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Autosolitons in electron-hole plasma in InSb under hydrostatic pressure

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Abstract

The rise in resistance and the initially growing threshold voltage of longitudinal autosoliton formation in p-InSb ⟨Cr⟩ crystals subjected to high pressure result from an increase in the energy gap width and decrease in carrier concentration with increasing pressure. The subsequent decrease in the threshold voltage is due to falling carrier mobility and growing energy spacing between the deep acceptor level and the conduction band bottom. The regularity of the current oscillations associated with the motion of transversal autosolitons along the sample is disturbed. With increasing pressure, the oscillations become chaotic and the number of oscillation modes decreases.

1. Introduction

As shown theoretically by Kerner and Osipov [1, 2], inhomogeneous stationary states—thermodiffusional autosolitons (AS) are generated in heated nonequilibrium electron-hole plasma (EHP). In an external electric field, these inhomogeneities appear as current layers directed along the electric field—longitudinal AS in dense EHP, and as layers of high electric field perpendicular to the current lines—transversal AS in low-density EHP.

It has been shown experimentally [3] that the nonequilibrium EHP stratifies in electric field into current filaments and electric-field domains in n-GaAs and moving AS in n-Ge [4]. Joule heat generated by strong electric field pulses in p-InSb at 77 K creates nonequilibrium EHP in which both longitudinal and transversal thermodiffusional autosolitons are formed. Since the EHP in InSb is nonsymmetric, $\mu_p^* \ll \mu_e^*$, the transversal AS move in the electric field along the sample towards the hot electrons, from cathode to anode, manifesting themselves in the external circuit of the sample as current oscillations [5, 6]. The velocity of the transversal autosolitons depends on applied electric field. Depending on excitation level, the oscillations may be regular or chaotic. Also, the effect of weak longitudinal magnetic field on the behaviour

of transversal and longitudinal AS has been studied. The magnetic field changes the velocity of transversal autosolitons and leads to the fission of longitudinal AS [7, 8]. This influence is due to thermomagnetic Nernst–Ettingshausen effects.

It is known from the theory of autosolitons that the key role in the formation and evolution of AS is played by such parameters of a semiconductor as carrier mobility and concentration and energy gap.

One promising way to study in detail the origin, kinetics and formation of the AS in EHP in semiconductors is by continuously varying the electronic spectrum and characteristic parameters of carriers during an experiment. For this purpose, we introduced into the experiment hydrostatic pressure as such a factor.

It is known that, in direct-band narrow-gap III–V, II–IV–V_2 semiconductors subjected to uniform compression, the energy gap and effective electron mass at the conduction band bottom grow steadily with increasing pressure, the activation energy of impurity centres changes, and the hole concentration in the valence band decreases [9, 10].

In contrast to the theory the so-called hydrogen-like impurities, the theory of deep centres is, irrespective of their origin, in its initial stage of development. Hence, an experimental study of the electronic spectrum of well-studied semiconductors in relation to hydrostatic pressure is a topical task.

It was established in [11–13] that the absolute values of the energies of deep impurity states in semiconductors with deep impurity centres (Ge, III–V, and II–IV–V_2) are virtually independent of the isotropic compression of the crystal lattice, and the energy level positions are determined by the motion of the entire band structure under pressure. The change in the energy spacing between a deep level and the valence band edge is, therefore, due to the motion of the valence band top. In semiconductors with diamond and zincblende structure (Ge, III–V, II–VI) this spacing grows with pressure [9, 12, 14–16].

The aim of the present investigation was to study experimentally the origin of autosolitons and their behaviour in a p-InSb sample under hydrostatic pressures of up to $P = 1$ GPa at 77 K.

2. Samples and experiment

Doped and compensated p-InSb ⟨Cr⟩ crystals with hole concentration of the order of 10^{12} cm^{-3} and mobility $\mu_p \sim (2500{-}4000)$ cm^2 V^{-1} s^{-1} at 77 K were investigated.

In the samples studied, the Fermi level lies near the valence band top, and the data on temperature and pressure dependences of the resistivity ρ and Hall coefficient R_H indicate, in agreement with [17], the presence of a deep acceptor level at $\varepsilon_{A2} = 0.07$ eV from the valence band top. With increasing hydrostatic pressure, ε_{A2} grows and the hole concentration in the valence band, correspondingly, falls. This follows on from our pioneering measurements of the kinetic coefficients ρ and R_H (figure 1). The hole mobility remains virtually constant with increasing hydrostatic pressure (figure 1). From the electroneutrality equation follows

$$\beta_2^* = \frac{1}{P} \ln \left(\frac{[1 - (p - \Delta p)/N_A](1 - \Delta p/p_0)P^2}{[1 - (p_0 - \Delta p)/N_A](1 - \Delta p/p)P^2} \right) \tag{1}$$

where $\beta_2^* = \beta_2/kT$; $\beta_2 = \mathrm{d}\varepsilon_{A2}/\mathrm{d}P$; P and P_0 are the hydrostatic and atmospheric pressure; k is the Boltzmann constant; T is temperature; p_0 and p are the hole concentrations at atmospheric and hydrostatic pressure; Δp is the concentration of shallow acceptors, uncompensated by higher lying donors; and N_A is the concentration of deep acceptor centres with activation energy ε_{A2}.

At $T = 77$ K the dependence R_H/R_{H0} is exponential in the pressure range studied. This fact and the dependence of the kinetic coefficients on temperature suggest that $N_A \gg p - \Delta p$,

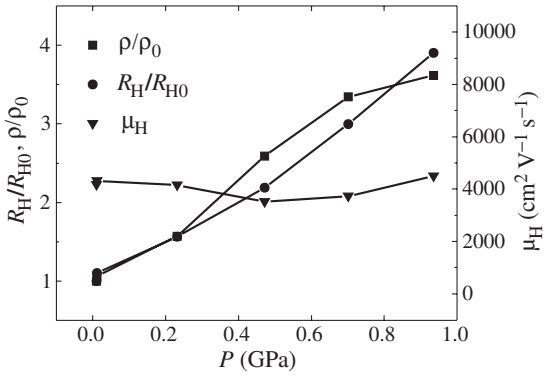

Figure 1. Pressure dependence of the resistivity ρ/ρ_0 and Hall coefficient R_H/R_{H0} (normalized to atmospheric pressure) and Hall mobility μ_H in an InSb sample at 77 K.

$p_0 \gg \Delta p$, and relation (1) takes the form

$$\beta_2^* \cong \frac{2}{P} \ln\left(\frac{p_0}{p}\right) = \frac{2}{P} \ln\left(\frac{R_{H0}}{R_H}\right) \tag{2}$$

From the experimental data in figure 1 and formula (2) it follows that $\beta_2 \cong 20\,\text{meV GPa}^{-1}$.

It was noted in [16] that the minima of the conduction band at the points X_1 and the valence band edge are shifted upon compression in nearly the same way. This observation is consistent with the β_2 value determined above.

The nature of the deep acceptor centre lying near the valence band top was discussed in [17]. A conclusion was made that the nature of the deep impurity centre is independent of the crystal growth technology and dopant, being associated with the presence of vacancies or interstitial atoms.

In addition to the deep acceptor centre with energy level ε_{A2}, a deep acceptor level ε_{A1} lying at a distance $\varepsilon_{A1} = 0.08$ eV from the conduction band bottom, whose position relative to the valence band varies only slightly with hydrostatic pressure [9], was found previously in p-InSb <Cr> crystals [18].

The nonequilibrium EHP in the samples was created by the Joule heat generated by applying rectangular 2.5 ms voltage pulses U with repetition frequency 10 Hz or single pulses. The created EHP was additionally excited by the same pulse, with autosolitons formed as current filaments in a hot and dense EHP ($\mu \sim T^{3/2}$) and as moving layers of a strong electric field in a cooler and less dense EHP [6]. The pressure was created in a high-pressure apparatus of piston-cylinder type with fluid pressure-transmitting medium.

3. Experimental results and discussion

The measurements show that the sample resistance ($l = 0.59$ cm, $S = 0.024$ cm^2) grows significantly with the hydrostatic pressure increasing to 1 GPa (figure 1). The threshold voltage U_{th} (figure 2(a)), at which a current filament (longitudinal AS) appears, increases from 16.25 to 42.54 V, passes through a maximum at $P = 0.47$ GPa and then decreases to 29.7 V (figure 2(b)).

The rise in the threshold voltage U_{th}, occurring up to pressure $P = 0.47$ GPa, is due to the increasing width of the energy gap. The decrease in carrier concentration with growing pressure also makes the threshold voltage higher.

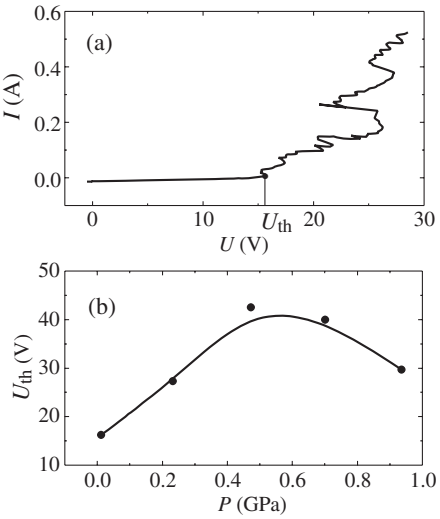

Figure 2. (*a*) Dynamic current–voltage characteristic of an InSb sample at 77 K and (*b*) threshold voltages versus pressure for an InSb sample at 77 K.

The subsequent fall in the threshold voltage of autosoliton formation can be explained as follows. The increase in pressure leads to a decrease in the electron mobility μ_e [9] appearing in the condition for origination of autosolitons: $\varepsilon = l/L < 1$, where $l = (\mu_e T_e \tau_\varepsilon / e)^{1/2}$ is the length of electron energy relaxation, and $L = (\mu T \tau_r / e)^{1/2}$ is the ambipolar carrier diffusion length.

As a result, we obtain the expression $\varepsilon = A(\mu_e/\mu_p + 1)^{1/2}$, where $A = (T_e \tau_\varepsilon / 2T\tau_r)^{1/2}$, τ_ε is the relaxation time of hot electrons, and τ_r is the carrier lifetime.

It is known that $\mu_e/\mu_p \approx 100$ and $\varepsilon \sim 10A$. According to [9], the electron mobility μ_e decreases by more than an order of magnitude on raising pressure to 1 GPa. Since $\varepsilon_p = l_p/L_p \approx \sqrt{10}A$ and $\varepsilon_p = 0.316\,\varepsilon$, we have $\varepsilon_p \ll 1$ at $\varepsilon < 1$.

With decreasing ε, the EHP excitation level necessary for autosolitons to be formed becomes lower, i.e. the strength of applied electric field falls.

In addition, the lowering of the electric field threshold U_{th} may be related to the presence of ε_{A1} levels. As mentioned above, according to [9], the position of the chromium impurity level at $\varepsilon_{A1} = 0.08$ eV changes only slightly relative to the valence band top, i.e. the conduction band bottom moves away from this level and the valence band top at the same rate equal to the pressure coefficient of the energy gap $\mathrm{d}E_g/\mathrm{d}P = 0.16$ eV GPa^{-1}. At a pressure $P = 1$ GPa, the ε_{A1} level lies at about 0.24 eV away from the conduction band bottom, which is comparable with the energy gap under atmospheric pressure. At high pressure, the ε_{A1} level can play the same role in the generation of a nonequilibrium EHP as the valence band at atmospheric pressure. Therefore, at a certain pressure the ε_{A1} levels will become the initial source of nonequilibrium EHP and only then the valence band will come into play as a result of Joule heating in the electric field. In the given experiment, this pressure was $P = 0.7$ GPa.

Investigations show that two jumps appear on the rectangular pulse of current on applying to a sample a voltage pulse at pressures in the range from $P = 0.7$ GPa to $P = 0.94$ GPa (figure 3). These results can be accounted for by double generation of EHP in which two longitudinal AS are formed successively.

The process of EHP generation from ε_{A1} levels is directly related to the threshold voltage U_{th}, which decreases just in the pressure range below 0.7 GPa.

Several modes of regular relaxation oscillations of the current in the external circuit of the sample, associated with autosolitons travelling along the sample in the electric field, have

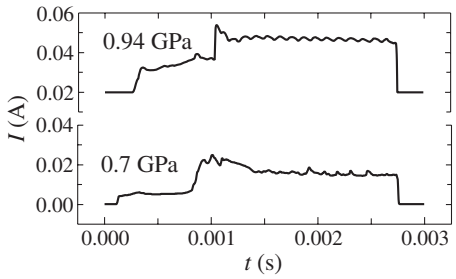

Figure 3. Oscillograms of current with two jumps for an InSb sample at 77 K.

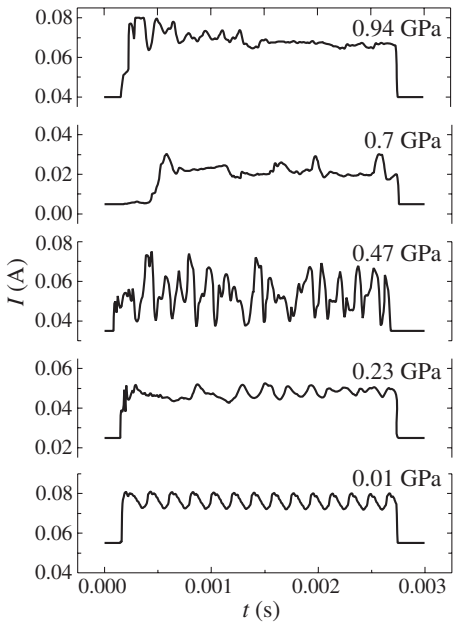

Figure 4. Oscillograms of current oscillations at different pressures applied to an InSb sample at 77 K.

been found [6]. In some modes, the frequency and amplitude of the current oscillations change monotonically with increasing electric field. Other modes are characterized by more complex oscillations, clearly indicating self-organization of the dissipative structure in InSb.

The regularity of oscillations is disturbed in samples subjected to high pressure, with the oscillations becoming absolutely chaotic (figure 4) at a pressure $P = 0.47$ GPa. The number of modes decreases, and the voltage range in which a mode exists becomes wider.

4. Conclusion

It has been shown for the first time that in p-InSb ⟨Cr⟩ crystals subjected to high uniform pressure the concentration of holes in the valence band decreases, with their mobility remaining unchanged. These and other known experimental results made it possible to reveal the influence exerted by changes in parameters of a crystal (μ_e, μ_p, n_p, E_g, ε_{Al}) on the threshold voltage at which EHP is generated in the crystal, AS appear in this plasma, and on the regularity of

current oscillations in the external circuit of the sample, associated with the AS travelling in the sample.

It has been demonstrated for the first time for the example of doped compensated p-InSb ⟨Cr⟩ crystal that application of a high hydrostatic pressure is an efficient tool for studying the dissipative structure. This is due to the possibility of continuously changing the electronic spectrum and characteristic parameters of carriers in the semiconductor crystals during the experiment.

Acknowledgments

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