate in the direction

* For indirect transitions, condition (1) is written differently (^{2}).

perpendicular to the p—n junction. This may give rise to reflection for radiation propagating at small angles to the plane of the p—n junction and to a reduction of the losses due to diffraction.

When negative absorption occurs, the spectral composition of the radiation changes. The intensity of radiation in the direction parallel to the plane of the p—n junction is determined by the expression

$$J(\omega) = \frac{(1-R)J_0(\omega)}{[\alpha(\omega)-\chi(\omega)]L}\frac{\exp\{(\alpha-\chi)L\}-1}{1-R^2\exp\{2(\alpha-\chi)L\}}, \tag{5}$$

where $J_0(\omega)$ is the intensity of spontaneous radiation in the direction parallel to the junction, $\alpha(\omega)$ is the gain coefficient, and $\chi(\omega)$ is the absorption coefficient determining the quality factor (2),

$$\chi(\omega) = \frac{2\pi\varepsilon_0^{1/2}}{\lambda Q_n}. \tag{6}$$

The gain coefficient near the edge of the absorption band of a semiconductor, in the case of direct transitions, can be written in the form [10]:

$$\alpha(\omega) = \frac{8\pi e^2(2m_n)^{3/2}}{3\varepsilon_0^{1/2}m^2\hbar^3\omega c}|M|^2(\hbar\omega-\Delta)^{1/2}\left[f_e(\varepsilon)+f_p(\hbar\omega-\varepsilon)-1\right], \tag{7}$$

where M is the transition matrix element, m_n is the reduced mass, and $f_e(\varepsilon)$ and $f_p(\hbar\omega-\varepsilon)$ are the distribution functions of electrons and holes with energies ε and $\hbar\omega-\varepsilon$, respectively, determined with allowance for the conservation of momentum (the energy is measured from the lower edge of the conduction band). The condition for positivity of $\alpha(\omega)$ is fulfilled in the energy interval where $f_e(\varepsilon)+f_p(\hbar\omega-\varepsilon)>1$, which can be rewritten as

$$\mu_e+\mu_p>\hbar\omega. \tag{8}$$

The vanishing of the denominator of the last factor in formula (5) corresponds to fulfillment of the self-excitation condition of the generator:

$$R\exp\{[\alpha(\omega)-\chi(\omega)]L\}>1. \tag{9}$$

As follows from formula (5), on approaching the self-excitation threshold the spectral width of the emission line decreases. Indeed, if the spectral width of the emission line is characterized by the frequency difference $\omega-\omega_0$, for which, respectively, $a(\omega)-\varkappa(\omega)=\frac{1}{2}[a(\omega_0)-\varkappa(\omega_0)]$, where $a(\omega_0)-\varkappa(\omega_0)$ is the maximum gain coefficient, then, for the intensity ratio on approaching the self-excitation threshold, to order of magnitude one will have:

Figure 2

Figure 2: Figure 2

$$\frac{J(\omega_0)}{J(\omega)} \simeq \frac{(1-R)^2}{4R^{1/2}(1-R^{1/2})[1-R\exp\{[a(\omega_0)-\varkappa(\omega_0)]L\}]}. \tag{10}$$

It follows from this that the spectral width of the emission line decreases, i.e.

$$\delta\omega \simeq \delta\omega_0 \frac{4R^{1/2}(1-R^{-1/2})}{(1-R)^2}\{1-R\exp\{[a(\omega_0)-\varkappa(\omega_0)]L\}\}. \tag{11}$$

Because of the large magnitude of the transition matrix element in semiconductors, the gain coefficient changes sharply when the value of $\mu_e+\mu_p$ changes; hence it follows that, when the self-excitation conditions are satisfied, $\mu_e+\mu_p$ will be close to the value $\hbar\omega$. Therefore $a(\omega)$ can be expanded in powers of $\mu_e+\mu_p-\hbar\omega$, and the self-excitation condition can be written in the form:

$$\mu_e+\mu_p \simeq \hbar\omega + \frac{1}{2}\left(\varkappa - \frac{1}{L}\ln R\right) \times \left[\left(\frac{\partial a}{\partial \mu_e}\right)^{-1} + \left(\frac{\partial \varkappa}{\partial \mu_p}\right)^{-1}\right]. \tag{12}$$

Fig. 2. Emission spectrum for two values of the current through the junction (the scale along the ordinate axis is different for the two curves)

Because of the saturation effect in the generation regime, the quantity $\mu_p+\mu_e$ will have a value close to that given by formula (12). This circumstance makes it possible to estimate the efficiency of a semiconductor optical generator with injection through a p—n junction:

$$\eta = \frac{\hbar\omega\,(I-I_0)}{eVI}\,\frac{1-e^{-\varkappa L}}{\varkappa L}, \tag{13}$$

where I_0 is the current corresponding to the self-excitation threshold, I is the total current, and V is the voltage applied to the semiconductor. The second factor in (13) takes into account absorption of the generated radiation before it leaves the sample.

Formula (13) shows that, for a sufficiently large ratio I/I_0 and small ohmic losses in the sample, the efficiency of such a generator can be rather high.

We have obtained generation of coherent radiation at p—n junctions in GaAs at a temperature of 77° K. The samples studied were prepared by diffusion of impurities into heavily doped GaAs in such a way that the p—n junction formed was sufficiently flat and optically

Figure 3

Figure 3: Figure 3

Fig. 3. Luminescence region of p—n junctions for different injection currents: a —10 A, b —18 A

homogeneous. Two surfaces perpendicular to the plane of the p–n junction were carefully polished and, because of the high reflection coefficient, with sufficient parallelism they provided the feedback necessary for generation. The area of the p–n junctions was about 10^{-3} cm^2. The radiation was observed in the plane of the p–n junction, perpendicular to the polished faces of the crystal.

Injection of minority carriers through the p–n junction was carried out by applying current pulses in the forward direction. The pulse duration was less than 3 μs, with a repetition frequency of 50 Hz. The dependence of the radiation intensity on the magnitude of the current for one of the samples is shown in Fig. 1. At low currents the emission line corresponded to interband transitions with a width of 130 Å. The current density corresponding to the sharp increase in intensity was about 10^4 $\mathrm{A \cdot cm^{-2}}$. At the same time, at this current density the radiation spectra showed the narrowing of the emission line depicted in Fig. 2. With a further increase in current, the spectral width of the line decreased sharply, and measurements with a Fabry—Perot interferometer showed that the line width was from 1 to 5 Å. The gradual narrowing of the emission line is associated with the appearance of population inversion in the p–n junction, leading to amplification of the radiation passing through the plane of the p–n junction. The subsequent sharp narrowing of the line indicates the establishment of feedback in the system and the transition of the system to the generation regime.

The luminescent region of the crystal was observed with an infrared microscope. When the current density corresponding to the onset of generation was reached, the brightness of a certain region of the crystal increased sharply. Photographs of the luminescent region obtained with the aid of the infrared microscope are shown in Fig. 3. The width of the luminous region is about 10–15 μ. We note that, as the current density increases, the width of the generating region decreases, which is apparently connected with the appearance of induced-recombination processes occurring in a region smaller than the initial diffusion length. In some of our samples we observed the simultaneous luminescence of two junctions whose planes were parallel and separated from one another by a distance of about 30 μ.

The authors express their gratitude to L. Ya. Krol'for providing gallium arsenide single crystals, to Yu. N. Korolev, N. N. Borzunov, L. N. Novak, and Yu. P. Zakharov for assistance in the work, and to V. I. Malyshev and A. M. Leontovich for a number of valuable suggestions.

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Academy of Sciences of the USSR

Received
11 February 1963

CITED LITERATURE

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