Stimulated emission on transitions between excited states and ground state of an acceptor impurity in germanium

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A discrete structure of the spectrum of the emission of long-wave IR laser by hot holes in Ge in **E**⊥**H** fields was observed. This structure is attributed to the additional gain on the transitions between the excited states and the ground state of the acceptor impurity. The mechanisms for the gain on the impurity-band transitions and transitions between the impurity states are discussed.

1. Two mechanisms are known for the inversion of the population of states of the valence band of Ge in an electric field crossed with a magnetic field **E**⊥**H**. One mechanism, which is responsible for the redistribution of holes between the light subband, l, and the heavy subband, h, in the inelastic scattering by optical phonons,[1] leads to a gain on the direct optical l–h transitions.[2-4] The other one accounts for the population inversion of the lower Landau levels of the light holes due to the intersubband tunneling[5] and leads to a gain on the cyclotron resonance of light holes[6,7] and on its harmonics.[8]

In the present letter we report the observation of a discrete structure of the spectrum of the emission of laser light by hot holes in Ge in the wavelength range $\lambda \simeq 150$–$200\ \mu$m, which cannot be explained by any gain mechanism and which we attribute to the gain produced on the transitions between the excited states and the ground state of the acceptor impurity in Ge. The corresponding population inversion occurs because of the saturation of the impurity band radiative transitions (l excited states) resulting from the increase in lasing on the l–h transitions.

2. The spectra of the stimulated emission of holes in $\mathbf{E}\perp\mathbf{H}$ were studied using commercial Ga-doped Ge samples (Table I). The faces of the samples were optically processed with mutual plane-parallel orientation of the faces better than 1′. The samples were cooled in liquid helium and a pulsed electric field $\mathbf{E}\parallel[110]$ was applied to them through ohmic contacts at the lateral faces. The magnetic field was oriented along the long axis of the samples: $\mathbf{H}\parallel[111]$ for samples $N1$ and $\mathbf{H}\parallel[110]$ for samples $N2$–$N6$. Lasing was increased either on total internal-reflection modes (samples $N1$ and $N4$) or on the axial resonator modes with external mirrors (sample $N3$), or on both modes (samples $N2$, 5, and 6), depending on the electrodynamic system. In all cases we used oversized, wide-band resonators. The laser light was transmitted through a grating monochromator and was recorded by cooled p-Ge(Ga) and n-GaAs photodetectors.

3. The emissions spectra near $\lambda \simeq 150$–$200\ \mu$m were found to have a discrete nature, in contrast with the complex spectrum near $\lambda \simeq 75$–$140\ \mu$m (the V region). The strongest discrete lines of those we observed correlate with the impurity absorption lines of Ge:Ga (Ref. 9)—the G line ($185\ \mu$m) and the E line ($155\ \mu$m) (Fig. 1). The position of these lines does not depend on the strength of the applied field in the lasing range (Fig. 2), on the type of resonator or on its size, on the crystallographic orientation, the degree of doping of Ge samples, or on the type of detector. Lasing or the E line, in contrast with the G line, does not develop without the lasing on the

TABLE I.

Ge quality	Ga $N_A - N_D$, 10^{13} cm^{-3}	Sample size, mm^3	Resonator circuit	Extrinsic transitions		V region, μm
				G	E	
GDG45D6	5,0	$N1$ 5 × 7 × 51	Fig. 1a	Ga,B,X	Al,X	80-140
GDG40D6/3/	7,0	$N2$ 5 × 7 × 65	Fig. 1b	Ga,X	Ga	75-130
- " -	- " -	$N3$ 4 × 7 × 40		Ga,Al	Ga,B	80-135
- " -	- " -	$N4$ 5 × 9 × 81	Fig. 1c	Ga	-	80-125
GDG30D6/3/	9,2	$N5$ 3 × 5 × 52	Fig. 1b	Ga	-	75-125
GDG20D6/3/	14	$N6$ 3 × 8 × 65	Fig. 1b	Ga	-	75-115

Note. Ga, Al, and B lines are identified; X line is not identified.

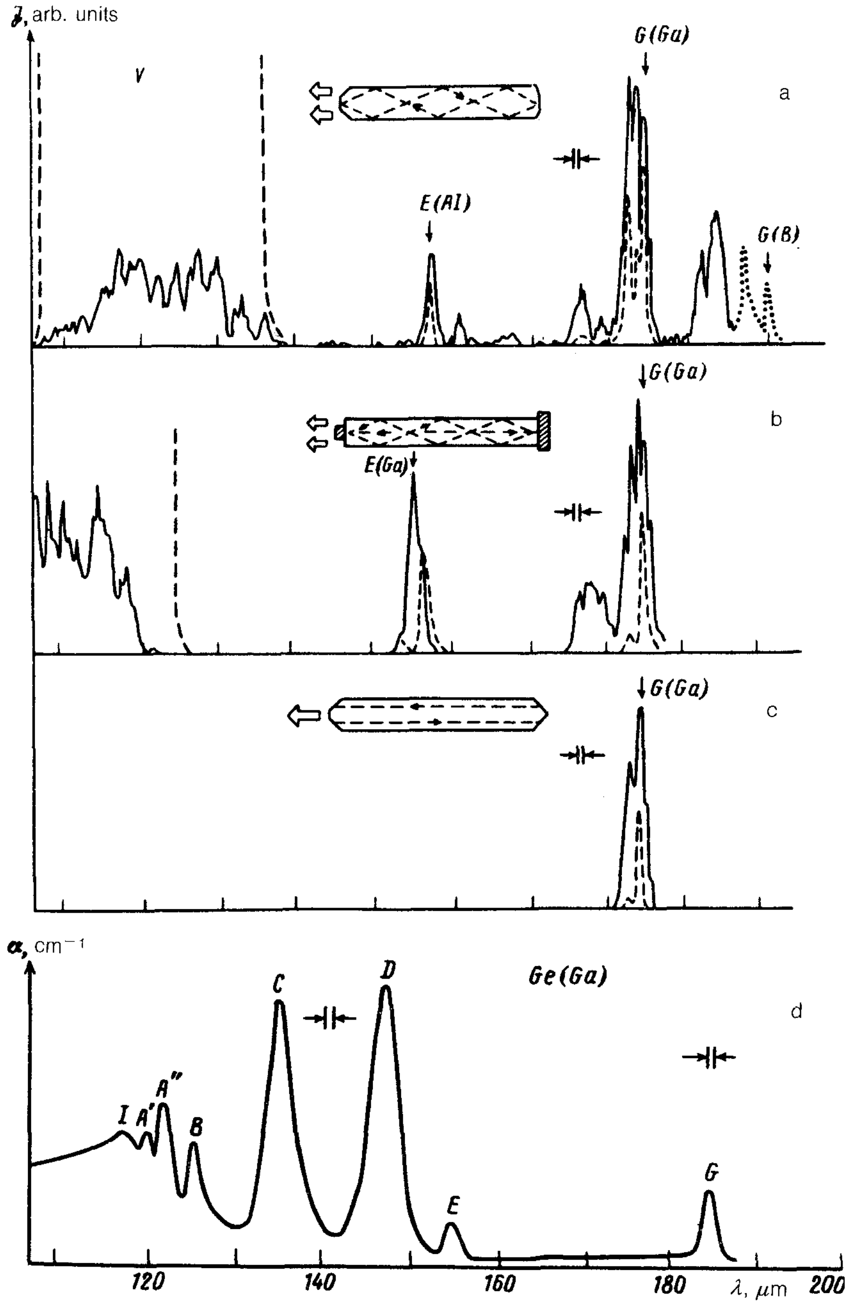

FIG. 1. Laser emission spectra (a–c): (a) sample $N1$, $H = 7$ kOe, $E = 900$ V/cm; the points denote the part of the spectrum which appears at $H = 5.5$ kOe, $E = 700$ V/cm; (b) $N2$, 6.5 kOe, 850 V/cm; (c) $N4$, 4.5 kOe, 600 V/cm; solid line—n-GaAs detectors; dashed line—p-Ge(Ga) detectors; (d) absorption spectra of Ge:Ga with $N_A \simeq 2 \times 10^{14}$ cm^{-3}, $T = 9$ K (Ref. 9).

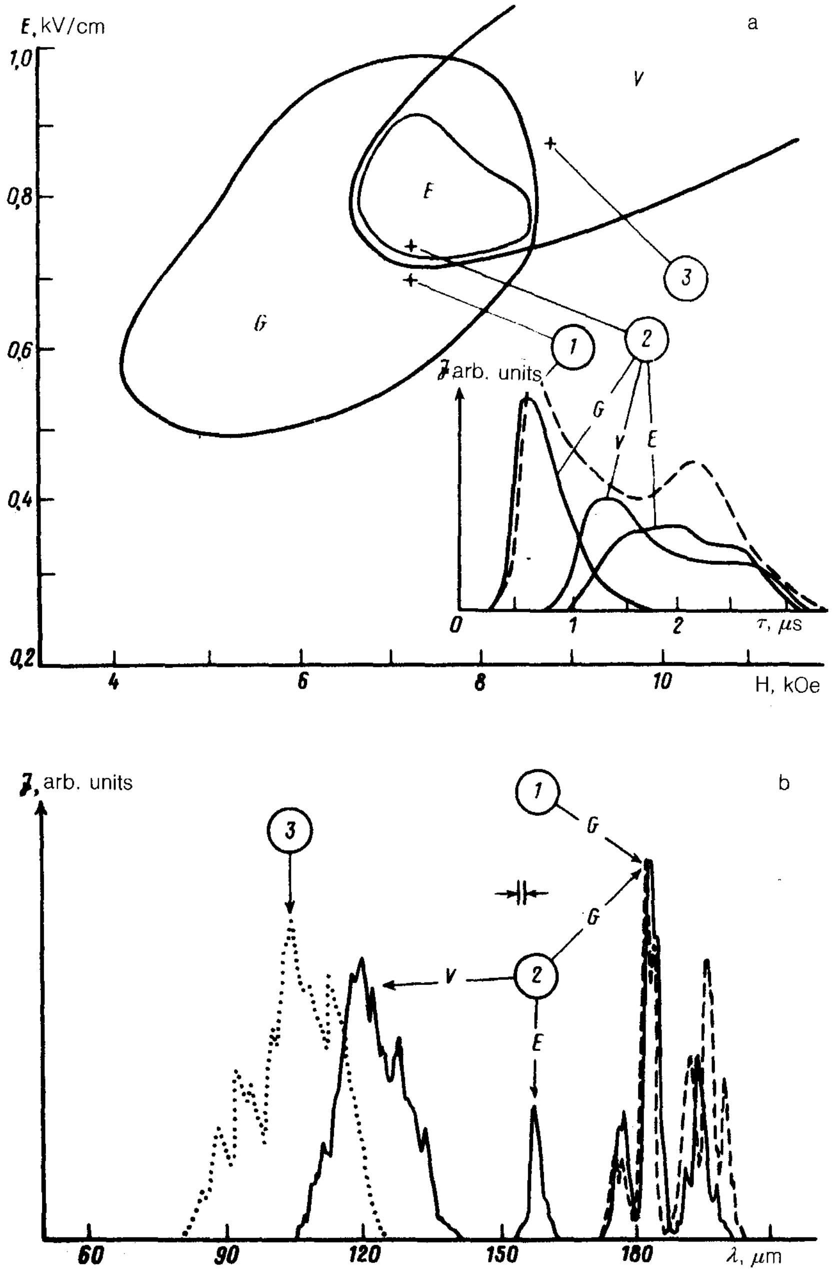

FIG. 2. Characteristic features of the emission of sample $N1$: (a) lasing zones and shape of the laser pulses (insets) at three wavelengths λ: $G \simeq 185$, $E \simeq 157$, $V \simeq 125$ μm and (b) the emission spectra in the fields: 1) $H = 7.2$ kOe, $E = 710$ V/cm (dashed curve); 2) 7.2 kOe, 740 V/cm (solid curve); 3) 8.8 kOe, 880 V/cm (points).

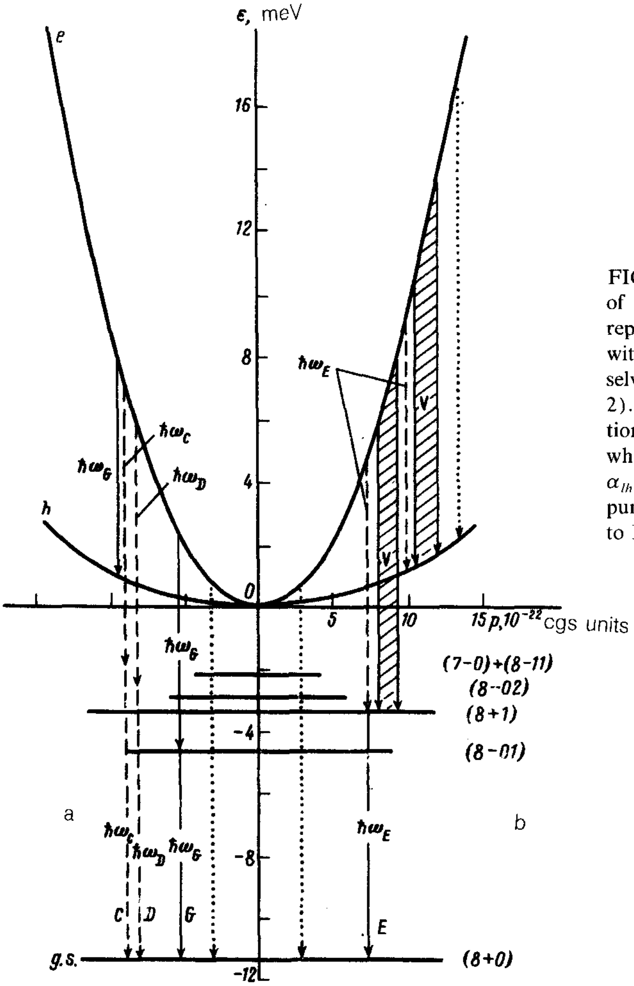

FIG. 3. Extrinsic radiative transitions of G (left) and E (right). The points represent the competing transitions with $\hbar\omega \geqslant \epsilon_{g.s.}$, which manifest themselves in strong fields (point 3 in Fig. 2). Dashed curve—Unobserved transitions C and D (left) and transitions which occur in the frequency gap on α_{lh} (right). The localization of the impurity states were established according to Ref. 10.

spectral band V (the "anticompetition" effect) (Fig. 2a). The curve on the G and E line intensities versus the magnetic field has several extrema which stem from the amplification of the resonance of the light holes on 3–5 harmonics, similar to that observed previously in the V region of lasing.[8]

4. To explain the results we obtained, we note that the process of impact ionization in a strong electric field equalizes the impurity state populations and the heavy hole subband states and the inversion on the l–h transitions automatically indicates an inversion in the transitions from the light subband to the impurity states. The corresponding optical transitions $l \rightarrow$ ground state and $l \rightarrow$ excited states are an additional amplification channel with a gain a_{li} (which for $N_A - N_D \gtrsim 10^{15}$ cm^{-3} can be compared with the l–h gain a_{lh}). The broad spectrum of these transitions is overlapped by the l–h gain band (the ionization energy of the ground state $\varepsilon_{g.s.} = 11.3$ meV corresponds to $\lambda \simeq 110\,\mu$m). These transitions are therefore difficult to identify against the background of lasing on the l–h transitions.

On the other hand, the induced $l \to$ excited state transitions equalize the population of the light subband and of the corresponding excited state, thus creating a population inversion on the excited state $\to$ ground state transitions. The probability for a cascade two-photon transition ($l \to$ excited state $\to$ ground state) is proportional to the product of the spectral intensity $J(\tilde{\omega})$ at the frequency $\tilde{\omega} = (\varepsilon_{ex.s.} - \varepsilon_{g.s.})/\hbar$ and the integral emission intensity $I = \int J(\omega)d\omega$, which is a kind of optical pumping. Figure 3 shows two types of such transitions: (a) one in which the energy of the inducing photon coincides with $\hbar\tilde{\omega}$ and (b) one in which it does not coincide with $\hbar\tilde{\omega}$. The latter case is possible if $\alpha_t = \alpha_{lh} + \alpha_{li} - \beta$ (where β is the loss factor) has a gap near the frequency $\tilde{\omega}: \alpha_t(\tilde{\omega}) < 0$. This gap is present in α_{lh} at $\lambda \simeq 140$–$160\,\mu$m because of the intersubband impurity scattering.[3,4] Disregarding the saturation, the total gain at the frequency $\tilde{\omega}$ is $\alpha(\tilde{\omega}) = \alpha_t(\tilde{\omega}) + \gamma I$. In case (a) the term γI leads to a faster than an exponential increase of $J(\tilde{\omega})$: $J(\tilde{\omega}) \sim 1/(\exp(-\alpha_t(\tau - \tau_0)) - 1$, and in case (b) it leads to a strict pumping regime at the frequency $\tilde{\omega}$.

The gain mechanism (a), in our view, accounts for the laser output in the G line and mechanism (b) accounts for the output in the E line. This also accounts for the anticompetition effect for the E line (the emission in the V band serves as the optical pumping) and for the fact that lasing in the G line occurs before it does at other frequencies. Suppression of G line upon increasing the lasing in the V band occurs because of the frequency competition on the l–h optical transitions (point 2 in Fig. 2). Expansion of the spectrum for the emission on the l–h transitions into the region $\lambda \leqslant 110\,\mu$m by increasing the E and H fields (point 3 in Fig. 2) leads to the appearance of induced $l \to$ ground state transitions which increase the ground state population and thus lift the population inversion in the excited state $\to$ ground state transitions, which leads to the disappearance of lasing in the G and E lines. The absence of the emission spectra of other extrinsic lines (C,D) is attributable to the inefficient optical ($l \to$ excited state) pumping at the frequency $\tilde{\omega}_C\,(\tilde{\omega}_D)$ (Fig. 3a), and especially in the V band because of the stronger localization of the wave functions of the corresponding impurity states in the **p** space.

Analysis of the results thus shows that the discrete nature of the long-wavelength part of the laser spectrum is due to the stimulated emission on the transitions between the lower excited states and the ground state of the acceptor impurity in Ge: G—$(8 - 01) \to (8 + 0)$ and E—$(8 + 1) \to (8 + 0)$.

We note, in conclusion, that in addition to Ga, the Ge samples which were tested could also have impurities of other group III elements: B, Al, In (Ref. 11) and some of the lines of the laser emission spectra correlate with the G and E transitions for B and Al (see Table I and Fig. 1). To confirm these conclusions, it would be desirable to study samples with a different dopant.

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