Effects of shallow acceptors in a germanium hot-hole laser

A. V. Murav'ev, S. G. Pavlov, E. E. Orlova, and V. N. Shastin
Institute of Applied Physics, Russian Academy of Sciences, 603600 Nizhniĭ Novgorod, Russia

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Recombination involving spontaneously emitted optical phonons leads to a significant filling of states of shallow acceptors in a *p*-Ge hot-hole laser. Under conditions corresponding to photoionization of the ground state, the recombination creates a population inversion involving these states. Calculations explain several features observed experimentally, including the effects of stimulated emission in impurity absorption lines.

The ballistic heating and scattering of holes by optical phonons emitted spontaneously in an electric field **E** crossed with a magnetic field **H** can set up a population inversion involving states of the valence band and can also lead to a stimulated emission on $l \rightarrow h$ intersubband optical transitions in *p*-Ge (Ref. 1). The model of intersubband transitions of free holes fails to explain several experimental results which have been obtained: the discrete lines in the emission spectrum of a Ge:Ga laser at the frequencies of the *C* and *E* absorption lines of the Ga acceptor[2,3] (Fig. 1), the increase in the conductivity of a *p*-Ge sample during a stimulated-emission pulse,[4] and the change in the sign of the time delay of the emission pulse from a *p*-Ge laser during pumping by long-wave IR light.[5]

Theoretical calculations show that these results can be explained on the basis of transitions in the spectrum of bound states of shallow acceptors (Fig. 2). Such transitions have not previously been taken into consideration because it has been assumed that such states are filled only slightly. That assumption is valid when these states are at thermodynamic equilibrium with the subsystem of hot holes, but it is not valid in the case of recombination accompanied by an emission of phonons at low lattice temperatures. It turns out that when holes are heated in crossed fields to effective energies T_{eff} on the order of the energy of an optical phonon ($\hbar\omega_0 = 37$ meV), at lattice temperatures no higher than 10–20 K (the working temperatures for a *p*-Ge laser), a recombination involving the emission of an optical phonon becomes effective. This recombination cools the charge carriers to impurity levels. As a result, the deepest acceptor levels, which cannot be emptied by impact processes, turn out to be highly populated.

The populations of the acceptor levels were calculated by the method of modified attachment probabilities, first used by Lax.[6] In that method, the effects of transitions involving the entire set of bound states on the formation of the populations of individual levels can be taken into account. The rates of transitions between states in the field of a Coulomb center are calculated in the model of a simple parabolic band with

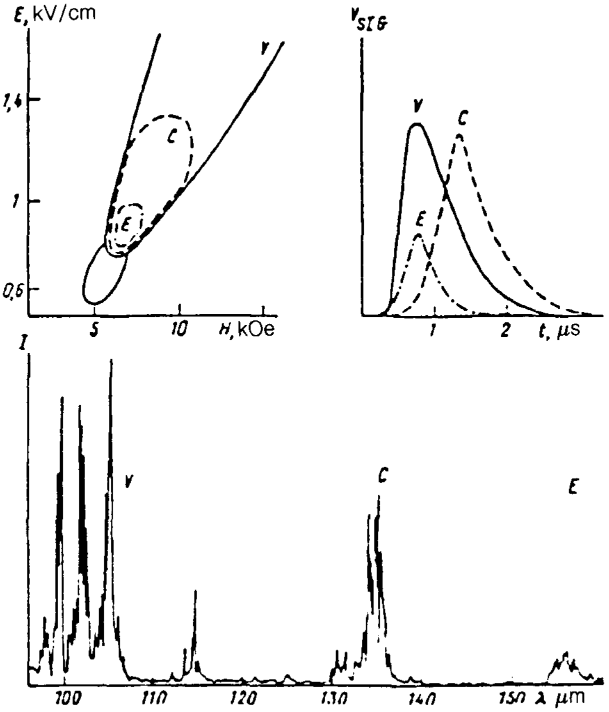

FIG. 1. Generation zones and oscilloscope traces of pulses in the E and C lines and the V region; output spectrum of a p-Ge laser at $E=0.8$ kV/cm and $H=7$ kOe.

a heavy-hole mass $m_h=0.38m_0$ (m_0 is the mass of a free electron). The acceptor states are assumed to be hydrogen-like.

In strong crossed fields $\mathbf{E}\perp\mathbf{H}$, many of the acceptors are emptied by impact ionization, and the distribution of free carriers is shaped by rapid acceleration in the fields and scattering by optical phonons. Since the time scales for these processes are much shorter than the recombination time, the population of the impurity levels was calculated in the approximation of a given distribution of free carriers.

At a hole concentration $n=10^{14}$ cm^{-3}, which is typical of a p-Ge laser, and at an average hole energy higher than the ionization energy of the ground state ($E_{\text{g.s.}}=11.4$ meV), the rates of transitions between acceptor levels in collisions with holes (Auger transitions) are at least an order of magnitude higher than the rates of the corresponding transitions in the interaction with acoustic phonons at low lattice temperatures. At $T_{\text{eff}} > E_{\text{g.s.}}$, on the other hand, Auger transitions in the spectrum of a Coulomb center, in which the density of states increases rapidly with decreasing ionization energy, are much more probable in the direction of higher-lying levels.

Under the conditions prevailing in a p-Ge laser, the cascade capture involving the emission of acoustic phonons is not an efficient mechanism for recombination, since the carriers are rapidly removed from highly excited impurity levels, which play a leading role in the cascade capture.[7] The carriers go to impurity levels through direct recombination, and the lifetimes in the impurity states are determined by cascade ionization.

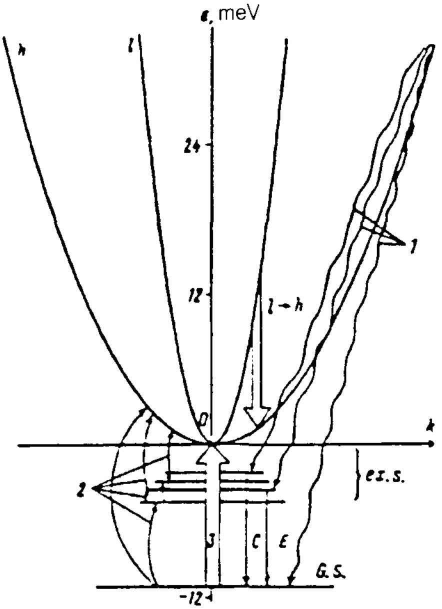

FIG. 2. Diagram of transitions in a Ge:Ga hot-hole laser. *1*—Recombination accompanied by emission of optical phonons; *2*—impact ionization of acceptor levels; *3*—photoionization of the ground state by stimulated emission on $l \to h$ transitions in the V region ($v = 100$ cm^{-1}).

At $T_{\rm eff} \simeq \hbar\omega_0$, on the other hand, there is a substantial number of free carriers with an energy sufficient for these carriers to be in an impurity level upon the emission of an optical phonon, and this process becomes the primary recombination mechanism. The recombination rate is calculated under the assumption of a constant energy of an optical phonon. As the wave functions for the free states we used asymptotic plane waves scattered by a Coulomb field.[8] For the bound states we used wave functions similar to those of a ground state with a localization length corresponding to the ionization energy, as in the hydrogen atom. Figure 3a shows the recombination rate versus the binding energy of the level, per free hole, for the case of a Maxwellian distribution with $T_{\rm eff} = \hbar\omega_0/2$. The increase in the rate of recombination to excited states with decreasing binding energy is due to a scattering of holes by the impurity potential.

In determining the overall rate of impact ionization we allowed for transitions through excited states, which we dealt with on the basis of calculations of the cross sections for excitation and ionization for the hydrogen atom.[9] This rate turns out to be $W_{\rm imp.ion.} = 4 \times 10^8$ s^{-1} for the ground state (g.s.); it increases roughly in inverse proportion to the square of the ionization energy of the excited states (ex.s.) (Fig. 3b).

In the absence of laser radiation, highly excited levels, which rapidly exchange particles with the heavy subband in the course of collisions, are thus in a state of thermodynamic equilibrium with that subband. Deeper levels are supersaturated as a result of recombination involving the emission of optical phonons and contain about 10% of the carriers (Fig. 3d).

Laser radiation on intersubband transitions in the V region may substantially change the populations of Ga acceptor levels. The rates of photoionization at a fre-

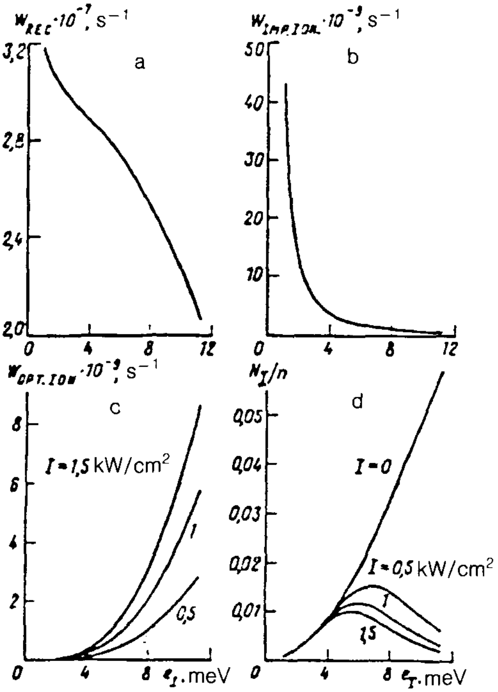

FIG. 3. Theoretical behavior of several properties as a function of the ionization energy of the level for various intensities of the laser radiation. a—Rate of recombination accompanied by the emission of an optical phonon; b—rate of impact ionization; c—rate of photoionization by $l\rightarrow h$ laser radiation; d—ratio of the populations of the impurity levels, N_i, to the number of free holes, n.

quency on the order of 100 cm^{-1} are shown in Fig. 3c for radiation intensities close to the level corresponding to saturation of $l \rightarrow h$ transitions. The photoionization rate is at a maximum for the ground state, since the frequencies of the V region (90–120 cm^{-1}) are near the threshold for photoionization. At intensities $I \geqslant 1$ kW/cm^2, it is much higher than the rate of impact ionization. In this case the ground state is essentially emptied. For excited states, the governing ionization mechanism is the impact mechanism, and the populations of these states are reduced to a lesser extent. As a result, a population inversion is set up between the excited and ground levels of the acceptor (Fig. 2). This inversion may result in a stimulated emission on ex.s. → g.s. optical transitions.

The model proposed here explains some experimental results which have been observed. The C and E lines in the output spectrum of a p-Ge laser are explained on the basis of a stimulated emission on corresponding ex.s. → g.s. optical transitions during photonionization of the ground state by radiation in the V region. The generation zones of the C and E lines are inscribed in the V region for $l \rightarrow h$ transitions, and the corresponding emission pulses always appear after a delay (Fig. 1). The increase in the conductivity of the p-Ge sample can also be explained on the basis of a photoionization of the acceptors by the $l \rightarrow h$ radiation. Measurements show that the "current jump" is more obvious for generation frequencies $\nu > 80$ cm^{-1} than for $\nu < 50$ cm^{-1}; this result corresponds to the frequency dependence of the efficiency of the photoionization of the acceptors. The shift of the output pulse of the laser during pumping by long-wave IR light is determined by two aspects of the effect of the light on the active medium of the p-Ge laser: first, the equalization of the populations of the subbands of light and heavy holes and thus the suppression of the intersubband $l \rightarrow h$ population inversion; second, the decrease in the population of acceptor states due to their photoionization. The first of these factors reduces the gain coefficient on $l \rightarrow h$ transitions. The second factor, which reduces the absorption on optical transitions from acceptor states, instead increases in the net gain coefficient. The relative weights of these factors depend on the photoexcitation frequency: The frequency[5] $\nu=48\ \text{cm}^{-1}$ turns out to be the one at which there is a transition from the delay effect to the stimulated development of laser radiation.

In summary, effects associated with states of shallow acceptors turn out to be important for reaching a qualitative understanding of the processes which occur in a germanium hot-hole laser. They point out some new possibilities for producing semiconductor active media for long-wave IR radiation with optical pumping. The effect of the strong fields $\mathbf{E} \perp \mathbf{H}$ on the states of the acceptors would be important for rigorous quantitative calculations.

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[1] *Special Issue on Far-Infrared Semiconductor Lasers*, J. Opt. Quant. Electron. **23**, No. 2 (1991).

[2] A. V. Murav'ev *et al.*, JETP Lett. **52**, 343 (1990); Yu. A. Mityagin *et al.*, Semicond. Sci. Technol. **7**, 641 (1992).

[3] R. L. Jones and P. Fisher, J. Phys. Chem. Solids **26**, 1125 (1965).

[4] S. Komiyama and S. Kuroda, Solid State Commun. **59**, 167 (1986); A. A. Andronov *et al.*, Infrared Phys. **27**, 31 (1987).

[5] F. Keilmann *et al.*, Appl. Phys. Lett. **58**, 2205 (1991); F. Keilmann and H. Zuckermann, "Transient gain of the germanium hot hole laser," to be published in Opt. Commun.

[6] M. Lax, Phys. Rev. **119**, 1502 (1960).

[7] V. N. Abakumov *et al.*, Zh. Eksp. Teor. Fiz. **72**, 674 (1977) [Sov. Phys. JETP **45**, 354 (1977)].

[8] H. A. Bethe and E. E. Salpeter, *Quantum Mechanics of One- and Two-Electron Atoms* (Academic, New York, 1957).

[9] K. Omidvar, Phys. Rev. A **140**, 26 (1965); K. Omidvar, Phys. Rev. A **140**, 38 (1965).

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