

OBSERVATION OF MOTION OF SLOW RECOMBINATION WAVES (RW) IN SILICON DOPED WITH ZINC

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In [1 - 4] it is shown, on the basis of the aggregate of experimental data, that the current instability arising at $T = 250 - 350^\circ\text{K}$ in silicon doped with zinc is due to slow RW [5]. However, the motion of the slow recombination wave itself, predicted by the theory [5 - 7], has so far not been observed experimentally by any one. For rapid RW in compensated germanium, the time variation of the undamped fluctuation recalls a standing wave [8 - 10]. We report here observation of the motion of the fluctuation in the case of slow RW in n-type silicon doped with Zn.

The picture of wave motion was reconstructed by analyzing the variation of the Lissajous figure as a function of the coordinate of a clamped probe. The sample was connected in series with a battery and a load resistor. The signal from the load was fed through an amplifier to the input of the horizontal sweep of an oscilloscope. The vertical sweep received the potential difference between the probe and one of the contacts. Its dc component was measured with a voltmeter.

The Lissajous figure has frequently a complicated form. In the case of regular oscillations, a stable figure (inclined line) was produced only when the probe was in the "passive" part of the sample. It follows directly from this that the oscillations are not in phase.

For a detailed investigation of the time variation of the fluctuation, the sample was made to execute sinusoidal oscillations near threshold. It is clear that when the probe passed through the "active" region, i.e., the region in which the conductivity oscillates, the phase¹) of the Lissajous figure (ellipse) should change by π . The method whereby the ellipse changes its phase depends on the behavior of the fluctuation. Thus, for example, in the case of in-phase oscillations, the ellipse should degenerate at a certain point of the sample into a horizontal line and change its phase jumpwise by π . In our case, the phase of the ellipse remained unchanged over a large distance ("passive" region) and then, starting with a certain point (x_0 on Fig. 1) and up to the contact (cathode), it varied continuously and shifted by π . The vertical projection of the ellipse changed somewhat in magnitude, but did not vanish. The circuiting direction of the ellipse was determined by the form of the spiral trace left by the beam upon displacement of the Lissajous figure on the oscilloscope screen.

Figure 1 shows 12 successive distributions of the ac component of the electric field E' in the active region of the sample. The maximum of the electric-field oscillation amplitude was $\sim 3\%$ of the dc component. The fact that the Lissajous figure in the entire active region remains an ellipse means that the oscillations at all points have a harmonic character and differ only in phase and in amplitude. This can be written in the form

$$E'(x, t) = f(x) \sin[\phi(x) - \omega t]. \quad (1)$$

Here $f(x)$ specifies the amplitude and the argument of the sine function specifies the phase of the oscillations. We put $-\pi < \phi(x) \leq \pi$. The experimental data (Fig. 1) enable us to determine $f(x)$ and $\phi(x)$ (see Fig. 2).

¹The phase difference between the current and potential of the probe will be called "phase" for brevity.

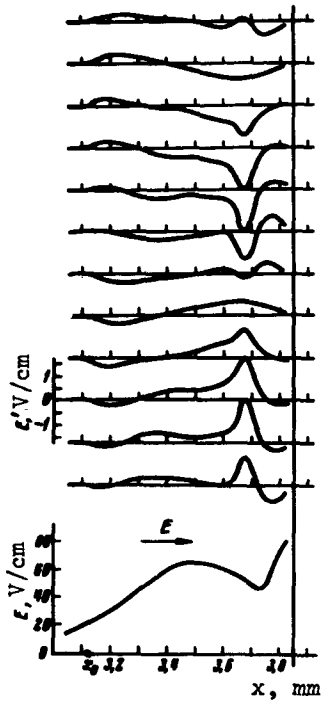


Fig. 1

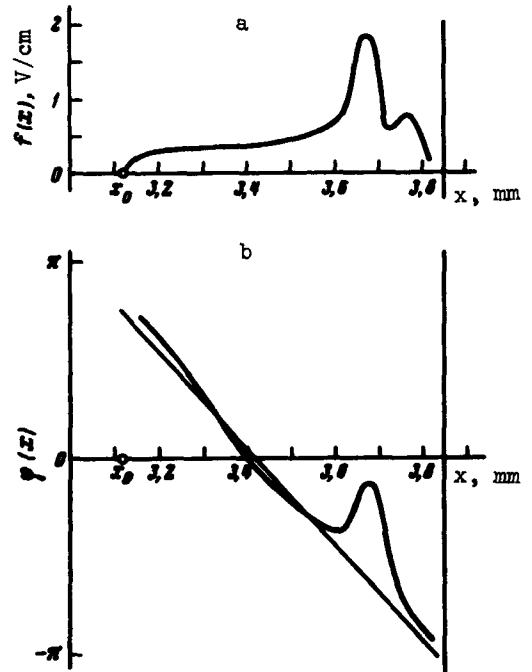


Fig. 2

Fig. 1. Character of time variation of E' in the active region of sample No. 562a. The scale of E' is indicated on one of the diagrams. The time direction is downward. The time intervals between arbitrary neighboring diagrams and between the first and last diagram are identical. x is the distance from the anode. The right-hand vertical line represents the cathode. Below - distribution of the dc component of the electric field.

Fig. 2. Wave parameters: a - $f(x)$, b - $\phi(x)$.

On the section $x_0 < x \leq 3.6$ mm and $x \geq 3.75$ mm, the function $\phi(x)$ is well approximated by a straight line (see Fig. 2b), i.e., $\phi(x) \approx kx + b$ ($k > 0$, and b depends on the choice of the zero value of the time). This means that on these sections the undamped fluctuation is a wave traveling with approximately constant phase velocity $v = \omega/(d\phi/dx) \approx -\omega/k$ in the direction of the electron drift. At $x < 3.6$ mm, the amplitude of the wave changes little. The direction of wave motion corresponds to the linear RW theory [5 - 7]. The phase velocity is $v \approx 23$ cm/sec. At a frequency $\nu = 325$ Hz, the wave number is $k \approx 90$ cm $^{-1}$, and the wavelength $\lambda \approx 0.07$ cm, which agrees in order of magnitude with the value $\lambda \approx 0.027$ mm calculated in [2] for an infinite sample. A comparison with the linear theory is justified, since the amplitude of the perturbations is small and one can expect the parameters of the oscillations not to differ strongly from the critical values given by linear theory.

On the section $3.6 \leq x \leq 3.75$ mm, the amplitude of the oscillations is somewhat larger, and the motion of the wave has a more complicated form. It is seen from Fig. 2b that the motion can be treated, for example, as a section of phase delay, compared with the wave described by the function $\phi(x) = -kx + b$. A representation is also possible in the form of a sufficiently arbitrary superposition of the waves. Indeed, the function (1) can be represented in the form of a superposition of two waves (and possibly an arbitrary number of waves) of the same form

$$f(x)\sin[\phi(x) - \omega t] = f_1(x)\sin[\phi_1(x) - \omega t] + f_2(x)\sin[\phi_2(x) - \omega t], \quad (2)$$

where $\phi_1(x)$ and $\phi_2(x)$ can be specified arbitrarily, but such that in the general case $\phi_1(x) \neq \phi_2(x) + m\pi$ ($m = -1, 0, 1$) for all the x under consideration. f_1 and f_2 can be obtained from the experimentally known f and ϕ and from the specified ϕ_1 and ϕ_2 . If we put in our case $\phi_1(x) = -kx + b$ and $\phi_2(x) = c$ ($c = \text{const}$), then the motion of the fluctuations in the entire active region can be described as a superposition of two waves: a traveling wave $f_1(x)\sin(-kx - \omega t + b)$ and a standing wave $f_2(x)\sin(c - \omega t)$, and on the sections $x_0 < x \leq 3.6$ mm and $x \geq 3.75$ mm we have $f_1(x) \equiv f(x)$ and $f_2(x) \equiv 0$. The amplitudes f_1 and f_2 on the section $3.6 \leq x \leq 3.75$ mm depend on the choice of the constant c .

The closest to the experimental conditions is the theoretically considered case of slow RW in a bounded homogeneous sample with ohmic contacts [7]. In such a sample, the perturbation in the threshold regime is described by a wave of the form (1), where $\phi(x) = -k'x + b'$ ($k'b' = \text{const}$, $k' > 0$). It was shown above that the experimental $\phi(x)$ dependence is close to such a form. The observed deviations are apparently the consequence of the inhomogeneity of the sample, the non-ohmic character of the contacts, and the finite values of the perturbation (unlike the premises of the linear theory). For the same reasons, the character of the function $f(x)$ deviates from the theoretical form. The absence of nodes (points where $f(x) = 0$) inside the active region corresponds to the fundamental mode of the oscillations [7].

Thus, the character of the motion (in main outline) and the direction of the displacement, and also the length of the slow RW in silicon doped with zinc agree with the RW theory.

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