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THE BARKHAUSEN EFFECT

V. M. RUDYAK

Kalinin State Pedagogical Institute

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I. INTRODUCTION

In the magnetization and reversal of magnetization of ferromagnets, as well as in the polarization and reversal of polarization of ferroelectrics, an important role is played not only by the smooth (reversible) changes of the magnetic or electric state of the crystal, but also by jumplike changes of the magnetization of ferromagnets or the polarization of ferroelectrics. In ferromagnets, this effect was discovered in 1919 by Barkhausen[1] and bears his name.

Jumps of reversal of magnetism and in ferroelectrics were observed by a number of workers[2-4] in the late '40's. In analogy with paramagnetism, they were also named Barkhausen jumps.*

An appreciable number of papers have been devoted to the Barkhausen effect both in ferromagnets and in ferroelectrics. Nonetheless, it has been assumed for a long time that this effect can serve principally only as an illustrative demonstration of the existence of a domain structure, and does not have great physical significance.

Recently, however, as a result of a number of investigations, it has been concluded that a study of the Barkhausen effect makes an appreciable contribution to the understanding of physical processes occurring during reversal of magnetization or reversal of polarization. A definite connection has been established between the Barkhausen effect (the number of jumps, their distribution over the field, etc.) and the main elements and the shape of the hysteresis loop. Unlike other methods of investigating domain-structure dynamics, the Barkhausen effect yields information on processes occurring not only on the surface of the sample but also in its interior. In spite of the fact that in many cases the percentage of the jumpwise polarization-reversal (magnetization-reversing) volume of the crystal is negligible, the Barkhausen effect makes it possible to assess certain aspects of the realignment of the domain structure of the crystal as a whole. As a method of studying the dynamics of the domain structure, the Barkhausen effect is valuable also because it is a sensitive indicator of the "fine structure" of this dynamics.

Owing to the high sensitivity of this effect to different external actions and to structure changes of the sample, it can be used to measure with a high degree of accuracy a number of magnetic and electric quantities. Particularly advantageous is an investigation of the Barkhausen effect when methods of directly observing the domain structure and its dynamics are either difficult or nonexistent. Therefore definite interest attaches not only to the study of the Barkhausen effect itself, but also to its use as one of the methods for investigating ferromagnets and ferroelectrics.

The study of the Barkhausen effect is also of definite significance in physics as a whole, being one of the problems of the kinetics of transient processes. Indeed, as is well known, one of the main features of all the transient processes is the jumplike character. In this sense, the problem of a jumplike growth of the equilibrium phase in a nonequilibrium phase is common to a number of phenomena: crystallization, condensation, crystal polarization, magnetization, etc. In all these cases, an important role is played by the jumplike growth of the nuclei of the new phase. In spite of the difference between the physical processes that occur in these phenomena, there is one common feature, namely, a small nucleus (or fluctuation) of the equilibrium phase in the nonequilibrium phase becomes suppressed if it is too small, whereas a nucleus larger than a certain critical dimension begins to grow. In all these cases, the critical dimension of the nucleus can be calculated in accordance with the same scheme, namely from energy considerations with allowance for the competition between the volume forces that contribute to the growth of the equilibrium phase and surface-type forces that prevent this growth.

In all transient jumplike processes, a common feature is also the following: if the jumps are frequent and are small, the process appears to be smooth. On the other hand, if the jumps follow each other rather infrequently and are large, then they can be observed. Examples of the use of jumplike processes in physics are well known (the cloud chamber, the bubble chamber, etc.). Barkhausen jumps in ferromagnets and ferroelectrics can also find certain applications, and indeed they do, as will be shown below.

We review in this article the fundamental work done on the Barkhausen effect, and show that the use of this effect can yield a number of new methods for the investigation of ferromagnetic and ferroelectric crystals. Assuming that the readers are more familiar with the ferromagnetic Barkhausen effect, an elementary description of which is contained in all textbooks (see also [132, 145]), we report here the results of research on ferromagnets in more compact form, and describe work devoted to ferroelectrics in somewhat greater detail.

II. BARKHAUSEN EFFECT IN FERROMAGNETS

1. General Description of Effect. Mechanism of the Jump of Magnetization Reversal

When an external magnetic field is applied to a ferromagnet, the magnetization process, as is well known,[8] consists of three main stages: displacement, rotation, and the paraprocess. The displacement proc-

*The first reports of the observation of the Barkhausen effect in Rochelle salt were made back in 1933 by Kluge and Schonfeld [5] and in 1935 by Miller [6]. Later on, however, Schonfeld has shown [7] that the noise observed by him was not of ferroelectric origin.

ess corresponds to the region of weak magnetic fields, where the magnetization curve is the steepest, and the magnetization is realized by displacement of the boundaries between the domains. A detailed investigation of the magnetization curve in the displacement region[9, 10] has shown that it is precisely in this region that the change of magnetization occurs jumpwise, i.e., a smooth change of the external magnetic field induces jumps in the magnetization of the sample. During the rotation and paraprocess stages, no Barkhausen jumps are observed.

Haworth[10] has shown that the jumps always occur on the steep part of the magnetization curve and on the steep part of the hysteresis loop. It was initially assumed that each Barkhausen jump corresponds to reversal of magnetization of an entire domain. Subsequently, by comparing data on the dimensions of the regions that reverse magnetization in one jump, obtained by Forster and Wetzel,[11] by Tsomakion and Ivlev,[12] and by others, with domain-dimension data obtained by the powder-figure method, it became clear that there is no direct connection between the dimensions of the magnetization-reversal jump and the dimensions of the domain. As a rule, the Barkhausen jump encompasses a region much smaller than the region of spontaneous magnetization, and the dimensions of the jumps oscillate in a rather wide range.

To determine the causes of the Barkhausen jumps* it is necessary to consider in greater detail the question of the displacement of the boundaries between domains.[13, 14] As shown by Landau and Lifshitz,[15, 16] the boundary between domains is not a geometric surface but is an intermediate zone of finite width with a continuous variation of the orientation of the spin magnetic moments. The width of this zone δ, for the case of a 180° neighborhood at room temperature, is of the order of 10^2–10^3 Å.** The surface density of the boundary energy γ is

$$\gamma = (k_{\text{eff}} A/a)^{1/2}, \tag{1}$$

where A is the exchange integral, k_{eff} is the effective constant of the magnetic anisotropy, and a has the dimension of length and is of the order of the crystal-lattice constant, i.e., $\sim 10^{-8}$ cm.

The dependence of γ on the coordinates determines the boundary displacement under the influence of the field. Indeed, in the absence of an external magnetic field, the boundaries between domains pass through those crystal locations in which the total energy has a minimum and the sample is demagnetized. This means that in the case of 180° neighborhoods the boundaries are located as a rule at locations with minimal internal stresses, so that according to [14] we have

$$k_{\text{eff}} \approx \alpha k + \beta\lambda\sigma, \tag{2}$$

where k is the constant of the natural crystallographic anisotropy, λ is the magnetostriction constant, σ are the internal mechanical stresses, and α and β are constant coefficients for a given crystal.

It is seen from (1) and (2) that a minimal increase of the free energy is produced by the boundary if it is located in places corresponding to a minimum of the internal stresses. Thus, the positions of the boundaries in the absence of the field are determined by the action of the internal forces. Among such "internal forces" are, first of all, the internal stresses due to the deformation of the crystal lattice or to some inhomogeneities (inclusions), and also the stray magnetic fields produced by such inhomogeneities.

If we now place the sample in an external magnetic field, then the demagnetized state becomes energetically unfavorable. This is manifested in the fact that a "hydrostatic" pressure P_H becomes applied to the

$$P_{H(i\to k)} = H(I_s^i - I_s^k);$$

boundary of a domain whose orientation is energetically less favored by a neighboring domain having a more favored orientation; this pressure is equal to
here H is the magnetic field intensity, I_S the saturation magnetization, and the index i corresponds to the domain with the more favored orientation.

The displacement of the boundary will obviously continue until this "hydrostatic" pressure becomes balanced by some "internal" pressure. It can be shown (see [13]) that the role of such an "internal" pressure is played by the gradient of the surface energy density $p_\gamma = \partial\gamma/\partial x$ (it is easy to see that p_γ has the dimension of pressure).

Let us assume for simplicity that the domains have the form of plane-parallel layers parallel to the easiest-magnetization axis, and γ is consequently a function of only one coordinate perpendicular to the sign of the boundary, say the coordinate x. Let the field be applied along the Oz axis. Then, when the boundary is displaced by an amount δx, the decrease Δw_M of the magnetic energy per unit surface of the boundary zone is

$$\Delta w_M = 2HI_s\delta x. \tag{4}$$

The growth of the energy of the boundary zone Δw_γ per unit boundary surface is

$$\Delta w_\gamma = \frac{\partial\gamma}{\partial x}\delta x. \tag{5}$$

The equilibrium condition for the boundary is obviously

$$2HI_s = \frac{\partial\gamma}{\partial x}. \tag{6}$$

Relation (6) gives the connection between the equilibrium value of the field H, which brings the boundary to the coordinate x, and the value of the gradient of the surface energy density of this boundary at the given point. This equilibrium value of the field is

$$H_0 = \frac{1}{2I_s}\frac{\partial\gamma}{\partial x}. \tag{7}$$

Figure 1 shows a plot of $P_S = \partial\gamma/\partial x$ against x for some possible distribution of the internal stresses in the crystal. Let the equilibrium value of the field correspond to the coordinate of the boundary x_0. If now we increase H further then, as is clear from the figure, the reversible displacement of the boundary will pro-

*The main mechanisms of the Barkhausen jump in ferromagnets, as well as the ferroelectrics, are the formation of nuclei with their subsequent growth, and the jumplike motion of the interdomain wall over defects and inclusions. In this chapter we consider the mechanism connected with the jumps of the wall, since in the opinion of most authors it plays the main role in ferromagnets. The mechanism connected with nucleus formation is considered in the chapter devoted to ferroelectrics.

**The measurements of the width of the boundary layer between domains are discussed in [17].

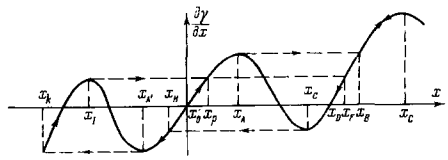


FIG. 1

ceed only until, after leaving its equilibrium state, it reaches the point with coordinate x_A, at which the nearest maximum of P_γ is located.

The value of the external field H_0 corresponding to this position of the boundary (the maximum of P_γ) is called the critical field. Obviously, after reaching H_0, the growth of the magnetization, i.e., further displacement of the boundary, can occur without a growth of the field up to the point with the coordinate x_B, since at all the points $x_A < x < x_B$ the internal pressure P_γ is smaller than the external pressure P_H. As a result, the boundary shifts jumpwise from the point x_A to the point x_B, and the magnetization of the crystal changes jumpwise by a certain amount ΔI. This jump (the displacement of the boundary from x_A to x_B) is irreversible, for when the field is subsequently decreased, as is clear from the figure, the boundary will not move again jumpwise from the point x_B to the point x_A, but will move reversibly through the point x_F, x_D up to the point x_C, from which it goes jumpwise to the point x_H.

Thus, owing to the presence of inhomogeneities, internal stresses, variations in the gradient of the surface energy density of the boundary layer, and other inhomogeneities, irreversible displacements of the boundaries between the domains are superimposed on the reversible ones. These irreversible jumplike displacements of the boundaries are the Barkhausen jumps.

Let us introduce some refinements. The definition of the critical field in accordance with formula (7) is accurate, strictly speaking, only in the case of a plane boundary. Actually, the boundary between domains, as shown by Becker and Doring,[18] is not flat and has in general a complicated shape, which is also determined by the distribution of the internal stresses. As a result of the curvature of the boundary surface, an additional surface pressure P_S is produced, equal to

$$P_s = \gamma (r_1^{-1} + r_2^{-1}), \tag{8}$$

where r_1 and r_2 are the Gaussian curvature radii of the boundary surface. Allowance for this additional pressure yields the following expression for the critical field:

$$H_0 = \frac{1}{2I_s}\left[\frac{\partial \gamma}{\partial x} - \gamma\left(\frac{1}{r_1} + \frac{1}{r_2}\right)\right]. \tag{9}$$

Although for estimating purposes the correction term in (9) is negligible, it must be borne in mind that at different points of the boundary surface p_S can change not only in magnitude but also in sign.

An appreciable influence on the value of the critical field may be exerted by the growth of the surface of the domain boundary, connected with the detainment of a section of the boundary by the inclusions.

If the Barkhausen jump is due to an irreversible displacement of a 90° boundary, then the right side of Eq. (9) for the critical field will contain also a term expressing the change of the magnetoelastic energy of the stresses, due to the rotation of the spontaneous magnetization when the Becker boundary is displaced. The order of magnitude of this term, which is proportional to $\lambda_S \sigma_i$ (where λ_S is the linear saturation magnetostriction and σ_i is the magnitude of the internal or external stresses), is as a rule larger than $\partial\gamma/\partial x$, and therefore the critical field H_0 in this case is determined primarily by the distribution of the maxima of the stresses σ_i that are encountered on the path of boundary motion. In this case, too, the picture of the appearance of these stresses can be represented in analogy with Fig. 1.

A more detailed analysis shows that the critical field corresponding to jumps of a 90° boundary (H_0, 90°) is much larger than the critical field of a 180° boundary (H_0, 180°). It follows therefore that the Barkhausen jumps produced by 90° boundaries should be observed only in strong fields, and consequently their number should be much smaller than that of the 180° jumps, since the stage of displacements corresponds to low values of the magnetic field. The experimental data of Honda and Kaya[19] and of Bozorth and Dillinger[20] confirm these conclusions.

All the foregoing reasoning was based on the fact that the magnetization reversal jump is caused by a jumplike motion of the boundary between domains. One can visualize, however, another Barkhausen-jump mechanism, namely a magnetization-reversal jump due to nucleus formation (see also Ch. III, Sec. 2). We note that in the opinion of most authors who investigated the Barkhausen effect in ferromagnets, nucleus-production play a much lesser role in the magnetization-reversal jumps than the jumplike motion of the domain boundary. This is confirmed also by observations of the dynamics of the domain structure.[83, 84]

2. Procedure for Investigating the Barkhausen Effect in Ferromagnets

The procedure of investigating the Barkhausen effect in ferromagnets consists in the following. The investigated sample is placed inside a measuring coil (pickup), which in turn is placed inside a magnetizing coil (or between the poles of a permanent magnet). The magnetic field in the magnetizing coil is varied smoothly with the aid of a potentiometer (or by smoothly varying the gap between the magnet poles), and Barkhausen jumps are then produced in the sample. The voltage pulses induced thereby in the search coil are fed to the input of an amplifier. The amplified pulses can be counted with the aid of a scaler system. In parallel with the amplifier output one usually connects a cathode-ray oscilloscope for visual observation of the process, or a loop oscilloscope that records the process on film. The use of additional instruments (amplitude discriminators, integrators, etc.) makes it possible to investigate the number of recorded jumps, their parameters (amplitude, duration, dimension, etc.), and also their variation under the influence of various internal and external factors (impurities, structure, temperature, mechanical stresses, annealing, rate of change of the magnetic field, etc.).

Figure 2 shows several schematic diagrams of in-

stallations for the investigation of the Barkhausen effect in ferromagnets, used by authors of [1, 21-25].

In the Soviet Union, the most widely used is the procedure developed by Kirenskiĭ and Ivlev.[12, 33]

An important role in apparatus intended for the investigation of the magnetic Barkhausen effect is played by the search coil. The role of the search coil and the question of its correct selection has been considered in a number of papers.[25-30] The sensitivity of the apparatus is obviously determined by the ratio of the useful signal at the amplifier input to the noise level.

As shown in [25, 27], the increase of the noise with increasing number of turns of the search coil is due principally to the growth of its inductance, and not of its ohmic resistance, as was assumed earlier.[26, 31-36] Therefore, to increase the sensitivity of the apparatus, the search coils should have a large number of turns but a minimum possible inductance, i.e., small internal and external diameters. By merely modifying the search coil, they succeeded in [25, 27, 37] to increase greatly the sensitivity of the apparatus compared with that of [32-36, 26] and to raise it to 0.9×10^{-7} cgs emu of magnetic moment.

At the same time it must be borne in mind that a decrease of the dimensions of the coil leads to a decrease of the time constant, i.e., to a decrease in the time of the transient process in the coil circuit. This, as shown in [26, 28, 30] leads in some cases to errors in the estimate of the dimensions of the jumps. An important role, depending on the purpose of the experiment, is played also by the length of the coil.[26, 29] Thus, the parameters of the search coil should be chosen with allowance for the foregoing with allowance made for the purpose of the research. For example, if the most important task of the experiment is to determine the total number of jumps, and it is desirable to include shallow jumps, then the dimensions of the measuring coil must be made as small as possible. On the other hand, if the characteristics of the individual jumps are investigated, it is necessary to take into account the influence of the coil dimensions on the transient processes.

An important factor in many investigations of the Barkhausen effect is a determination of the dimensions of the jumps, i.e., a determination of the change of the magnetic moment ΔM corresponding one jump, or the volume ΔV of the magnetization-reversing region. It is easy to show[25] that the change of the magnetic flux through the coil, $\Delta\Phi$, corresponding to the magnetization-reversal jump, is proportional in turn to the change of the magnetic moment ΔM occurring during this jump, i.e., to the dimension of the jump, and consequently

$$\Delta M \sim \int_0^\tau \mathcal{E}\, dt, \qquad (10)$$

where τ is the duration of the Barkhausen jump and $\mathcal{E}$ is the emf induced in the measuring coil.

It follows therefore that the areas of the pulses fed to the input of the amplifier are proportional to the dimensions of the magnetization-reversal jumps. If the jump durations do not differ greatly from each other, then it can be assumed in first approximation that the pulse amplitude is proportional to the change of the magnetic moment, i.e., to the jump dimension ΔM. Consequently,

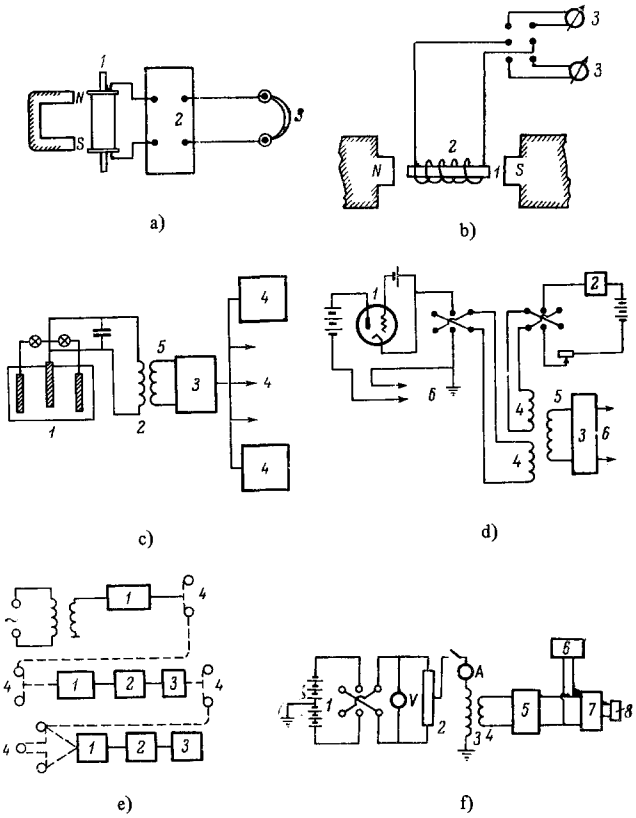


FIG. 2. a) 1—Sample, 2—vacuum tube amplifier, 3—earphone (after [1]); b) 1—sample, 2—pickup, 3—galvanometer (after [21]); c) 1—liquid potentiometer, 2—solenoid, 3—amplifier, 4—recording device, 5—pickup (after [22]); d) 1—current regulator, 2—magnetization source, 3—amplifier, 4—solenoid, 5—pickup, 6—to vibrator (after [23]); e) 1—amplifier, 2—discriminator, 3—counter, 4—tape recorder (after [24]); f) 1—power source, 2—rotating potentiometer, 3—magnetizing coil, 4—pickup, 5—amplifier, 6—oscilloscope, 7—scaler circuit, 8—mechanical counter (after [25]).

in first approximation, the dimensions of the jumps and the relations between them can be assessed from the amplitudes of the pulses at the amplifier output (assuming that the amplifier does not distort the pulse waveform). In the presence of a large scatter in the durations of the individual pulses, an estimate of the jump dimensions on the basis of the amplitudes (which, strictly speaking, are proportional to $\Delta M/\Delta t$) may turn out to be too crude. To estimate the jump dimensions for any scatter in the duration, it is necessary to connect in the circuit (Fig. 2) a pulse integrator following the amplifier.[30, 39]

3. Principal Experimental Results

a) General laws. Jump parameters. When the magnetic state of the sample varies along the magnetization curve or the hysteresis loop, the Barkhausen jumps do not occur at all values of the applied field. For each ferromagnetic sample, depending on its structure and state, the jumps begin at a certain perfectly defined value of the field intensity (start field H_{st}) and terminate at a certain value in the field (finish field H_f).[33, 38]

In the case of magnetization along the normal curve the field corresponding to the start of the jump can be

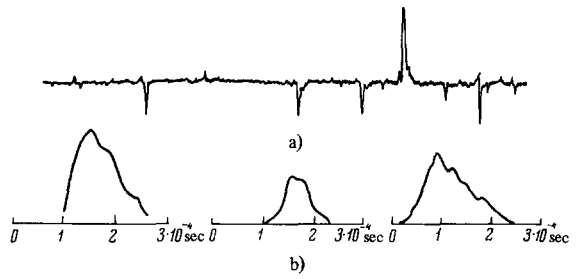


FIG. 3. Oscillograms of the Barkhausen jumps for permalloy [20] (a) and for iron [11] (b).

naturally identified with the end of the Rayleigh region, and H_f can be identified with the end of the displacement process. Many authors[20, 33, 38] note that the Barkhausen jumps occur most intensely in fields close to coercive.

The main parameters characterizing the Barkhausen jump are the jump duration τ and the volume ΔV that becomes remagnetized in one jump, or else the jump dimension $\Delta M = 2I_S \Delta V$ (I_S is the saturation magnetization), which is uniquely defined by the volume ΔV.

Figure 3 shows oscillograms of jumps obtained by Bozorth[40] and Forster.[11] The volumes of the regions have become remagnetized during the jump, as estimated from such oscillograms, fluctuate in the range 10^{-7}–10^{-9} cm^3. These values depend very strongly on the deformation of the sample, a fact in good qualitative agreement with the "critical field" theory considered above. A series of investigations by Bozorth and Dillinger[20, 41, 42], Tsomakion and Ivlev,[12, 43] and others[27, 30-35, 38] has confirmed these data. The average duration of the jumps, according to the data of most authors, is on the order of 2×10^{-4} sec.

The total contribution introduced by the Barkhausen jumps to the magnetization reversal process, for different samples, fluctuates in a wide range, from several percent[32] to 86%.[26]

Investigations of the Barkhausen effect in single crystals, carried out by Tebble and Newhause[44] and by Ivlev and Aseeva,[35, 45] have revealed an appreciable anisotropy of the number of jumps along different crystallographic directions.

Telesnin[46] observed delayed Barkhausen jumps—a viscous phenomenon, consisting in the fact that the jumps are observed with a considerable time delay after the change of the magnetic-field intensity. This phenomenon was subsequently investigated by Huzimura[47] and by Telesnin and his co-workers.[48-50] It was shown by these investigations that in some cases the jump delay time after the change of the field reaches several minutes. The most intensely delayed jumps also occur on the steep part of the magnetization curve and on the steep part of the hysteresis loop. The sizes and numbers of the delayed jumps depend on the loads and on the temperature.

Gerlach and Lertes[21] observed the so-called "mechanical" Barkhausen effect—the appearance of remagnetization jumps following the action of mechanical stresses on the sample. This effect was subsequently investigated by Rodichev and Savchenko[51] and by Kharitonov.[52]

Kirenskiĭ and Ivlev[53] observed inverse Barkhausen jumps, i.e., jumps corresponding to a magnetic-moment change opposite to the applied field. However, Votruba[54] and Fisher[55] were unable to observe the inverse jumps and thought that the observations of Kirenskiĭ and Ivlev are the result of a defect in their apparatus. Subsequently, Kranz and Shauer[56] succeeded in observing inverse jumps by using the amplified magnetooptical Kerr effect. Recently Zentko and Hajko[152] observed reliably and investigated negative magnetization-reversal jumps in single-crystal Fe-Si. Their results are in good agreement with the data of [53]. Thus, the question of the presence of inverse Barkhausen jumps in ferromagnets can be regarded as answered in the affirmative.

b) Distribution of the jumps by dimensions and durations. Important questions attracting the attention of many investigators of the Barkhausen effect in ferromagnets are the dimension and duration distributions of the number of jumps. The first attempt to obtain the dimension distribution of the Barkhausen jumps was made by Tyndall.[23] However, the faulty procedure and the small number of jumps with which he operated (on the order of several hundred) do not make it possible to regard his results as sufficiently reliable.

Bush and Tebble[57] reached the conclusion that the number of jumps decreases monotonically with increasing size (Fig. 4a). Similar results were obtained by Ivlev, Ilyushenko, and Aseeva.[33-35, 45] Tebble, Skidmore, and Corner[26] using apparatus more sensitive than in [32], obtained for one sample, in addition to the monotonic distribution curves, also a distribution curve with clearly pronounced maximum (Fig. 4b). However, the authors did not pay due attention to this curve, and considered it to be the result of an experimental error.

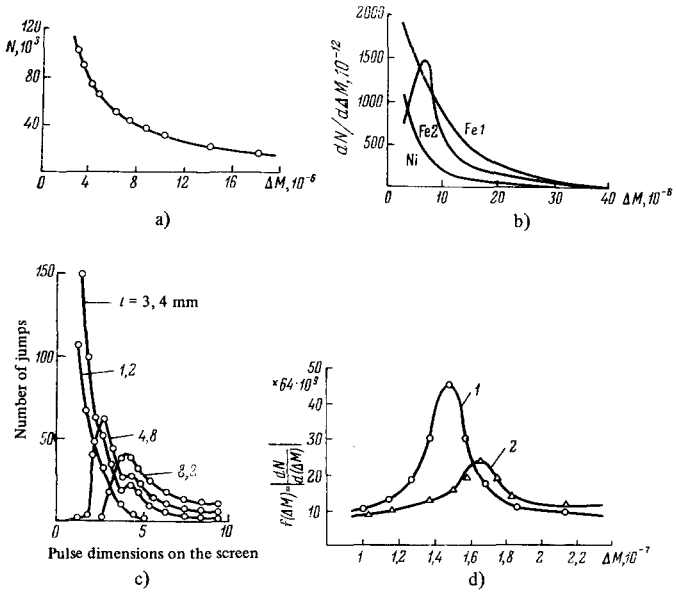


FIG. 4. Distributions of jumps by dimensions. Abscissas—changes of the magnetic moment corresponding to one jump in units of cgs emu (with the exception of curve c, where the jump dimensions are given in relative units). In Figs. a and c the ordinates represent the number of jumps whose dimensions exceed the value of the Jump ΔM. In Figs. b and d they represent the number of jumps where the dimensions lie in a unit interval of variation of ΔM. Sources: a) [12,57], b) [26], c) [58], d) [25,37,38,39].

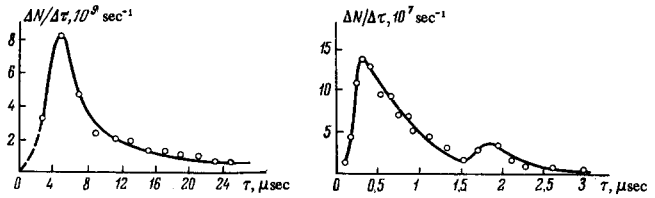
Sawada[58] investigated the distribution of the jumps by dimensions for a wire of silicon steel. The measurements were performed with seven measuring coils of different length, but with equal numbers of turns per unit length. For short coils, Sawada obtained a dependence similar to that obtained by Bush and Tebble, whereas for longer coils the distribution curves had characteristic maxima (Fig. 4c). He concluded that the jump-dimension distribution function can have two forms, monotonic and extremal.

In a number of studies, Ivlev and Rudyak[59, 37, 38, 25] have shown that if the sensitivity of the apparatus is sufficiently high the experimental distributions of the jumps by dimensions have a clearly pronounced maximum, i.e., for each state of the sample there exists a characteristic most probable dimension of the magnetization-reversal jump. The distributions of the jumps by dimensions for a nickel sample, obtained by these authors, are shown in Fig. 4d. A similar form is possessed also by the distribution curves for iron. In [37], is given a justification for the existence of a most probable jump dimension. In a later paper by Pfrenger and Stierstadt,[60] no maximum was observed in the dimension distribution of the jumps. The authors assume that the question of the character of the distribution of the Barkhausen jumps by dimensions, remains open. However, the measurements given in [52, 63], where a pulse integrator was used, have shown that the jump dimension distribution curves have a clearly pronounced extremum, i.e., they have a form analogous to the curves of Fig. 4d. A monotonic distribution was apparently obtained in [60], either because of the incorrect choice of the measuring coil (see [25-30]) or because of insufficient sensitivity of the apparatus.

An analysis of the plot of the dimension distribution of the number of jumps, carried out in [38] by the methods of mathematic statistics, shows that the obtained distribution deviates strongly from a Gaussian distribution. A calculation of the average variance coefficient shows that this deviation does not have a random character. Pearson's method[61] was used to find a distribution function having a form close to the experimental curve.

Rodichev, Salanskiĭ, and Sinegubov[62] have shown that the jump-duration distribution curve also has a clearly pronounced extremal character (Fig. 5a), i.e., most jumps have durations that do not differ strongly from a certain most probable duration characteristic of the given state of the sample. An analogous dependence is obtained in [30].

Rudyak and Kharitonov[63] observed an independent group of anomaously long Barkhausen jumps in ferromagnets, the durations and dimensions of which extend by almost two orders of magnitude the corresponding parameters of the previously investigated ordinary jumps. A detailed analysis of anomalously long jumps in nickel, iron and permalloy samples is the subject of a number of papers.[28, 52, 64-66] It was shown in these papers that in spite of their relatively small number (5-10%), the anomalously long jumps make a contribution of the same order to the irreversible part of the magnetization reversal as the ordinary jumps. It was established that anomalously long jumps have their own natural duration distribution, with the most probable



a) b)

FIG. 5. Jump distribution by dimensions. Abscissas—jump durations (in microseconds for Fig. a and in milliseconds for Fig. b); ordinates—number of jumps whose durations lie in a unit interval of variation of the duration τ. a) Data of [62], b) [63].

duration on the order of 1-2 msec (Fig. 5b). As one of the possible mechanisms for the appearance of anomalously long jumps, there is considered in [52] the irreversible motion of mutually coupled 180° and 90° walls, a motion observed in experiments by Haake and Lauman.[67] It is shown there that an independent group of anomalously long jumps is observed also in the mechanical Barkhausen effect.

c) Influence of different factors on the Barkhausen effect. Almost all the investigators of the Barkhausen effect note the high sensitivity of this effect to different external influences and to structural changes of the sample. Knowledge of the character of this influence on the different aspects of the Barkhausen effect makes it possible to apply this effect for a number of measurements and investigations.

The temperature dependence of the Barkhausen effect was investigated by Gerlach and Lertes,[21] Ivlev,[33] Papp,[68] Il'yushenko,[34] Stierstadt and co-workers.[69-72] Gerlach and Lertes[21] and Papp[68] have noted that with increasing temperature the number of jumps in the nickel decreases. Ivlev investigated the Barkhausen effect in polycrystalline nickel in the temperature interval from liquid nitrogen to the Curie point. He has shown that the total number of jumps N and the average volume ΔV that becomes remagnetized in a jump decrease exponentially, in a definite temperature interval, with increasing temperature. Investigating the distribution of the jumps over the field at different temperatures, he has shown that when the temperature is decreased the interval of fields in which the jumps are observed broadens, and the maximum of the distribution curve of the jumps with respect to the field shifts in accordance with the change of the coercive force. Stierstadt's researches, performed on single-crystal nickel, confirmed in the main the character of the temperature dependence obtained by Ivlev. The investigations of Il'yushenko[34] have shown that for iron the dependence of the effect on the temperature has an extremal character. At a certain temperature, which depends on the chemical purity of the sample, a maximum is observed in a number of jumps.

Newhause[73] has shown that the changes of the temperature of a ferromagnet placed in a constant magnetic field are also capable of causing magnetization-reversal jumps.

A considerable number of investigations has been devoted to the influence of annealing and deforming stresses on the Barkhausen effect. The influence of annealing on the Barkhausen effect was noted by Bozorth

and Dillinger, and also by Tebble, Skidmore, and Corner.[26] Ivlet and Rudyak[25] have established that in nickel, under the influence of annealing, the total number of jumps decreases, and the most probable jump dimension shifts towards larger jumps (Fig. 4d).

Forster and Wetzel[11] have shown that plastic deformations in nickel lower the effect greatly. Ivlev[33] has shown that at sufficiently strong stresses the magnetization-reversal jumps in nickel disappear completely. In a number of investigations of the influence of plastic deformations on the Barkhausen effect in different ferromagnets, Votruba[74-76] has shown that with increasing deformation the number of jumps increases noticeably in mu-metal and in hypernik, decreases weakly in iron, and drops strongly in nickel.

It is shown in [25] that if internal stresses are produced in a nickel sample by tension, and the measurements are performed after removing the load, then up to loads $\sigma = 9$ kg/mm^2 the total number of jumps increases, and the most probable jump dimension decreases, i.e., the fraction of shallow jumps increases. At $\sigma > 9$ kg/mm^2, the number of jumps decreases sharply, becoming smaller than in an annealed sample. With increasing σ, the field interval in which jumps are observed becomes much narrower.

The results of the influence of annealing and internal stresses can be explained by starting from the theory of the critical field, considered in Sec. 1. According to this theory, the Barkhausen jumps occur when the external field reaches values satisfying the condition (9). It can be assumed[13] that the principal role in this respect is played by the first term, determined by the gradient of the surface density of the boundary energy. According to [18]

$$\gamma = \{\alpha A [bk + (3\lambda_s \sigma/2)]\}^{1/2} \qquad (11)$$

(the notation is the same as in Sec. 1). As shown by Kondorskiĭ,[153] the main cause of the inhomogeneity γ are the inhomogeneities of the internal stresses σ_i. Then, taking into account the expression for the thickness of the interdomain boundary δ,[13] in terms of the quantities that enter in (11), we can obtain for the critical field H_0 the relation

$$H_0 = \frac{3}{4}\frac{\lambda_s \delta}{I_s}\left(\frac{\partial \sigma}{\partial x}\right)_{\max} \qquad (12)$$

Any cause leading to a change of the number of extrema of the internal stresses gives rise to a change in the number of jumps.

Let the initial state of the sample correspond to a definite number of jumps, and also to a definite distribution by dimensions. Annealing draws away the sites of internal stress, for the most part the shallow ones. Some of the $\partial\sigma/\partial x$ peaks disappear. Therefore annealing decreases the total number of jumps and leads to a growth of their most probable dimension.

If the sample is under load, then homogeneous tension occurs in it, leading in ferromagnets with negative magnetostriction to a decrease of the irreversible magnetization processes. Homogeneous tension leads to a decrease in the number of stress peaks. Therefore the number of Barkhausen jumps for a loaded sample is smaller than for an unloaded one. If the load is removed, on the other hand, then sites of local internal stresses arise at different points of the sample, the number of maxima of $\partial\sigma/\partial x$ increases, and this in turn leads to a growth in the number of jumps. If the load is sufficiently large, then even when it is removed the residual stresses play an important role and the sample behaves like a loaded one.[38]

It is easy to show that the change of the second term of (9) under the influence of annealing and internal stresses leads qualitatively to the same results as described above.

In contrast to the appreciable number of investigations of the influence of static stresses on the Barkhausen effect, the influence of dynamic stresses has hardly been investigated. There is a paper by Markeet,[77] in which it is noted that the number of jumps is decreased under the influence of ultrasound, as well as a paper[146] in which it is shown that ultrasound causes a shift in the starting field of the jumps in nickel, iron, and permalloy, namely, the jumps begin earlier in all three materials. It was also shown recently that ultrasound can cause jumps on magnetization reversal at a constant value of the external magnetic field.[147]

d) Connection of the Barkhausen effect with the domain structure and with the elements of the hysteresis loop. We have presented above a review of the investigations of either the characteristics of the jumps themselves or of the influence of different factors on their numbers, parameters, and distribution with respect to these parameters. At the same time, the greatest interest, in our opinion, attaches to establishment of the connection of the Barkhausen effect with the domain structure, with the magnetization and magnetization-reversal processes, and especially with hysteresis phenomena.

The connection between the Barkhausen effect and the change of the domain structure was first established by Williams and Shockley.[82] Kirenskiĭ, Savchenko, and Rodichev[83, 84] carried out parallel observations of the change of the domain structure and of the Barkhausen effect in silicon iron crystals stressed by tension along the three principal crystallographic directions (001), (110), and (111). These experiments have shown that the Barkhausen jumps are due not only to irreversible interdomain-boundary displacements caused by presence of stresses and inclusions in the ferromagnet. In some cases, the jumps can be due to a radical realignment of the domain structure. Plots of the number of jumps against the tension load reflect all the changes occurring in the domain structure when the sample is stretched, and the jumps reveal changes in the domain structure earlier than, for example, the method of powder patterns.

Inasmuch as the Barkhausen effect is connected with irreversible magnetization-reversal phenomena, and the most important characteristic of the irreversibility is the hysteresis loop, it is natural to expect a connection between the Barkhausen effect and the elements of the hysteresis loop. The first to establish a qualitative connection between the induction and the intensity of the effect were Gerlach and Lertes.[21] They have shown that when the magnetization of a ferromagnet is reversed, the induction of the sample and the intensity of the effect proceed in parallel fashion in a certain field interval. The maximum intensity of the effect in fields

close to coercive has been observed, as already mentioned, by many workers. By studying the dependence of the coercive field, the residual magnetization, and the intensity of the Barkhausen effect in iron-nickel alloys on the nickel content, Zschische[85] has shown that all three curves reflecting these dependences have a similar form.

A direct connection between the residual magnetization and the Barkhausen effect was established in [86]. Parallel measurements of the value of the residual magnetization I_R of a nickel sample and of the number N of jumps corresponding to magnetization reversal on one of the branches of the hysteresis loop, carried out first for an unloaded sample and then at different internal stresses produced by tension, have shown that the residual magnetization and the number of jumps are connected by the simple linear relation

$$I_R = I_R^0 + kN, \tag{13}$$

where k is a certain constant.

Starting from the existing theory of hysteresis phenomena, this relation can be interpreted as follows: according to Kondorskiĭ,[87] hysteresis is due to three causes: (a) delay in the displacement of the interdomain boundaries; (b) delay in the growth of the magnetization-reversal nuclei, (c) irreversible rotation processes. Inasmuch as the first two causes are the ones that cause also the Barkhausen jumps, it is natural to assume that the residual magnetization is made up of two parts. The first comprises the residual magnetization of the domain boundaries and the delay of the magnetization-reversal nuclei. This part of I_R should be proportional to the number of defects causing the delays. But since these defects cause also the Barkhausen jumps, this part should be proportional to the number of jumps in the sample. When the structure of the sample changes, the number of defects causing the jumps changes, and there should be a corresponding change in this first part of the residual magnetization. The second part of the residual magnetization is due to irreversible processes of rotation of the spontaneous-magnetization vector I_S. Defects influencing the motion of the interdomain walls have little effect on the processes of rotation, and therefore the change of the number of jumps does not influence this part of I_R.

It follows from the foregoing that in weak fields, when the rotation processes do not play an important role, the following relation should hold

$$I_R = kN. \tag{14}$$

An experiment in which parallel measurements were made of the number of jumps N and of the residual magnetization of the sample I_R for a number of partial hysteresis loops has confirmed the correctness of this relation.[86] An analogous connection between I_R and N was established recently for nickel films obtained by electrolytic deposition, and also for iron.[154]

In concluding this section, it should be noted that recently the attention of many investigators has been focused on the Barkhausen effect in thin ferromagnetic films.[30,78-81] It is shown in these investigations that the general laws of the effect remain the same as in bulky samples, but the dimensions of the jumps themselves are smaller in films.

III. BARKHAUSEN EFFECT IN FERROELECTRICS

1. Procedure for Investigating the Barkhausen Effect in Ferroelectrics

From the point of view of the character of the behavior in an external electric field, ferroelectrics[88-90] are the electric analogs of ferromagnets.

Polarization-reversal jumps are produced in a ferroelectric crystal when the electric field applied to it is altered. Observation of these jumps is more difficult than in the ferromagnetic effect, owing to the need of producing a contact between the metal and the ferroelectric in order to apply the field. A dependable observation and study of the Barkhausen effect in ferroelectrics has become possible only after a procedure was involved for high-grade deposition of electrodes. Another feature of the experimental procedure of investigating the Barkhausen effect in ferroelectrics, compared with ferromagnets, is the method of varying the applied field in time. Unlike the magnetic jumps, the Barkhausen jumps in ferroelectrics are predominantly delayed jumps of polarization reversal (this will be discussed in detail below), so that the main procedure employed by most workers is to investigate the jumps occurring during a considerable time after the change of the field, i.e., when the field is already constant. In [92-100], the electric field applied to the investigated crystal was varied by one of the methods shown in Fig. 6c. The advantage of the method is that it makes it possible to change the electric state of the sample both along the polarization curve (Fig. 6c) and along the hysteresis loops (Figs. 6c″–c‴), so that the features of the effect at different stages of polarization and polarization-reversal of the crystals can be determined.

A schematic diagram of a setup for the investigation of the Barkhausen effect in ferroelectrics, used in a number of investigations, is shown in Fig. 7. When the field applied to the sample (C_S) is changed, the polarization-reversal jumps occurring in the sample lead to a jumplike change of the current through the resistance R, which is connected in series with the crystal. Vol-

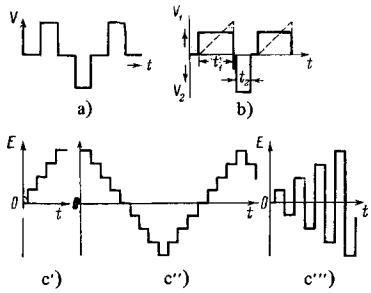


FIG. 6. Methods of change in the electric field applied to a sample: a) data of [92], b) [93,94], c')–c‴) [99].

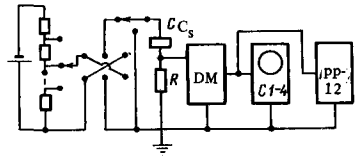


FIG. 7. Schematic diagram of setup for the investigation of the Barkhausen effect in ferroelectrics.

Investigated crystal and reference	Average pulse duration, msec	Average volume repolarized in one jump, cm^3	Fraction of total crystal volume repolarized by the jumps, percent
Barium titanate [93-97]	0.06—0.5	10^{-8}—10^{-9}	0.4—1
Rochelle salt [92,102]	0.1—1	10^{-8}—10^{-9}	0.01
Triglycinsulfate (TGS) [99,102]	0.5—0.8	10^{-7}	0.5—1.5

tage pulses corresponding to the Barkhausen jumps are picked off this resistance and fed to the input of a broadband amplifier (DM), and analyzing apparatus (oscilloscope, scaler device, etc.) is connected to the output of the amplifier.

Knowing the amplitude and duration of the pulses, and also their number, it is possible to estimate the average dimension of the pulse, the volume that becomes repolarized in one jump, and the fraction of the total volume of the crystal that becomes repolarized by the jumps.

It should be noted that the estimate of the value of the jump expressed in terms of the change of the electric charge Δq and cited in practically all foreign papers[91-97] should be regarded as quite unsuitable, since this quantity, other conditions being equal, is determined not only by the volume that becomes repolarized, but also by the thickness of the sample. On the other hand, the dimension of the jump, naturally, should characterize the jump itself and should not depend on the dimensions of the crystal. Therefore the magnitude (dimension) of the jump should naturally be taken to be the change of the electric moment of the sample ΔP(C-cm) occurring in one jump.

Elementary calculations[111] yield for the jump ΔP and the volume ΔV of the repolarizing region the following relations:*

$$\Delta P = U\,d\tau/2R, \quad (15)$$
$$\Delta V = U\,d\tau/4RP_s, \quad (16)$$

where U is the amplitude of the voltage pulse at the amplifier input, τ the pulse duration, R the input resistance of the amplifier, d the crystal thickness, and P_S the spontaneous polarization.

2. Fundamental Experimental Results

a) General laws. Possible jump mechanisms. Just as in ferromagnets, the Barkhausen jumps in ferroelectrics, according to the data of most authors,[92, 93, 99] are observed most intensely in fields corresponding to the steep section of the polarization curve and to the steep part of the hysteresis loop.

The table lists the main parameters of the jumps and the fraction of the crystal volume that becomes repolarized by the jumps, for the three most investigated crystals.

The pulses corresponding to the individual jumps as seen on the oscilloscope screen have a shape similar to those shown in Fig. 3.

The distribution of the Barkhausen jumps by dimensions in ferroelectrics has hardly been investigated.

*With allowance for the fact that most pulses have a nearly triangular shape.

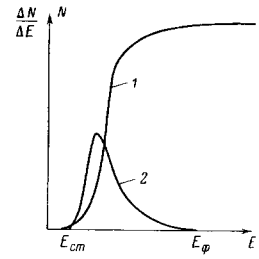


FIG. 8. Typical curves (1–integral, 2–differential) of the distribution of the number of Barkhausen jumps with respect to the field for a ferroelectric crystal whose electric state is varied along the polarization curve in steps.

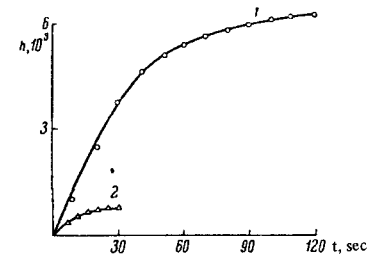


FIG. 9. Growth of the number of jumps with time after switching over the field in TGS (1) and in Rochelle salt (2).

Chynoweth[93] notes that the number of jumps decreases with increasing jump dimension.

Considerable information concerning the course of the Barkhausen effect in ferroelectrics is obtained from curves of the distributions of the number of jumps with respect to the field and with respect to time. A typical distribution of the number of jumps with respect to the field with the electric state of the sample varied along the polarization curve is shown in Fig. 8. The integral curve is similar to a typical ferroelectric polarization curve. The differential distribution curve has accordingly an extremum. The jumps begin at a certain value of the external field (E_{st}). The number of jumps corresponding to a unit interval of variation of the field $\Delta N/\Delta E$ increases with increasing field, passes through a maximum, and then decreases to zero (E_f).

The polarization-reversal jumps in ferroelectrics occur not only at the instants when the field is switched over, but also within a considerable time after switching. Typical curves showing the growth of the total number of jumps with time, for TGS and Rochelle-salt crystals, are shown in Fig. 9.[102] The existence of such delayed jumps of polarization reversal points to the presence in ferroelectrics of a viscous phenomenon analogous to the phenomenon of magnetic viscosity and superviscosity in ferromagnets.[46] This phenomenon can be naturally called dielectric viscosity.[113, 114]

Indeed, so long as the jumps take place, the domain structure of the sample becomes realigned even though the value of the external applied fields remains unchanged. Thus, the electric state of the sample, corresponding to an external applied field, is not established immediately, since this (like any other relaxation process) requires a definite amount of time, and this indicates to the presence of viscosity phenomena. It is natural to regard the dielectric viscosity as larger in those cases when, other conditions being equal, the jumps last longer, i.e., when the electric state of the sample is established more slowly.

We emphasize that the delayed jumps in ferroelectrics play a considerably greater role than the delayed

jumps in ferromagnets. Whereas for ferromagnets the delayed jumps of the magnetic viscosity constitute a small fraction of the total number of magnetization-reversal jumps, in ferroelectrics the bulk of the polarization-reversal jumps are delayed jumps, i.e., jumps of the dielectric viscosity.

It was shown in [115, 148], that when a constant electric field of intensity E is applied to a depolarized crystal, the time evolution of the polarization P is described by the equation

$$P = P_0[1 - \exp(-Et/\beta)], \tag{17}$$

where P_0 is the value of the polarization corresponding to the equilibrium state of the crystal in the field E, and β is the coefficient of dielectric viscosity of the crystal.

Inasmuch as the time evolution of the total number of jumps (Fig. 9) is described by an analogous equation, a connection is established in [148] between the coefficient of dielectric viscosity of the crystal β and the number of jumps:

$$\beta = E(t_2 - t_1)/\ln[(N_0 - N_1)/(N_0 - N_2)], \tag{18}$$

where N_0 is the total number of jumps due to applying a field E to the depolarized crystal, N_1 is the number of jumps occurring by the instant of time t_1, and N_2 is the same for the instant of time t_2.

A question of fundamental importance in the investigation of the Barkhausen effect in ferroelectrics is the connection of this effect, i.e., the jumplike polarization-reversal processes, with processes of polarization and polarization reversal of the crystal as a whole, i.e., processes of reorientation of the entire polarization, which have been investigated in a number of well-known papers.[155-158] In [159], in which a parallel study was made of the Barkhausen effect and of the reversal current in TGS crystals (the applied external field ranged from 10 to 10^3 V/cm) it is shown that the time of establishment of the entire polarization of the crystal is equal to the time of establishment of its irreversible part due to the jumps. At the same time, in strong fields, with increasing rate of realignment of the domain structure (i.e., with increasing applied or switched field), the fraction of the volume of the crystal subject to polarization reversal by jumps becomes smaller and smaller.

A number of workers[96, 103, 109] have observed inverse polarization-reversal jumps. Although the general laws and the causes for the occurrence of inverse jumps have not yet been investigated, the very existence of inverse jumps of polarization reversal in ferroelectrics is undisputed.

The question of the mechanism of occurrence of Barkhausen jumps in ferroelectrics has been discussed by many authors. Whereas in ferromagnets the predominant mechanism of the Barkhausen jump is the intermittently jumplike motion of the domain wall over various types of inhomogeneities, and the process of nucleus formation has low probability because of the considerable thickness of the boundary wall, in ferroelectrics, owing to the small thickness of the boundary wall (on the order of several Å units), the process of nucleus formation may play an appreciable role in the occurrence of the polarization-reversal jumps.

The mechanism of the jump connected with nucleus formation can be visualized as follows. Inside the crystal there are always individual regions that are in the stressed state. These regions serve as centers for nucleus production, for when an external field E is applied the reorientation of the spontaneous polarization P_S in these regions will be easier than in other regions of the crystal. Growing rapidly, these nuclei cause the polarization-reversal jumps. In order for such a Barkhausen jump to occur, it is necessary that the growth of the nucleus be energetically favored. Let us determine the critical dimensions of such a nucleus. If the value of the nucleus is ΔV, then upon reorientation of the spontaneous polarization the energy loss will amount to $\Delta w_V = -2P_S E \Delta V$. However, the appearance of such a nucleus is connected with a growth $\Delta w_S = \sigma \Delta S$ of the boundary energy, where ΔS is the surface of the boundary enclosing the nucleus, and σ is the surface density of the boundary energy. Let the nucleus have the form of an ellipsoid of revolution, strongly prolate along the ferroelectric axis (so that the depolarizing field does not affect the reorientation of the vector $\mathbf{P_S}$). To simplify the estimate of the volume and surface, we assume this ellipsoid to be a cylinder of length $l = 10\,r$, where r is the radius of the base. The total change of the crystal energy as a result of the reorientation of such a nucleus is

$$\Delta w = 20\pi r^2\sigma - 20\pi r^3 P_s E. \tag{19}$$

The critical dimension of the nucleus r_0 is obtained from the condition $\partial(\Delta w)/\partial r = 0$. From this condition we get

$$r_0 = 2\sigma/3P_sE\,^*). \tag{20}$$

This means that only nuclei with $r \gg r_0$ will grow. When $r < r_0$, an accidentally produced nucleus will be "suppressed" by the surface forces. Substituting in (20) the values of σ and P_S from [149] and choosing for E a value on the order of the coercive field (it is precisely in such fields that the jumps occur most intensely), we obtain $r_0 \sim 10^{-4}$ and $\sim 10^{-3}$ for $BaTiO_3$ and TGS, respectively, corresponding to minimal jump dimensions on the order of 3×10^{-11} and on 3×10^{-8} cm for $BaTiO_3$ and TGS, respectively.

In view of the large degree of anisotropy of ferroelectric crystals, the nucleus will grow principally along the ferroelectric axis (along the same direction that the field E is applied). The maximum growth of the nucleus is limited by the crystal thickness d. The volume that becomes repolarized in such a jump is $\pi r^2 d$. At a crystal thickness on the order of 2 mm,[99] this amounts to about 10^{-6} cm^3 for TGS.

Recognizing that the growth of the nucleus through the entire crystal is rare, owing to microcracks and other defects, we can assume the average volume corresponding to the jump to be 10^{-7} cm^3, which is in good agreement with the experimental data (see the preceding table). With increasing crystal thickness, the aver-

*An analogous expression for one of the dimensions of the critical nucleus, with allowance for the depolarizing field, were obtained by Miller and Weinreich [160], who considered nucleus production as one of the mechanisms of the lateral motion of 180° domain walls in $BaTiO_3$ crystals.

age dimensions of the jumps should increase. This agrees with the data of Chynoweth.[93]

It should be noted that the probability of polarization reversal with subsequent growth of the nucleus greatly increases near the interdomain wall. Therefore in the process of polarization reversal, the jumps will occur principally as the wall approaches the future nucleus. The formation and growth of the nucleus far from the boundary (inside the domain oriented opposite to the field) are much less probable, although they are also possible.

Certain investigators believe nucleus production to be the only cause of jumps in ferroelectrics.[93] To the contrary, Miller,[94] who observed simultaneously domain-wall motions and Barkhausen jumps in barium titanate, obtained results that indicate convincingly that these jumps occur also both when the domains grow and when the domain boundaries come together.

It is natural to assume that the process of the decay of a single-domain state of the ferroelectric crystal begins with the nucleation of new domains having a spontaneous polarization directed opposite to that previously existing in the crystal. The resultant jumps must be regarded as due to nucleus formation. Subsequently, however, when the crystal already has domains with different directions of the spontaneous polarization, a change of the electric field inevitably leads to a displacement of the domain walls, and in this case, the nucleus formation should be accompanied by the jump mechanism considered by us in the case of ferromagnets.

In the investigation and discussion of the behavior of Barkhausen jumps it is necessary, in our opinion, to take into account all the aforementioned possibilities of their occurrence (nucleus formation, jump formation, motion of domain walls, and coalescence of domain boundaries). We note, incidentally, that a study of the topography of the jumps themselves does not afford an unambiguous answer to the question of the possible cause of their appearance. Therefore, in the investigation of the Barkhausen effect in ferroelectrics, much attention must be paid not to the jump parameters, but to their field and time dependences, to the influence of the different factors on the effect, to the connection of the effect with other properties of the crystal, etc.

b) Features of the evolution of the Barkhausen effect in different ferroelectrics. An analysis of the results of investigations of the Barkhausen effect in different crystals[92-95, 98-102, 106] shows that besides the general regularities noted in the preceding section, the evolution of the effect in different ferroelectrics exhibits essential differences, not only quantitative but also qualitative.

For example, in barium titanate and in the $BaTiO_3$-based varicaps VK-2 and VK-4, when the electric state is varied along a branch of the hysteresis loop, i.e., when the field is decreased from the maximum value corresponding to the polarized state of the sample, the jumps begin long before the zero field is reached.[106] In TGS this process[99] begins only after passing through the zero field value.

Such a different behavior is connected, in our opinion, with the different degree of rectangularity of the hysteresis loop of TGS and of materials based on $BaTiO_3$.

The largest amount of material for a comparison of features of the Barkhausen effect was accumulated for Rochelle-salt and TGS crystals.[92, 99, 102] At identical geometrical sample dimensions and at the same temperature, the number of jumps in TGS is much larger than in Rochelle salt. The average dimension of the region that reverses polarization in one jump is also much larger in TGS. This explains the large difference in the percentage of the jumpwise repolarized volumes of the two crystals (see the preceding table). The time during which a jump is observed after the change in the field is much larger in TGS samples than in Rochelle salt samples, thus pointing to a different value of the coefficient of dielectric viscosity of these crystals (larger for TGS) (see Fig. 9).

Entirely different influences are exerted on the Barkhausen effect by mechanical stresses in the two crystals. In Rochelle-salt crystals with an $x = 45°$ cut, the number of jumps decreases under the influence of static stresses applied along the normals to the side faces of the sample. Mechanical stresses applied in similar fashion to TGS samples have no influence whatever on the Barkhausen effect.

Shuvalov, Rudyak, and Kamaev[100] succeeded in observing in Rochelle-salt crystals a new modification of the Barkhausen effect, namely polarization-reversal jumps due to applied mechanical stresses (for details see below). This effect does not appear in TGS crystals.

To a considerable degree, the foregoing differences in the manifestations of the Barkhausen effect can be explained on the basis of the crystal-physics classification proposed by Shuvalov for ferroelectrics,[116, 117] based on crystallographic attributes characterizing the differences in the geometry of the domain structure of ferroelectric crystals[88, 102, 111, 118]. In fact, the crystal lattice of antiparallel domains in TGS crystals is oriented in the same manner, and when the polarization is reversed no additional energy is consumed in the realignment of the structure, as is the case in Rochelle-salt. It is therefore natural that the polarization-reversal jumps in TGS encompass a larger volume. Another cause of the considerable difference between the volumes that become repolarized in one jump in these two crystals is, in our opinion, the fact that in Rochelle-salt the surface density of the boundary energy σ is much smaller than in TGS.[149] Therefore, according to (20), even when account is taken of the difference between the values of P_S, the minimal and average volumes of the nuclei in Rochelle-salt turned out to be smaller than in TGS by 1–2 orders of magnitude.

c) Influence of different factors (external actions) on the Barkhausen effect in ferroelectrics. We have already noted that mechanical stresses exert a noticeable influence on the Barkhausen effect in Rochelle-salt. A similar influence should be exerted by mechanical stresses also on other ferroelectrics of the second crystallographic class, which includes, according to [116], uniaxial ferroelectrics without piezoelectric properties in the initial paraelectric phase in general or along the direction of occurrence of spontaneous polarization.

Inasmuch as the temperature of the sample influences strongly the ferroelectric properties of the crystal, and primarily the spontaneous polarization P_S, a

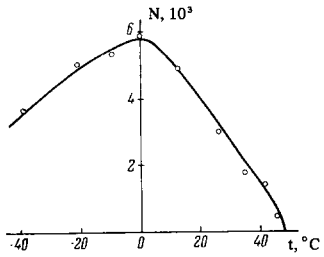
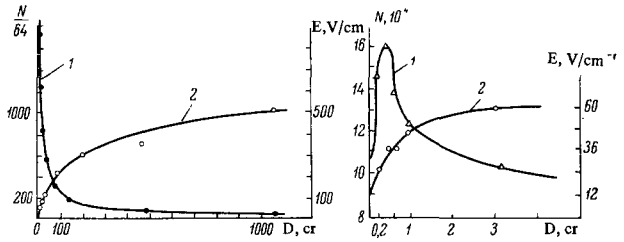


FIG. 10. Dependence of the number of jumps on the temperature for a TGS crystal.



a) b)

FIG. 11. Influence of γ rays (a) and x-rays (b) on the number of jumps (1) and on the starting field (2) for the TGS crystal.

change of the temperature should become strongly manifested also in the evolution of the Barkhausen effect.

Kibblewhite[91] has noted a full analogy between the behavior of the number of jumps in barium titanate and the temperature evolution of the spontaneous polarization. Detailed temperature investigations of the Barkhausen effect in Rochelle-salt were carried out by Abe[92] and in TGS by Kamaev.[111] According to Abe the total number of jumps decreases when each of the Curie points is approached. The temperature evolution of the number of jumps is analogous to the temperature evolution of the spontaneous polarization. It is shown in [111] that in TGS the change of the temperature greatly influences not only the total number (Fig. 10) but also the field dependences of the jumps. With increasing temperature, the character of the curves does not change, but the starting field and the field corresponding to the maximum number of jumps decrease monotonically. Above the Curie point, no jumps are observed. We succeeded in establishing recently that at the liquid-nitrogen temperature the Barkhausen jumps in TGS vanish, although the crystal certainly remains in the ferroelectric phase. A certain "blocking" of the domain structure takes place. A similar "blocking" is observed also in ferromagnets.[34, 120]

In [103, 108, 110] the Barkhausen effect was investigated in TGS and Rochelle-salt crystals subjected to the action of x-rays and γ rays. It is shown in [103, 108] that, in a wide range of doses (from 5 kr to 1 Mr), γ radiation decreases the total number of jumps and increases the starting fields with increasing irradiation dose (Fig. 11a). These data are in good agreement with those of Zheludev and Yurin[123-125] on the influence of γ rays on the domain structure and other properties of ferroelectrics. According to [121-125], decay products are formed in irradiated samples and stabilize some of the domains, thereby hindering the motion of the domain walls. As a result fewer domains participate in the polarization reversal, leading to a decrease in the number of jumps with increasing irradiation dose. Stabilization of the domains and the decrease of the mobility of the domain walls lead also to stretching of the hysteresis loop, until a section with linear polarization appears. On such sections, no realignment of the domain structure occurs, and the ferroelectric behaves like a paraelectric. Naturally, on the linear section of the polarization curve, where there are no irreversible processes, there are likewise no polarization jumps. This causes the growth of the starting field in γ-irradiated crystals.

Under the influence of x-rays, the number of jumps first increases significantly with increasing dose, goes through a maximum, and then decreases. The starting field of the jumps increases monotonically with increasing irradiation dose (Fig. 11b).

The extremal dependence of the number of Barkhausen jumps on the x-ray dose in VK-4 film varicaps was observed in [106]. It is interesting to note that in [126] there was observed a similar dependence of the dielectric constant of the same material on the irradiation dose. These dependences can be explained[110] in the following manner. If the sample is sufficiently "pure," i.e., the number of defects in it is relatively small, then irradiation with a small dose should lead to a certain increase of the number of defects, which in turn leads to the appearance of new centers of nucleus formation, but small doses cannot cause stabilization of the domain structure. Therefore the total number of jumps first increases with increasing irradiation dose, and then (when the stabilization of the domain structure comes into play) the number of jumps decreases. As to the monotonic increase of the starting field of the jumps with increasing irradiation dose, this is connected with the fact that the formation of any additional defect hinders the motion of the domain wall from the equilibrium position under the influence of the electric field.

The influence of annealing and aging of samples on the Barkhausen effect was investigated in [106, 111]. These investigations have shown that aging of TGS samples[111] and varicaps[106] leads to a decrease in the total number of jumps and in their lifetime; the starting fields increase. These results indicate that stabilization of spontaneous polarization occurs during the aging of the sample. One of two possible directions of the dipole moment becomes energetically favored in the volume of each domain (or of the entire crystal), and this causes a certain "blocking" of the domain structure. Thus, the influence exerted by aging on the polarization-reversal processes is analogous to γ irradiation. Annealing, to the contrary, leads to an increase in the number of jumps, i.e., it facilitates the reorientation of the domains in external fields.[127]

d) New modifications of the Barkhausen effect in ferroelectric crystals. It was already mentioned that it became possible to observe[100] and to investigate in Rochelle-salt a new modification of the Barkhausen effect, namely polarization-reversal jumps due to application of mechanical stresses in the absence of an external electric field. If a load is applied to a sample of Rochelle salt with an x = 45° cut along the normals to the side faces of the plate, in one of mutually perpendicular directions (i.e., so as to produce a homogeneous mechanical compression stress equivalent to the shear

stress σ_{yz} (or σ_{zy}), and if the stress is varied in steps, then polarization-reversal jumps will occur, within the ferroelectric temperature interval, on each stress stop. These jumps are analogous to those produced by varying the electric field along the x axis. The dimensions and the durations of these jumps are the same as of the "electric" ones. The plots of the distribution of the number of jumps as functions of the mechanical stresses are analogous to the plots of the distribution with respect to the field for the jumps produced by an electric field. When the mechanical stress is decreased, and also when a compression stress is applied in a direction perpendicular to the initial one (corresponding to a reversal of the sign of the equivalent shear stress), Barkhausen jumps of the opposite sign appear. If the number of jumps of one sign is regarded to be positive and that of the other sign negative, then the dependence of their algebraic sum on the applied mechanical stress (if the latter is cyclically varied) will have the form of a hysteresis loop (Fig. 12). These results are in good agreement with the data of Zheludev and Romanyuk[118] on direct observation of the dynamics of the domain structure in Rochelle-salt crystals under the influence of mechanical stresses. Inasmuch as the spontaneous deformation of Rochelle-salt crystals (as well as other ferroelectrics with analogous geometry of the domain structure) contains a shear component[116, 117] that has different signs for domains with oppositely directed vectors $\mathbf{P}_S$, application of a corresponding shear stress can cause a displacement of the domain boundaries. The polarization-reversal jumps occur during the course of this displacement. In TGS crystals (as well as in other ferroelectrics having a similar domain-structure geometry), homogeneous mechanical stresses cannot directly cause displacements of the domain boundaries. Therefore the effect described above is not observed in TGS crystals.[100, 102]

In the ferroelectric semiconductor SbSi, Rudyak and Bogomolov[112] observed, in the wide temperature interval from −78° C to the Curie point (Fig. 13); polarization-reversal jumps produced by illumination. The polarization-reversal jumps due to light cease after a certain time interval and are not observed following a second illumination. This indicates that the observed effect cannot be attributed to photoconductivity noise. We are dealing here apparently with an easing of the nucleus-production processes under the influence of the light.

One more modification of the Barkhausen effect was observed recently, namely polarization reversal jumps occurring in phase transitions of ferroelectrics (in the absence of an electric field).[143, 150] This effect was observed in crystals of $BaTiO_3$, SbSi, TGS, KDP, RbDP, and Rochelle salt. The jumps occur in both directions (Fig. 14).

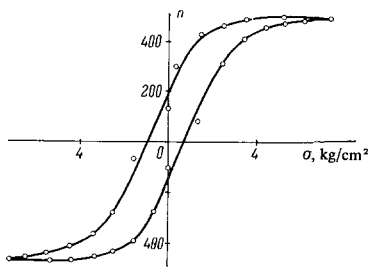


FIG. 12. Dependence of the algebraic sum of the number of jumps of both directions in a sample with x = 45° cut of Rochelle salt on the applied mechanical stress in the case of cyclic polarization reversal of the sample (t = 12.5°C).

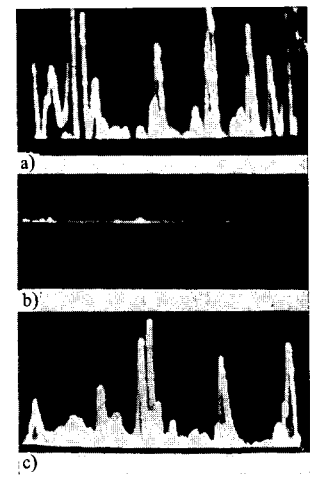


FIG. 13. a) Polarization-reversal jumps in SbSi, due to an electric field, at the instant of the most intense repetition of the jumps: b) picture of the electric jumps on the oscilloscope screen one minute after the application of the electric field; c) polarization-reversal jumps produced by illumination (t = 0°C).

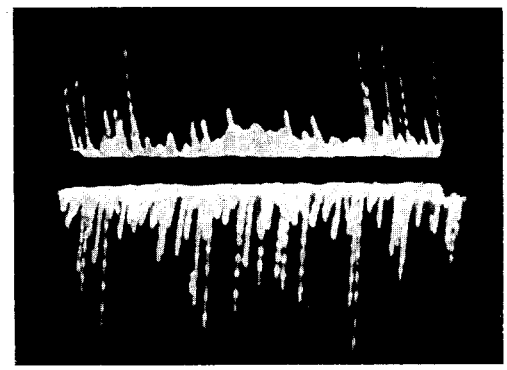


FIG. 14. Barkhausen jumps produced in an SbSi crystal on going over from the ferroelectric phase into the paraelectric phase (photographed from an oscilloscope screen).

The occurrence of Barkhausen jumps in phase transitions may be due, in our opinion, to two factors: jumplike decay (occurrence) of regions of spontaneous polarization as the crystal goes over from the ferroelectric phase into the paraelectric phase (or vice versa), or the process of realignment of the domain structure within the ferroelectric phase itself in the immediate vicinity of the Curie point. In either case, a study of this effect is of undisputed interest. It is not excluded that both mechanisms take place simultaneously.

IV. BARKHAUSEN EFFECT AS A METHOD OF INVESTIGATING FERROMAGNETIC AND FERROELECTRIC CRYSTALS

The connection between the Barkhausen effect and the domain structure as well as the main elements of the hysteresis loop, the high sensitivity of this effect to different factors, the stability of the main characteristics of the effect (the jump starting field, the finishing field, the time of passage of the jumps, etc.), for each state of the sample, all these make it possible to em-

ploy the Barkhausen effect as a method for the investigation of ferromagnets and ferroelectrics, and also for the measurement of certain magnetic and electric quantities.

1. Measurement of the Coercive Force of Ferromagnets by the Barkhausen-jump Method

The first suggestion that the Barkhausen effect be used for magnetic measurements was made in [131], where it is used to measure the coercive force. It is shown in that paper that if the number of jumps corresponding to a change in the magnetic state of the sample is measured along one of the branches of the hysteresis loop, i.e., from $-I_{max}$ to $+I_{max}$ (using the procedure described in Ch. II, Sec. 1), and then, after again returning to state $-I_{max}$, the field is smoothly varied from $-H_{max}$ to $+H_{max}$, then the field at which the number of jumps is equal to half the total number of jumps corresponding to the total branch of the hysteresis loop is equal to the coercive force.

In fact, assume that during the displacement stage, when the magnetization of the sample is varied from I_1 to I_2, i.e., when the boundary* is displaced from x_1 to x_2, there occur n Barkhausen jumps. Inasmuch as during the displacement stage the change of the magnetization ΔI is determined completely by the boundary displacement Δx, we can put

$$\Delta I = \Delta x I_0 / l, \tag{21}$$

where l is the width of the domain and I_0 is the magnetization corresponding to the end of the displacement stage.

Since each jump occurs on some nonmagnetic inclusion or local site of internal stresses, when the boundary moves back from x_2 to x_1, an equal number of jumps in the opposite direction will occur. Thus, if n_1 Barkhausen jumps are produced when the magnetization is varied from I_1 to I_2, then $n_2 = n_1$ jumps will be produced when the magnetization is varied back from I_2 to I_1. In particular, if N jumps are produced when the magnetization is varied from zero to I_0, then N jumps (in the opposite direction) will be produced also on going back from I_0 to 0.

Since no Barkhausen jumps are observed in the case of $I > I_0$ (in the rotation stage), the number of jumps N obviously corresponds to the change of the magnetization of the sample from zero to I_S (saturation magnetization), or conversely from I_S to zero. Consequently, when the magnetization of a sample is changed from $-I_S$ to $+I_S$ along the entire hysteresis-loop branch, the number of Barkhausen jumps will be 2N, and the field corresponding to half this number as the magnetization is varied from $-I_S$ to $+I_S$ is equal to the coercive force.

The conclusions of the foregoing reasoning remain valid also for a polycrystalline sample. Experiments carried out with samples of nickel, iron, and a number of ferromagnetic alloys have shown that in all cases the field corresponding to half the total number of jumps is indeed equal to the coercive force.

Notice should be taken of the fact that this method makes it possible, owing to the large number of Barkhausen jumps and the good reproducibility of the results, to measure the coercive force with accuracy to 10^{-2} Oe even for samples with diameter 0.1 mm. The method can be used also for samples with diameters of several dozen microns.

*For simplicity we consider the motion of only one 180° boundary.

2. Some Other Magnetic Measurements

In the investigation of the Barkhausen effect in ferromagnets, using the procedure described above, there is a high degree of reproducibility, for each sample, not only in the total number of jumps, but also in the field corresponding to a definite number of jumps (particularly, the starting field H_{st}, the finishing field H_f, the field $H_c = H(N/2)$, etc.). Since each of these fields is a characteristic of the sample and determines its domain structure, the field can be deduced from data given by a scaler unit independently of the readings of the instruments in the magnetizing circuit. This fact is the basis of a number of methods [132] described below.

a) Determination of the demagnetizing factor. If the sample is in an external homogeneous magnetic field of intensity H_e, directed along the sample axis, then, as is well known, [13] the true field H inside the sample differs from H_e, namely

$$H = H_e - NI, \tag{22}$$

where N is the demagnetizing factor of the sample and I is the magnetization corresponding to the field H.

Assume that there are two samples, one of which can be regarded as infinitely long ($l \gg d$, where l is the length and d the diameter of the sample), and the demagnetizing factor of the other is to be determined. Let us find the starting field (or the finishing field) of the jumps for both samples. If the samples of one material are subjected to identical treatment (for example, annealing), then their starting fields should be the same. But since the starting field of the jumps is determined by the true field inside the sample, and the demagnetizing factors on the samples are different ($N_1 = 0$ and $N_2 \neq 0$), the values of the external fields at which the jumps begin will also be different. The difference between the external starting fields, determined from the readings of instruments in the magnetizing circuit, is equal, as follows from (22), to the demagnetizing field NI of the second sample. Knowing I, we determine N.

b) Measurement of the earth's magnetic field. By placing a magnetizing coil with a sample in such a way that its axis is oriented in the direction of interest to us, say in the vertical direction, we determine the value of the field corresponding to half the total number of jumps H(N/2) when the sample is magnetized in one direction, and then, when it is magnetized in the opposite direction. Since in one case the component of the earth's field H_e^B is added to the coil field, and in the other it is subtracted from it, the readings of the instrument corresponding to $H_1(N/2)$ and $H_2(N/2)$ will be different in the two cases. It is easy to see that the sought component H_e^B is given by

$$H_e^B = [H_1(N/2) - H_2(N/2)]/2. \tag{23}$$

In [132], the vertical component of the earth's field was determined accurate to 0.01 Oe. The method makes it possible to perform measurements with high accuracy.

Since this method makes it possible to measure any component of the earth's magnetic field intensity H_e, it makes it also possible to measure the vector H_e.

c) Sensitive indicator of the change of the magnetic field, based on the Barkhausen effect. As was noted above (Ch. II, Sec. 3), the Barkhausen effect is the most intense in the steep part of the hysteresis loop, i.e., in fields close to coercive. In this range of fields, 10^7 jumps are counted when the magnetic field is changed by 1 Oe per cm^3 of an annealed iron sample, i.e., on the average one jump for each field change of 10^{-7} Oe. This fact was used in [134] to detect small changes of a magnetic field.

A ferromagnetic sample placed in a magnetizing coil of the apparatus is first magnetized to saturation. Then, a potentiometer is used to vary the field smoothly to a value at which the jumps are the most intense. This state of the sample is the initial one for the operation of the indicator. If now an additional weak magnetic field appears in the space near the magnetizing coil, directed along the field of the coil, or if a slight change of the external field in the same direction takes place, the apparatus will record this change by means of one or several jumps. This method was used in [52, 134] to register reliably an external-field change amounting to $\Delta H = 10^{-5}$ Oe.

The Barkhausen effect can also be used to compare the coefficient of a magnetizing coil with a standard coil without using a ballistic setup.[132]

3. Determination of the Elastic Limit in Ferromagnets with the Aid of the Barkhausen Effect

Among the methods of determining the elastic limit in solids there are many magnetic methods.[135] The high sensitivity of the Barkhausen effect to external stresses makes it possible to use it as one more magnetic method of determining the elastic limit in ferromagnets.

It is shown in [136] that when the elastic limit is reached in iron, nickel, and permalloy samples, a sharp increase in the number of jumps N is observed. This makes it possible to use the plot of the relative change of the number of jumps $\Delta N/N_0$ against the stress σ to determine the elastic limit more accurately than by using the plot of the induction B against σ.[135]

By way of illustration, Fig. 15 shows these two plots for an iron sample, in the same scale. It is seen from these plots that the Barkhausen effect method is indeed more sensitive than the induction-change method. It is shown in [52, 137] that the elastic limit in ferromagnets can be determined also with the aid of the mechanical Barkhausen effect.

4. Determination of the Depolarized State and Determination of the Coercive Field of Ferroelectrics with the Aid of the Barkhausen Effect

Most grown ferroelectric crystals have considerable unipolarity,[138, 139] which influences their electric properties and the polarization processes. The dielectric hysteresis loop of such crystals is not symmetrical (especially in weak fields), this being a manifestation of the asymmetry of the domain structure of the crystal in the absence of a field. The unipolarity of the crystals

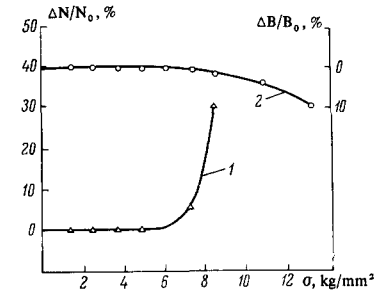


FIG. 15. Relative change of the number of Barkhausen jumps (1) and relative change of the magnetic induction (2) against the applied stress after its removal.

becomes particularly strongly manifest in the investigation of the Barkhausen effect. Thus, for example, it was observed in [99, 111] that when the electric state of certain samples is varied along the polarization curve, the number of jumps and their starting field are essentially different when the field varies from zero to $+E_{max}$ and from zero to $-E_{max}$. At the same time, for a number of measurements (not only in the investigation of the Barkhausen effect), it is necessary to start the polarization process from the depolarized state, i.e., from a state with a symmetrical domain structure.

Attempts to depolarize a sample by the method employed in magnetism, i.e., by slowly decreasing the applied alternating field, did not yield the desired result. The samples retained consistently the "built-in" unipolarity. Only application of a constant field of suitable magnitude and sign is capable of eliminating the unipolarity of the sample, i.e., depolarizing it completely. The difficulty lies precisely in the choice of this constant field and in fixing the depolarized state.

The high sensitivity of the Barkhausen effect to the state of the domain structure makes it possible to employ it to establish the depolarized state of a sample. It is shown in [111, 140] that a symmetrical state of the domain structure of a sample can be obtained by counting the number of polarization-reversal jumps on one of the branches of the hysteresis loop, while varying the electric state of the sample corresponding to a stepwise passage along the total hysteresis loop, and then tracing the loop again and terminating the process of polarization reversal at the instant when half the previously observed had been counted.

The depolarization of the crystal in this manner is confirmed both by direct oscillography of the hysteresis loop—the total and partial loops become symmetrical—and also by a more sensitive method, with the aid of the Barkhausen effect. The number of jumps and the character of their appearance on the "positive" and "negative" polarization curves coincide. The same method can be used to determine the coercive field of the ferroelectric.

5. Study of the Processes of Polarization Reversal of Ferroelectrics and of the Influence of Various External Factors on These Processes with the Aid of the Barkhausen Effect

Figures 8 and 9 (Ch. III, Sec. 2) show typical plots of the distribution of the number of polarization-reversal jumps with respect to the field for a ferroelectric crys-

tal, and also of the growth of the number of jumps with time. An analysis of such plots can provide considerable information both on the time characteristics of the polarization and polarization-reversal processes and on the features of these processes on different sections of the polarization curves and of the hysteresis loop.[114]

From the start of the appearance of the jumps, i.e., from the value of the starting field E_{st}, it is possible to determine with sufficient accuracy the value of the electric field at which the process of irreversible polarization of the crystal begins under the influence of an external field applied to the depolarized sample. The value of E_{st} should correspond to the limit of the Rayleigh region on the polarization curve. The cessation of the jumps with increasing field makes it possible to determine the external field E_f at which the polarization of the crystal reaches saturation.

In cyclic tracing of the total dielectric-hysteresis loop, the start of the appearance of the jumps is evidence of the start of the destruction of the single-domain state, i.e., the nucleation of domains polarized in a direction opposite to that existing in the crystal. In different crystals (depending on the degree of rectangularity of the hysteresis loop), this process begins in different fields. The Barkhausen effect makes it possible to determine the values of these fields. Such a possibility is particularly valuable for crystals in which the domain structure cannot be observed directly under a polarization microscope (for example for TGS or SbSi).

The curves showing the distribution of the number of jumps in time make it possible to use the Barkhausen effect for the study of the duration of the realignment of the domain structure in different sections of the polarization curve and the hysteresis loop and for the study of switching processes in different ferroelectrics. This has both theoretical and practical significance. This method is used in [106, 151].

The high sensitivity of the Barkhausen effect to different external actions makes it possible to use this effect as a sensitive method of investigating the influence of these actions on the dynamics of the domain structure and on polarization-reversal processes. The influence of different factors on the polarization and polarization-reversal processes has been investigated with the aid of the Barkhausen effect in a number of works. In [111] it is shown that the Barkhausen effect is much more sensitive to changes of the state of the domain structure than, for example, internal friction.[141] In [103], a definite connection was established between the character of the influence of γ irradiation on the shape of the dielectric-hysteresis loop and the distribution of the jumps with respect to the field. It is known that stretching and displacement of the hysteresis loop can result from irradiation.[124, 125] Observation of the Barkhausen effect in irradiated crystals makes it possible not only to confirm this but also to ascertain some additional details, which are not always sufficiently pronounced in simple oscillography of the loops.

When each of the branches of such a stretched and displaced hysteresis loop is traced, two maxima are observed in the distribution of the number of jumps with respect to the field (Fig. 16), thus evidencing the presence of two steep sections on the hysteresis-loop

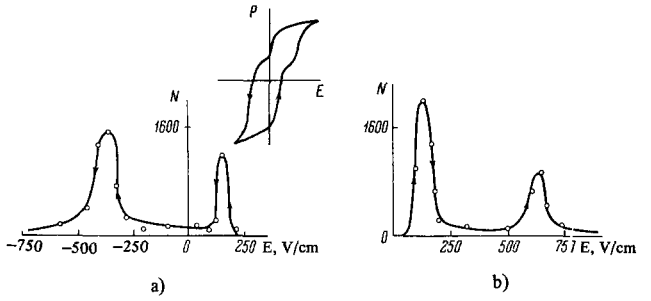


FIG. 16. Distribution of the Barkhausen jumps with respect to the field in an irradiated TGS crystal (D = 0.5 Mr), obtained by stepwise variation of the field on tracing the descending (a) and ascending (b) branches of the hysteresis loop. Top—appearance of the loop on the oscilloscope screen.

branch, connected with the stretching. The location of the maxima produced when the branches of the hysteresis loop are traced in opposite directions is asymmetrical. This asymmetry is connected with the displacement of the hysteresis loop. From the distribution of the number of jumps with respect to the field it is possible to determine the values of the field corresponding to the stretching of the loop (the minimum in the distribution), and the asymmetry of the distribution makes it possible to obtain a quantitative estimate of the displacement of the loop; this can be done more accurately than with an oscilloscope.

We note also that the picture of the jump distribution with respect to the field can also reveal slight distortions of the hysteresis loop, which are practically invisible on the oscilloscope or are not fixed reliably.

The use of the Barkhausen effect as a research method has made it possible[128–130] to establish the character of the action of ultrasound on the polarization and repolarization of TGS and Rochelle-salt crystals in the quasistatic regime, in contrast with the dynamic regime.[142, 144] The Barkhausen effect was used in [150, 161, 162] to investigate the action of illumination on polarization and polarization-reversal processes in SbSi crystals. It was established[161] that under certain conditions (depending on the magnitude of the applied field) light can produce either polarization or depolarization of the crystal, and in some field interval (near the coercive field) it can produce both processes simultaneously. We emphasize that in the case of SbSi the Barkhausen effect is presently the only method of observing the dynamics of both processes simultaneously; measurements of the dielectric constant, of the switching current, etc., give only the integral picture. It is shown in [162] that light from the spectral region in which the SbSi crystals are photosensitive accelerates both the polarization-reversal process and the process of establishment of the residual polarization of these crystals.

The presented examples, of course, do not exhaust the possibilities of using the Barkhausen effect in the investigation of ferromagnets and ferroelectrics. It is possible to use it to register phase transitions from the ferroelectric state to the paraelectric state (or vice versa) (see Ch. II, Sec. 2d).

We point out also the possibility of using the Barkhausen effect to investigate ferroelectric magnets.[163] Using the high sensitivity of this effect, it is possible to

observe jumps of the polarization reversal due to changes of the magnetic field, or jumps of the magnetization due to the changes of the electric field.

Finally, the overall physical significance of the Barkhausen effect, noted in the introduction (Ch. I), allows us to assume that methods used in the investigation of this effect, and also its applications, may turn out to be useful also in other branches of physics, in those cases when phase transitions are accompanied by phenomena analogous to realignment of the domain structure.

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