Surface waves at the boundary of a static domain

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(Submitted March 14, 1980)
Pis'ma Zh. Eksp. Teor. Fiz. **31**, No. 9, 528–532 (5 May 1980)

The existence of waves in a space charge, which forms a static-domain "wall" of recombination origin in copper-doped germanium samples, was observed. These waves are spatial oscillations of the space-charge layer that propagates along the domain boundary (at right angles to the current direction).

PACS numbers: 73.20.Hb

In a semiconductor exhibiting bulk negative differential conductvity (NDC) the homogeneous field distribution is unstable and the semiconductor passes into a new, drastically inhomogeneous state—mobile or stationary, electric domains are formed. The similarity between domain formation and a first-order phase transition has been pointed out many times in the literature[1,2]; in both cases a sudden transition into an inhomogeneous state occurs under certain critical conditions. Accordingly, an analogy can be drawn between a sample with a domain and a two-phase system: two regions with drastically different properties, which are separated by a thin boundary layer, are formed in the crystal. The crystal with a domain is essentially a nonequilibrium system; therefore, its similarity to a two-phase system is usually considered to be purely external. However, the results presented below show that this analogy goes much deeper than that.

The experiments were performed on copper-compensated germanium samples at 80 K. All the effects, associated with the appearance of a recombination-created NDC

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in an initially homogeneous sample, are observed in these crystals; in particular, at intermediate illumination intensities static domains are formed in the intrinsic absorption band region.[3] The field distribution in the sample has the form of a step function, and the strong- and weak-field regions are separated by a thin layer of space charge (the domain "wall"). The domain wall thickness does not exceed 10^{-4} cm according to theoretical[4] and experimental[5] estimates. We note that the analogy between a sample with a static domain and a two-phase system was actually used in Refs. 6 to calculate the impedance and the current noise spectrum by means of a model that takes account of the finite amplitude and the inertia of the oscillations of the domain wall whose thickness was assumed to be infinitely small. The one-dimensional problem was analyzed in these calculations, and a one-dimensional configuration was also used in the corresponding experiments, since the measured current was averaged over the crystal cross section. In real samples the domain wall is a surface and it is difficult to assume that it oscillates as a single unit, especially for a local perturbation of this surface.

We investigated the spatial oscillations of a domain wall as a result of a local displacement by means of a modulated light beam (LG-126 laser, $\lambda = 0.63$ μm) that was focused on a lateral face of the sample near its edge (Fig. 1a). The light spot diameter was a fraction of a millimeter. A ML-3 electro-optic modulator produced an ~80% modulation of the light beam.

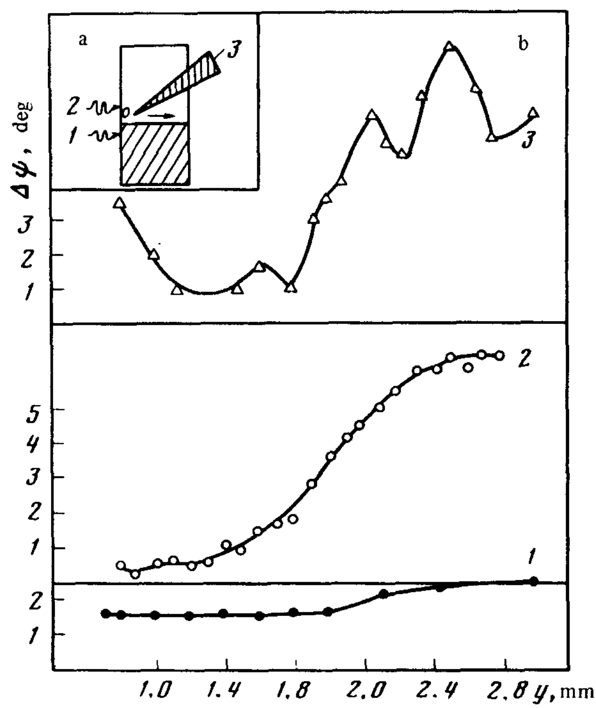

FIG. 1. Arrangement of probes on the sample: 1,2-voltage probes; 3-capacitance probe; *b*-dependence of the phase of the capacitance probe potential on the transverse coordiante for different values of the dc voltage *U*. *U*, *V*: 1-1200, 2-1800, 3-2000; $f = 34$ Hz.

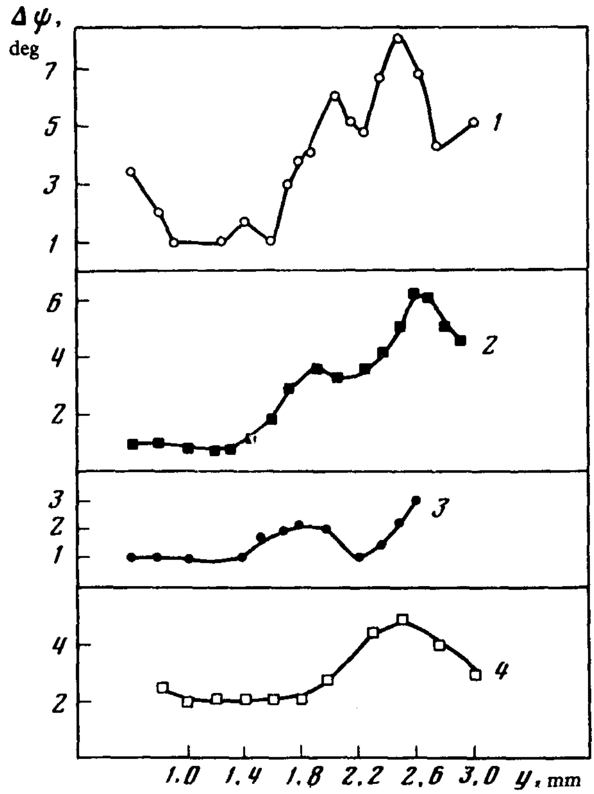

FIG. 2. Dependence of the phase of the capacitance probe potential on the transverse coordinate for different light beam modulation frequencies f: f, Hz: 1-34, 2-74, 3-134, 234; $U = 2000$ V.

A movable capacitance probe, which could be moved along the domain boundary (at right angles to the current direction), was used to observe the domain wall oscillations. The probe was a pointed brass plate (point diameter $\sim 100\ \mu$m) that was passed against the sample surface, from which it was insulated by a mica seal (Fig. 1a). The voltage region, for which the wall was near the capacitance probe, was determined beforehand by means of a pair of voltage probes (Fig. 1a).

We measured the voltage between the capacitance probe and the end of the sample and the phase difference $\Delta\psi$ between this voltage and a reference voltage. As the reference voltage we used the voltage by means of which the light beam intensity was modulated. As the probe was moved at right angles to the sample, this phase difference varied differently for different values of the dc voltage. The measurement results are shown in Fig. 1b. At 1200 V, when the domain wall is located far from the probe position, $\Delta\psi$ was almost independent of the transverse coordinate y (curve 1). As the voltage increases the domain wall approaches the probe and $\Delta\psi$ becomes dependent on y. This dependence is monotonic initially (curve 2), and then clearly defined oscillations appear on it (curve 3).

The spatial oscillations of the phase of the probe voltage indicate that a potential wave, which propagates at right angles to the direction of the dc current, exists. In fact, let us represent the voltage at the capacitance probe in the form of a sum of two signals

$$U = U\sin[\omega t + \psi(y)] = U_1 \sin\omega t + U_2 \sin[\omega t + \phi(y)]$$

the first of which is due to the field redistribution in the sample when it is locally illuminated, while the second one corresponds to the potential wave. Thus, the phase ψ of the probe voltage is determined by the expression

$$\tan = \frac{U_2 \sin\phi(y)}{U_1 + U_2 \cos\phi(y)} .$$

It can be seen that the phase ψ in the presence of a wave is an oscillating function of the transverse coordinate y.

Figure 2 shows the transverse distribution of the phase of the capacitance probe potential for different modulation frequencies of the intensity of the light beam. As the frequency increases, the number of oscillations decreases. This shows that the observed potential waves follow the universe dispersion law that is similar to the dispersion law for trap charge exchange waves.[7] This seems natural, since in both cases the space charge is produced primarily by the electrons bound by impurities.

The observed waves are associated with the domain wall, which is indicated by the data in Fig. 1b. In fact, as a result of a 200-V variation, i.e., as a result of extending the distance between the wall and the probe by about 0.5 mm (this estimate is easy to obtain by taking into account that the field in the domain is $\sim$4kV/cm and the sample length is $\sim$1 cm), the oscillations disappear.

The wave of the space charge that forms the domain wall can arise either because of a spatial displacement of the wall or because of a periodic variation of its thickness. The latter, however, is unlikely to occur, since in this case the variation of the wall thickness must be comparable to the probe size ($\sim$100 μm). On the other hand, the spatial oscillations of an infinitely thin wall account for the impedance and noise of such samples.[6] We shall therefore assume that the observed waves are caused only by spatial displacements of the domain wall, which greatly resembles, for example, the waves on a liquid surface.

The given data show that a sample with a static domain is similar to a two-phase system in that both crystals have two regions with an interface between them.

The authors thank S. G. Kalashnikov and A. Ya. Shul'man for a discussion of the results.

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