# Intracenter population inversion as the reason for induced emission in highly deformed *p*-type Ge

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(Submitted 18 February 1994)
Pis'ma Zh. Eksp. Teor. Fiz. **59**, No. 7, 455–458 (10 April 1994)

Experimental results show that stimulated emission from *p*-type Ge subjected to uniaxial compression results from an inversion of the filling of impurity levels. These levels form from the ground state of the acceptor, which is split by the deformation. One of the levels lies in a continuous band spectrum.

The far-IR stimulated emission of hot holes which we have observed[1] in uniaxially compressed *p*-type Ge in the absence of a magnetic field was linked to a population inversion of valence subbands split by the deformation. We proposed a model[2] which has the intersubband inversion resulting from a ballistic acceleration of holes of the lower band (lower along the energy scale) to the energy corresponding to the edge of the upper band, followed by an intersubband transition involving acoustic phonons. Monte Carlo calculations[3] have shown, however, that an intersubband redistribution of hot holes does not lead to an inversion. The reason for the inversion which leads to the stimulated emission from deformed germanium[1,2,4,5] has thus remained an open question. In this letter we report experimental data which demonstrate that the reason for the stimulated emission observed in uniaxially deformed *p*-type Ge is a population inversion of acceptor states which are split by the compression.

Uniaxial deformation lifts the degeneracy of the valence band at $k=0$ and splits this band into two subbands, which are separated by an energy gap $\Delta$ proportional to the pressure $P$ (with a proportionality factor of about 4 meV/kbar for $P\|[111]$ and about 6 meV/kbar for $P\|[100]$; Ref. 6). The degenerate ground state of an acceptor in Ge is also split into two levels, separated by an energy gap which depends on $P$. Figure 1a shows the energy distance between these levels (1) and the ionization energy of the lower level (2), as calculated from Eqs. (27.18) of Ref. 6, as a function of $\Delta$. Figure 1b is a schematic diagram of the structure of the valence band; also shown here are the positions of the impurity levels for various values of $\Delta$. At $\Delta \geqslant 16$ meV, the top level among these levels is in a energy region corresponding to a continuous spectrum (the point at which the curves in Fig. 1a intersect and band scheme 2 in Fig. 1b). It is natural to suggest that, beginning at this splitting, the filling of the two acceptor ground states may be inverted, since the filling of the lower level, in the band gap, is reduced by impact ionization caused by the electric field to a point below the filling of the upper level, in the valence band. Indeed, the minimum pressure at which stimulated emission could be observed in the configuration $E\|P\|[111]$ in certain samples was 4 kbar ($\Delta \approx 16$ meV) (Ref. 5).

In most of the samples a stimulated emission arises at $P \approx 9$ kbar for the $P\|[111]$

  

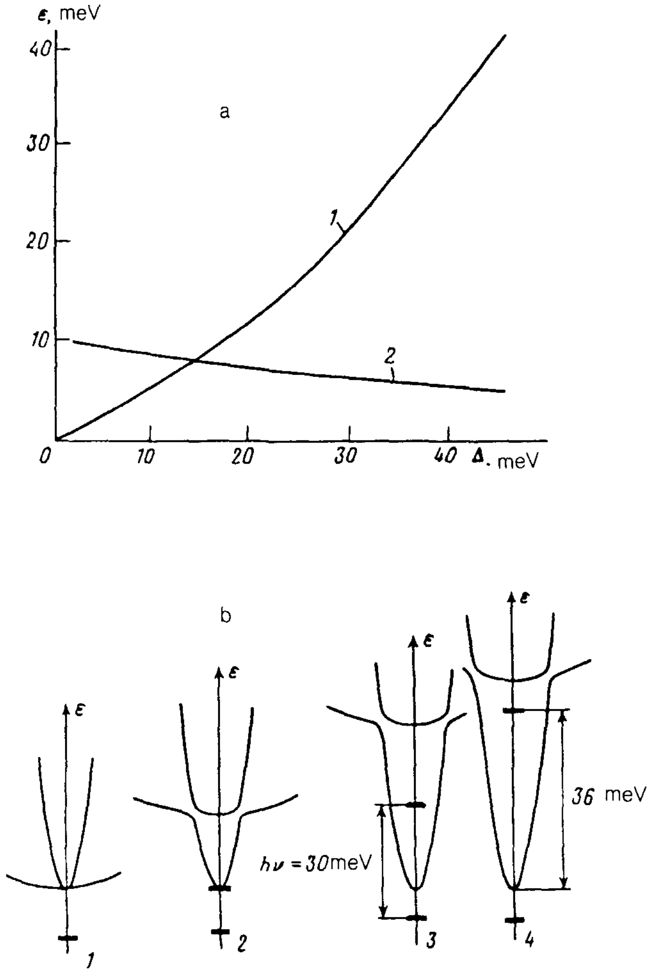


FIG. 1. a: Energy distance betwen the ground states of the acceptor (1) and the ionization energy of the lower level (2) as a function of the energy gap (Δ) between the valence subbands. b: Structure of the valence band and position of the impurity levels for various values of Δ, in meV: *1*—0; *2*—16; *3*—36; *4*—45.

orientation. The energy distance between the impurity levels turns out to be on the order of 30 meV (see curve 1 in Fig. 1a and band scheme 3 in Fig. 1b). Accordingly, in addition to the Ge⟨Ga⟩ detector (with a sensitivity band near 10 meV) which was used in Refs. 1 and 2, we used a Ge⟨Zn⟩ detector (which is sensitive near 30 meV). Figure 2 shows the emission intensity as a function of the pressure, which was detected simultaneously by these photodetectors. The emission spectrum obviously contains frequencies corresponding to the spectral bands of both detectors. The peak in the signal from the Ge⟨Zn⟩ photodetector is the result of a change in the photon energy

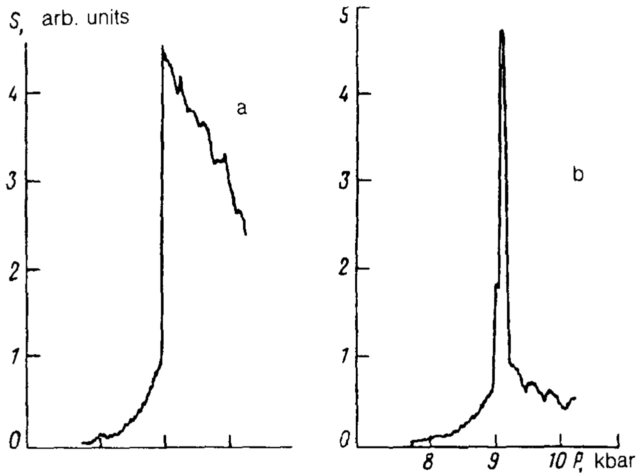


FIG. 2. Emission intensity $S$ versus the pressure $P$ for $E \| P \| [111]$. a—Measured by a Ge ⟨Ga⟩ photodetector; b—measured by a Ge ⟨Zn⟩ photodetector.

of the stimulated emission with increasing pressure. This peak approximately reproduces one of the sensitivity peaks[7] of Ge⟨Zn⟩.

The wavelength of the intensity peak in Fig. 2 was measured by a home-brew Michelson interferometer with a Ge⟨Zn⟩ detector. This wavelength does indeed correspond to 30 meV, i.e., to the photon energy of the optical transition between the acceptor levels split by the compression. The signal from the Ge⟨Ga⟩ detector ($\approx 10$ meV) could have been caused by optical transitions to the lower impurity level from excited states or from the valence band. Nevertheless, the primary cause of the stimulated emission, at all frequencies, is a population inversion of the two ground states of the impurity. That this is true can be seen from Fig. 3, which shows the signal from the Ge⟨Ga⟩ photodetector as a function of the pressure in the orientation $P \| [100]$ for various electric fields $E$. Although the stimulated emission can arise at various threshold pressures in different fields, it is cut off at a common pressure. At this pressure, the energy of the upper impurity level, reckoned from the bottom of the light-hole band, is about 36 meV—the energy of an optical phonon (see band scheme 4 in Fig. 1b). The upper level is emptied because of an emission of optical phonons; this effect results in a cutoff of the stimulated emission at all frequencies.

In summary, the data show that radiative transitions between impurity levels split by the pressure play a leading role in the stimulated emission from compressed *p*-Ge when the upper of these levels is in a continuous band spectrum. Murav'ev *et al.*[8] have observed lines corresponding to transitions between excited and ground states of shallow acceptors in the spectrum of stimulated emission from undeformed *p*-type Ge in an electric field crossed with a magnetic field. However, Murav'ev *et al.*[8] believe that those intracenter transitions are initiated by a population inversion of the light- and heavy-hole subbands in the crossed fields. This population inversion is the primary cause of the stimulated emission in this case. The cause of the stimulated emission in uniaxially deformed *p*-type Ge is, as can be seen from the data reported here, a population inversion of acceptor levels split by compression.

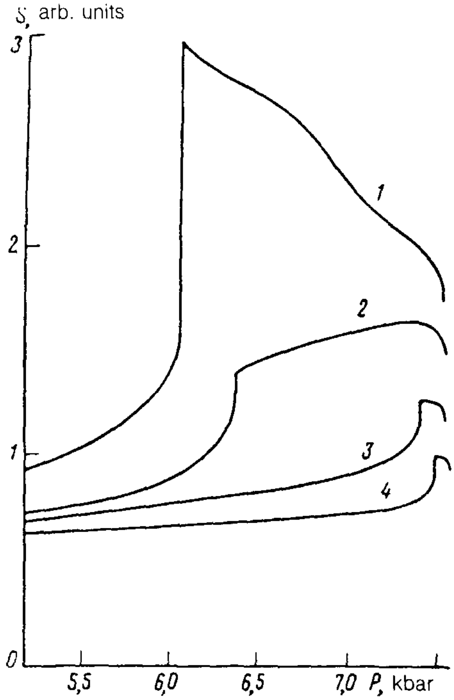


FIG. 3. Emission intensity $S$ versus the pressure $P$ for $E \| P \| [100]$, detected by a Ge⟨Ga⟩ photodetector, for various values of $E$, in kV/cm: *1*—4.1; *2*—3.5; *3*—3.1; *4*—2.6.

We wish to thank N. G. Zhdanova for a discussion of these results.

This study was supported in part by a grant from the Soros Foundation, awarded by the American Physical Society, and by individual grants from the International Science Foundation.

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Translated by D. Parsons