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## Abstract

## Full Text

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*PHYSICS*

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# POSSIBILITY OF MODULATING THE RADIATION OF A SEMICONDUCTOR QUANTUM GENERATOR BY HEATING THE CURRENT CARRIERS

The small dimensions and short lifetimes of nonequilibrium current carriers in semiconductor quantum generators make them especially promising for use as ultrafast optical switches. The switching rates that can be achieved here are determined by several characteristic times.

1) If the applied excitation is modulated, then the change in radiation intensity is determined by the spontaneous lifetime of the nonequilibrium carriers (for gallium arsenide, $\sim 10^{-9}$ sec.) ([1]).

2) A second characteristic time that can determine the speed is the time of change of the inverted population in induced transitions, either due to external radiation or due to the field within the generator itself (various types of spikes). In this case the characteristic time may be considerably shorter than the spontaneous lifetime of the nonequilibrium carriers, although at present it is difficult to indicate the limiting speed that can be obtained using this characteristic time ([2]).

The presently achieved magnitudes of the electromagnetic field in the resonator of semiconductor quantum generators make it possible to realize times of $10^{-10} \div 10^{-11}$ sec.

3) The modulation time of the resonator $Q$. In principle, the characteristic time in this case can be reduced to the establishment time in the resonator ($\sim (\omega_0/Q)^{-1}$, where $Q$ is the resonator $Q$, $\omega_0$ is the frequency of the emitted light). For semiconductor generators this time can be made shorter than $10^{-12}$ sec. However, as yet no ways are evident for the technical realization of even much longer switching times by changing the resonator $Q$.

4) In this article we discuss the possibility of changing the radiation intensity of a semiconductor generator by decreasing the inverted population, in fact the gain coefficient, upon heating the electron-hole gas. Heating can be carried out by intense optical radiation. In contrast to case 2), here

no change occurs in the number of active electron-hole pairs; only their effective temperature changes.

If in case 2) the frequency of the external radiation cannot be less than the band-gap width and the radiation must have a sufficiently narrow spectrum, then it is more convenient to heat the carriers with longer-wavelength radiation, and this radiation may have a broad spectrum. When long-wavelength radiation is used to quench generation, as follows from the conclusions obtained at the end of the article, a lower power is also needed in comparison with case 2) (there this power is comparable with the generated power).

As will be shown below, the time of increase and decrease of the carrier temperature is connected with the slowing-down time of the carriers having the largest effective mass (3).

We shall assume that in the semiconductor the generation regime is realized near the self-excitation threshold and, consequently, only one type of oscillation is excited (single-mode regime). In this case the rate equations for the time variation of the number of photons and nonequilibrium electron-hole pairs have the form

$$dN/dt = -N/\tau_r + ckNV; \tag{1}$$

$$dn_e/dt = (n_e^0 - n_e)/\tau_e - kcN; \qquad dn_p/dt = (n_p^0 - n_p)/\tau_p - kcN,$$

where $N$ is the number of photons in the resonator; $c$ is the speed of light; $k$ is the gain coefficient (cm$^{-4}$); $V$ is the volume of the active region of the semiconductor diode; $n_e$ ($n_p$) is the density of nonequilibrium electrons (holes); $n_e^0$ ($n_p^0$) is the initial density of electrons and holes characterizing the pumping; $\tau_e$ is the electron lifetime; $\tau_p$ is the hole lifetime in the absence of an electromagnetic field; $\tau_r$ is the photon lifetime in the resonator.

An increase in the temperature of the nonequilibrium carriers will naturally reduce the population inversion, which will lead to a decrease in the gain coefficient and to a decrease in the number of generated photons.

In the calculation we shall everywhere assume that the collision time between carriers is so small that the electron-hole gas has a single temperature, which may differ from the lattice temperature. This assumption is justified, since in semiconductor generators the carrier-carrier collision time is $\sim 10^{-13}$ sec, which is shorter than all other characteristic times (4).

The influence of the temperature of the electron-hole gas on the gain coefficient is connected primarily with the degree of degeneracy of the electrons and holes. Under strong degeneracy of the recombining electrons and holes, a comparatively small change in temperature will have little effect on the population inversion, and the effect of decreasing the number of photons will be small. If, however, carriers of one kind are nondegenerate (whether holes or electrons), then a small change in their temperature will strongly affect the population inversion and the gain coefficient.

We shall proceed from a semiconductor model in which radiative recombination occurs in an interband transition. Such a model is valid for a pure semiconductor excited by an electron beam or by optical radiation.

We shall assume that the electron gas is degenerate, while the holes, since they have a larger effective mass, are nondegenerate. The relation between the concentration of electrons (holes) and the corresponding quasi-Fermi levels has the form

$$n_e = \frac{1}{3\pi}[8m_e\mu_e/\hbar]^{3/2}; \qquad n_p = 2[2\pi m_p kT/h^2]^{3/2}\exp(\mu_p/kT). \tag{2}$$

Here $\mu_e$ and $\mu_p$ are the quasi-Fermi levels; $m_e$ and $m_p$ are the masses of the electrons and holes. If one uses the form of the gain coefficient for the case of direct interband transitions (4), then for the case of interest to us, under assumption (5), it is not difficult to obtain the gain coefficient at the maximum:

$$K(\omega) = \frac{2\alpha}{3\sqrt{3}}\,\frac{1}{kT}\,|\mu_e + \mu_p|^{3/2}\exp(\mu_p/kT), \tag{3}$$

where

$$\alpha = 4\sqrt{2}\,e^2|\langle M\rangle|^2(m^*)^{3/2}/\overline{D}m^2\hbar^3\omega c;$$

$\omega$ is the radiation frequency; $D$ is the dielectric constant of the semiconductor; $\langle M\rangle$ is the matrix element of the momentum operator; $m^*$ is the reduced mass of the electron and hole.

Substituting expressions (2) and (3) into the system of equations (1), for the stationary case we obtain an expression for the number of photons $N$ in the resonator as a function of temperature. The calculations are simple but cumbersome; the final expression for the number of photons is also cumbersome, so that we···

we shall not give it here, but shall proceed as follows. Introduce the quantity $\delta$, characterizing the change in the temperature of the electron-hole gas,

$$\delta = (T - T_0)/T_0,$$

and the quantity $\beta$, which we introduce in the following way:

$$\beta = [n_e^{\Pi}(T_1) - n_e^{\Pi}(T_0)]/n_e^{\Pi}(T_0),$$

where $n_e^\Pi(T)$ is the threshold electron density at temperature $T$. If generation occurred at $T = T_0$, then the quantity $\beta$ determines (in relative units) by how much the threshold value of the electron density must be changed in order to disrupt generation.

We are interested in the question: by how much must the temperature of the electron-hole gas be changed in order to disrupt generation? The answer to this question is given by the relation between $\delta$ and $\beta$.

For the case of direct interband transitions, the calculation shows that the relation between $\delta$ and $\beta$ is determined by the formula

$$\beta = \delta \left[ {}^5/_2 + {}^9/_4 kT_0/(\mu_e^0 + \mu_p^0) - {}^3/_2 \mu_p^0/(\mu_e^0 + \mu_p^0) \right], \tag{4}$$

where $\mu_e^0$, $\mu_p^0$ are related to the initial concentrations of electrons and holes* by expressions (2), in which $n_e$ and $n_p$ are replaced by $n_e^0$, $n_p^0$, and $\mu_e$, $\mu_p$, $T$ by $\mu_e^0$, $\mu_p^0$, $T_0$. From formula (4) it is seen that $\beta$ and $\delta$ are related by a coefficient 5/2, i.e., when the carrier temperature is changed by 10%, generation can be disrupted if the initial excess over threshold is 25%.

Since in the case of heavily doped semiconductors other mechanisms of radiative recombination are possible, in addition to interband transitions we also considered other models: a band-impurity transition, with the density of states in the conduction band either $\sim (\hbar\omega - \Delta)^{1/2}$, or $\sim \exp(E/E_0)$, while the impurity level is described by a $\delta$-function. If the population of the impurity level does not depend on temperature, then the calculation shows that $\beta \sim \delta$ (the proportionality coefficient, depending on the assumptions, ranges from several units to several tenths).

If, however, the number of holes on impurities changes with temperature, with

$$P(T) = N_\Pi^2 / 2N_{\text{eff}} \exp\left(\frac{\Delta}{kT}\right),$$

then disruption of generation due to carrier heating may prove very effective. Thus, if the density of states in the conduction band is $\sim (\hbar\omega - \Delta)^{1/2}$, then the relation between $\beta$ and $\alpha$ has the form $\beta = \dfrac{3\Delta}{kT_0}\delta$, and if $3\Delta \gg kT_0$, then generation is comparatively easy to disrupt.

Let us now consider the question of the relation between the temperature of the electron-hole gas and the intensity of the heating optical radiation. Since the temperature of electrons and holes is the same, then, according to work (6), energy transfer from the electron-hole gas to the lattice will be carried out by the carriers having the lower mobility, i.e., by holes. In the absence of degeneracy, the change in energy is determined by (6)

$$dE/dt = 2a_0(kT)^{1/2}kT_0\delta n_p. \tag{5}$$

If light of intensity $I$ falls on the semiconductor, then the energy absorbed per unit volume is

$$dE/dt = I(\sigma_e n_e + \sigma_p n_p), \tag{6}$$

where $\sigma_e$ and $\sigma_p$ are the light-absorption cross sections for an electron and a hole. Equating (5) and (6), we obtain:

$$I = \frac{2a_0(kT_0)(kT)^{1/2}\delta}{\sigma_e n_e/n_p + \sigma_p} \approx \frac{2a_0(kT_0)^{3/2}\delta}{\sigma_e n_e/n_p + \sigma_p}.$$

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* The initial concentrations of electrons and holes $(n_e^0, n_p^0)$ are determined by the initial excitation (see equations (1)).

Here

$$a_0 = 8u^2e/3\sqrt{\pi}\mu(T)(kT)^{3/2}.$$

For $T = 78°\text{K}$, $\mu(T) = 10^5$ cm$^2$/CGSE sec, $\frac{n_e}{n_p}\sigma_e \sim 10^{-17}$ cm$^2$ $(\lambda = 1\mu)$, we have $I \approx 4 \cdot 10^7\delta(T_0/78)^{3/2}$ W/cm$^2$.

If we take $\delta = 0.1$, i.e., $\beta$ (see formula (4)) equal to 0.25, and this means that a 10% change in temperature disrupts generation when the threshold is exceeded by 25%, then $I$ is $4 \cdot 10^6$ W/cm$^2$. Since the absorption cross section by free carriers is proportional to the square of the wavelength, for longer-wavelength radiation this value will be considerably smaller.

In what times will the electron-hole gas be heated? Combining (5) and (6), we find that the change in the energy of the gas as a function of time is determined by

$$dE/dt = I(\sigma_e n_e + \sigma_p n_p) - 2a_0(kT)^{1/2}kT_0 n_p\delta.$$

If we assume that $E = 1.5kT(n_e + n_p)$ $(5')$ and take into account that $n_e$ and $n_p$ do not change during heating, then we find that the temperature of the electron-hole gas approaches the stationary value (see formula (7)) according to an exponential law with exponent $-2a_0(kT_0)^{1/2}/1.5$, i.e., the gas is heated in a time $\sim 1.5/2a_0(kT_0)^{1/2}$. Substituting a characteristic value of $a_0$, we obtain a value $\sim 10^{-11}$ sec.

After the heating optical radiation is switched off, the carriers slow down over the same characteristic time $\sim 1.5/2a_0(kT_0)^{1/2}$, i.e., the slowing-down time is $\sim 10^{-11}$ sec.

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## References

1. W. F. Kosonocky, IEEE, Spectrum, 2, No. 3, 183 (1965).
2. N. G. Basov, Yu. M. Popov, A. N. Oraevskii, Proc. Leipzig Conf., 1965.
3. O. N. Krokhin, Yu. M. Popov, JETP, 38, 1589 (1960).
4. Yu. M. Popov, Proc. Phys. Inst. named after P. N. Lebedev, USSR Academy of Sciences, 31, 3 (1965).
5. O. N. Krokhin, Fiz. Tverd. Tela, 7, 2612 (1965). Yu. M. Popov, Fiz. Tverd. Tela, 6, 2445 (1964).

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

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