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LETTER TO THE EDITOR

Thermodiffusional autosolitons in non-equilibrium electron–hole plasma in Ge

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Abstract. We report on the experimental observation of strongly non-equilibrium solitary formations, i.e. hot autosolitons (AS), in the stable, weakly non-equilibrium electron–hole plasma that was uniformly photogenerated in Ge samples at 77 K and slightly heated by an applied electric field. AS revealed themselves as narrow strata, perpendicular to the lines of current and moving along them without attenuation, which were distinguished by a lowered concentration of carriers and increased strength of electric field.

Theoeretical consideration [1–4] of the homogeneous quasi-neutral electron–hole plasma (EHP) with sufficiently high density, weakly heated by an electric field, showed that strongly non-equilibrium states may be generated in the form of strata perpendicular to the lines of current. The strata prove to be static or moving layers of quasi-neutral EHP with an elevated temperature of carriers, T, an increased strength of electric field, E, and a reduced concentration of plasma, n. Excitation of a solitary stratum, i.e. an autosoliton (AS), can be achieved by applying a localised disturbance to a stable EHP [4, 5]. In particular, an EHP can be locally heated for a short time using a strong electric field or by incident light absorbed by free carriers to produce the desired effect. The heating pulse having terminated, an AS is formed at the focus of the applied disturbance with its shape governed only by the EHP parameters and independent of the parameters of the impulse disturbance [5].

An experimental investigation of these theoretical predictions was performed at 77 K with n-Ge samples ($\rho \simeq 40\ \Omega$ cm, $N_D \simeq 10^{13}$ cm^{-3}) shaped as parallelepipeds measuring $0.8 \times 0.1 \times 0.05$ cm^3. The quasi-neutral homogeneous EHP with hole concentration $p \simeq n$ ($n - p = N_D \ll p$) was generated in the sample under uniform illumination by light of a fixed intensity (figure 1(*a*)). The concentration n of the photogenerated EHP ranged from 10^{14} cm^{-3} to 10^{16} cm^{-3}. The voltage U was applied to the antilocking n^+–n contacts along the crystallographic ⟨111⟩ direction (figure 1(*a*)). The patterns of the photogenerating light pulses $I(t)$ and voltage $U(t)$ are illustrated in figure 1(*b*).

The observed time variations of the local electric field E_l were measured at different points of a sample with the aid of probes arranged along the direction of the current with a spacing $\Delta l = 0.4$ mm between them. Below the threshold voltage ($U \leqslant 60$ V), the shape of a current pulse $J(t)$ was the same as that of a light pulse $I(t)$ and the field E was uniform over the whole sample, with the exception of a narrow high-strength region

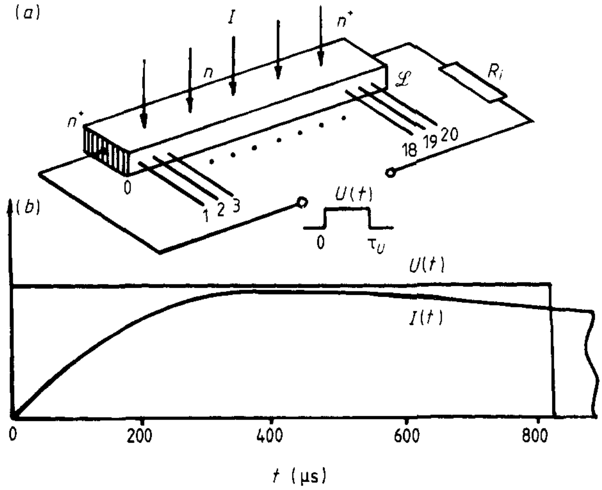

Figure 1. (*a*) The sample connection circuit and arrangement of the probes. (*b*) The shapes of the applied voltage $U(t)$ and excitation light pulses.

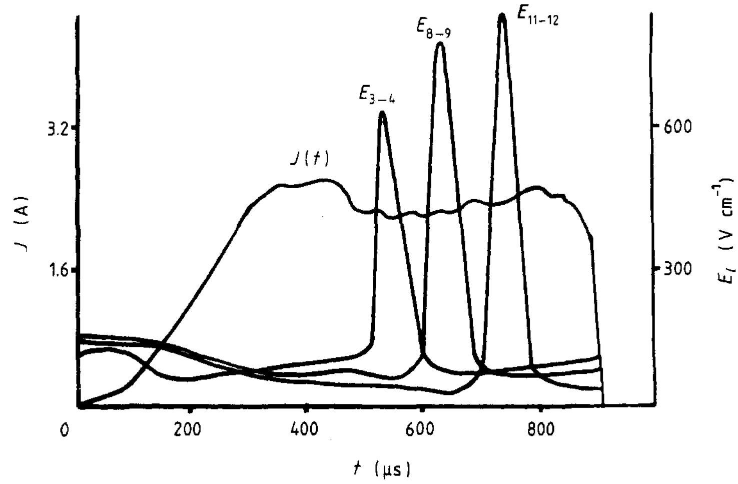

Figure 2. Oscillograms of the photoconductivity current, $J(t)$, and electric field, E_l, recorded at different pairs of neighbouring probes: $E_{3-4}(t)$, $E_{8-9}(t)$ and $E_{11-12}(t)$

($\Delta l' \leqslant 0.4$ mm) at the plate. At voltages and illumination above their threshold values ($U \gtrsim 80$ V and $n \gtrsim 10^{14}$ cm^{-3}), we observed the spontaneous formation of AS near the plate followed by their motion along the sample as a solitary high-field ($E \gtrsim 800$ V cm^{-1}) stratum (figure 2). The formation of AS was accompanied by a rapid drop in current and subsequent photocurrent oscillations $J(t)$.

As can be seen from figures 2 and 3(*b*), AS form in a region of high field strength E and decreased carrier concentration n; the AS shape† qualitatively fits the theoretical predictions [2] (figure 3(*a*)).

† In our data processing we made use of the data on hot carriers in Ge that had been presented in [4, 5].

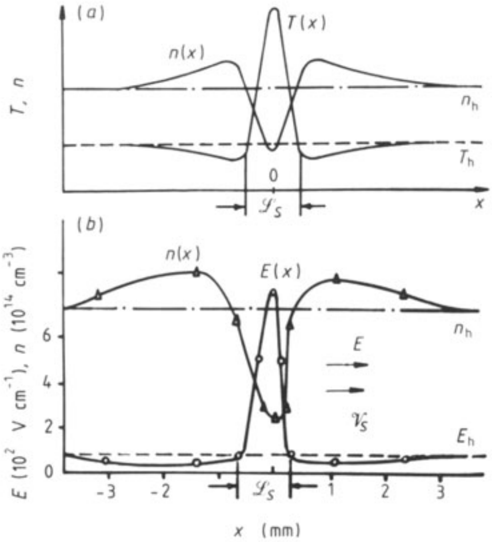

Figure 3. (*a*) Theoretical calculations [4] of the distribution of carrier concentration $n(x)$ and temperature $T(x)$ in the AS. (*b*) The distribution patterns of $n(x)$ and $E(x)$ calculated according to the data obtained.

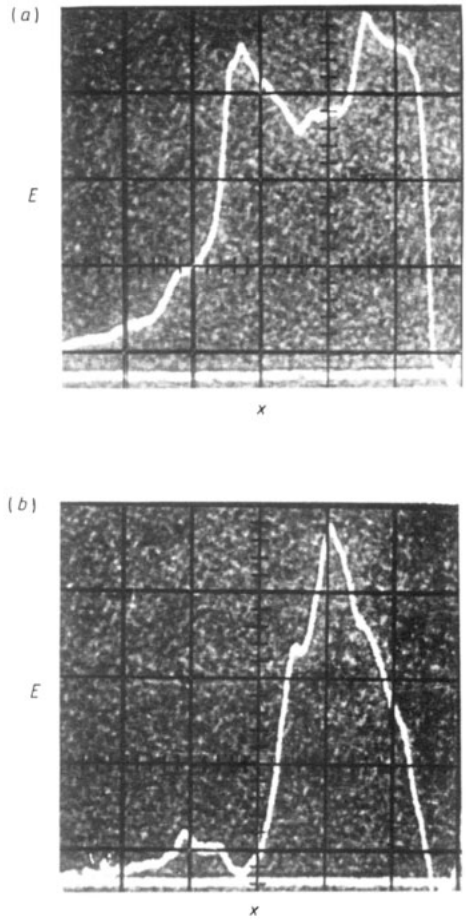

Figure 4. Distribution patterns of $E(x)$ (1 unit = 200 V cm^{-1}) inside an AS plotted for the instants of time when the AS passed (*a*) the probe separated by $l_1 = 2.17$ mm from the plate (x axis: 1 unit = 0.4 mm), (*b*) the probe at $l_2 = 3.7$ mm from the plate (x axis: 1 unit = 0.6 mm).

The existence of such a self-sustaining AS in an EHP is due to the intensive escape of hot carriers from a high-temperature region which occurs through heat diffusion. As a result, the carrier concentration and, hence, the conductivity σ decrease at the centre of the AS (figure 3). This process favours elevated values of T at the centre of the AS; the decreased-concentration region inside the AS does not spread because the diffusion and thermodiffusion flows of current counterbalance one another [3, 4].

The theory [3, 4] predicts that the effect under consideration takes place when the following conditions hold in quasi-neutral EHP ; $\tau_p \ll \tau_{cc} \ll \tau_\varepsilon$ ($\tau_p \sim T^\alpha$, $\tau_\varepsilon \sim T^S$ and τ_{cc} are the times of energy/momentum relaxation and inter-electron collisions, respectively), $L \gg l$ and $\alpha + S > -1$ (L and l denote the diffusion length and that of the energy relaxation of carriers), $\alpha = \partial(\ln \tau_p)/\partial(\ln T)$, $S = \partial(\ln \tau_\varepsilon)/\partial(\ln T)$. The condition $\alpha + S > -1$ is satisfied if the carrier temperature T exceeds the Debye temperature θ_D

due to an increase in τ_ε with T. In semiconductors such as Ge and Si, at $T > \theta_D$ we have $S = \frac{1}{2}$, $\alpha = -\frac{1}{2}$ and, therefore, $\alpha + S = 0$.

In line with the theory [4, 5], the AS size was approximately equal to the length of the carrier bipolar diffusion and the velocity of the AS motion was governed by the ambipolar drift rate. With the intensity I of the illumination and, hence, the EHP concentration increasing, the maximum field strength E inside the AS increases rapidly up to $E \simeq 3\ \mathrm{kV\ cm^{-1}}$ at $n \simeq 10^{16}\ \mathrm{cm^{-3}}$, whereas the size $\mathscr{L}_S$ and velocity $\mathscr{V}_S$ of the AS becomes smaller ($\mathscr{L}_S$ decreased from 1 mm to 0.2 mm and $\mathscr{V}_S$ dropped from $2 \times 10^3\ \mathrm{cm\ s^{-1}}$ to $3 \times 10^2\ \mathrm{cm\ s^{-1}}$). On the other hand, with I decreasing and U remaining constant, the field at the centre of the AS was also decreasing and it became impossible to generate AS even at high applied voltage $U \simeq 250$ V provided the illumination I, i.e. the EHP concentration, was below a certain threshold value ($n \simeq 5 \times 10^{13}\ \mathrm{cm^{-3}}$).

The high-field region at the plate played a major role in the generation of a thermo-diffusional AS. Having escaped from the high-field region near the plate, the generated AS was moving, without attenuation, in a stable, homogeneous, weakly heated ($E \simeq 40$–$60\ \mathrm{V\ cm^{-1}}$) EHP. In the course of its motion we observed slight changes of the shape, amplitude and velocity of the AS due to small inhomogeneities of the sample (figure 2).

As increased in the EHP heating (achieved due to higher applied voltage) affected both the shape of the AS and all its parameters during the AS motion in different parts of the sample (figure 4(a), (b)). The shape of the AS shown in figure 4 was reconstructed from straightforward measurements of $E(x)$, taken as the AS was passing by a chosen probe, by differentiating and subtracting the potential data $U_l(t)$ obtained at two different probes separated by a distance $\mathscr{L} > \mathscr{L}_S$. By varying the magnitudes of U and I, we could form an AS in different parts of the sample (i.e. at the inhomogeneities occurring there) rather than at the probe.

In some samples, during the first AS run another or even two more moving autosolitons appeared. The generation conditions and parameters of the AS were extremely sensitive to the crystallographic orientation of the applied electric field.

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