Experiments on Electrets

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WE have performed a systematic study of the electret effect,[1] guided by the idea that it must be related to the various other aspects of anomalous behavior, of solid dielectrics. The manufacture of electrets, as it is usually accomplished, involves a heat treatment. Prior, therefore, to the investigation of the fields of electrets, we studied the influence of the temperature on the dielectric absorption. A preliminary report of our results is presented here.

TERMINOLOGY

Following Gemant,[1] we call homocharges the true (surface or space) charges, the sign of which is the same as that of the corresponding polarizing electrode, and we call heterocharges the true charges of contrary sign. Both kinds of charges coexist in a polarized dielectric. In the shorted capacitor, their superposed fields induce on the electrode a charge q, which is measured by lifting the electrode. An apparent surface charge $-q$ is then ascribed to the dielectric.

INFLUENCE OF TEMPERATURE ON DIELECTRIC ABSORPTION

Here we are not concerned with the measurement of isothermic current—time curves, but with non-isothermic effects, which have a bearing on the electret effect. Their existence, suggested by former papers,[2] could be verified: A capacitor containing an absorptive dielectric (like carnauba wax) is charged at a high temperature and then, always connected with the voltage source, cooled until a considerably lower temperature is reached; finally it is short-circuited. Nevertheless, only a partial discharge occurs. A part of the quantity of electricity stored up during the preceding charging cycle behaves like a "frozen" charge and is retained within the dielectric as long as the temperature is kept low. The value of the frozen charge depends on the nature of the dielectric, on the charging time, and on the difference of temperature between charge and discharge, but it is independent of the rate of cooling. The explanation of the effect is found in the enormous increase, with rising temperature, of both the charging and the discharging velocity. The true absorption capacitance of capacitors with solid dielectrics is frequently much higher than is usually believed. But the charging velocity at room temperature is so low that at such temperatures the capacitors are never charged completely. On the contrary, in the first stage of our experiment the capacitor is almost completely charged in a brief time, because it is charged at a high speed at the high temperature. In the second stage (beginning with the short circuit), the capacitor is far from being completely discharged even after a long time, because at the low temperature it is discharged at a low speed; thus the dissipation of the absorbed quantity of electricity is so small that a part of it is trapped in the dielectric. Whatever may be the nature of these frozen charges, they must produce electric fields. This type of dielectric absorption yields therefore necessarily the electret effect; but it does not explain everything, because (a) the mechanism, which according to current theories (dipole and ionic theories) is responsible for dielectric absorption, accounts only for the heterocharges, not for the homocharges of electrets; and (b) electrets can be made without heat treatment.

DECOMPOSITION OF THE CURRENT INTO DISPLACEMENT CURRENT AND CONDUCTION CURRENT

We have investigated the nature of the homocharges by varying the intensity and time of application of the polarizing field, by modi-

[1] Cf. M. Eguchi, Phil. Mag. **49**, 178 (1925). S. Mikola, Zeits. f. Physik **32**, 476 (1925). E. P. Adams, J. Frank. Inst. **204**, 469 (1927). M. Ewing, Phys. Rev. **36**, 378 (1930). R. D. Bennett, Phys. Rev. **37**, 103 (1931). A. Gemant, Phil. Mag. **20**, 929 (1935). G. Groetzinger and H. Kretsch, Zeits. f. Physik **103**, 337 (1936). P. A. Thiessen, A. Winkel, and K. Herrmann, Physik. Zeits. **37**, 511 (1936). W. M. Good and J. D. Stranathan, Phys. Rev. **56**, 810 (1939). B. Gross, Anais Acad. Bras. Ci. **15**, 63 (1943).

[2] H. Frei and G. Groetzinger, Physik. Zeits. **37**, 720 (1936). O. G. v. Altheim, Ann. d. Physik **35**, 417 (1939).

fying the temperature, and by speeding up the disappearance of the field of the electret by heating. During the discharge, the total current J and the charge q of one of the electrodes were measured. According to the equation $J = i + dq/dt$, this method permits us to split up the current into its two components, the conduction current i and the displacement current dq/dt, both referred to the interface dielectric-electrode. The conduction current originated by the decay of a homocharge has the usual direction of the discharging current, but the corresponding displacement current flows in the direction of the charging current; just opposite in direction are the currents for heterocharges. The decay of the homocharges proceeds partially by conduction across the interface dielectric-electrodes, partially by conduction *within* the dielectric. If the second effect is sufficiently strong, the total discharging current may reverse.[3] These current reversals are not to be confused with those which are accounted for by the principle of superposition and which are observed after a brief application of a voltage of one sign succeeding a prolonged application of a voltage of the same value but contrary sign.[4]

MEASUREMENTS ON CURRENTS AND CHARGES IN ELECTRETS

Even without heat treatment, numerous dielectrics produce strong fields after the application of high voltages (cf. S. Mikola).[1] An important factor is the duration of the polarization. The results are particularly clear for carnauba wax. (1) If the time of polarization has been very short, the apparent charge—with the sign of a homocharge—decays at first rapidly. The decay is associated with a strong displacement current so that the total current flows in the same direction as during the charging period. Later the apparent charge becomes more stable and the current goes down. When the temperature is increased, the charge disappears completely and a transient displacement current is raised. (2) If the time of polarization has been long, shortly after the short circuit an increase, and later a maximum of the apparent charge (which again has the sign of a homocharge), are observed. The current is now mainly conduction current. It is the usual discharging current familiar from the numerous experiments on anomalous currents in solid dielectrics. A later increase of the temperature is followed by an immediate decay of the apparent charge, accompanied, as in the first case, by a displacement current.

The usual heat treatment produces the same effect as an enormous prolongment of the duration of the polarization. The value of the temperature itself has only quantitative influence. It need not be raised above the melting point of the substance. Strong permanent electrets can be obtained by polarization in the solid state. It becomes now evident that immediately after the short circuit the sign of the apparent charge is always that of a heterocharge; but sooner or later a change of polarity occurs and it turns into that of a homocharge. Simultaneously a strong discharging current, almost entirely conduction current, is observed. If the temperature of the shorted system is raised temporarily, the value of the apparent charge (homocharge) is greatly enhanced, but it returns slowly to its former level after room temperature has been reached again. If the temperature is raised and maintained high for a long time, the apparent charge disappears after a transitory increase and a strong discharging current surges, again a conduction current.

The systematic deviations from the principle of superposition, which at high voltages become obvious, are accounted for by the presence of homocharges.

Ionization in an air gap eventually existing between dielectric and electrode is not significant. We have observed current reversals indicating the existence of homocharges on hard rubber disks with silvered surfaces.

THEORY OF ELECTRET BEHAVIOR

Two mechanisms act simultaneously: (1) dielectric absorption related to the movement of ions or the orientation of dipoles in the interior of the dielectric originates heterocharges; (2) conduction in the interphase dielectric-electrode which originates homocharges. Without heat

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[3] Reversals of a similar kind seem to have been observed by H. H. Race, Trans. A. I. E. E. **47** (October, 1928) and by Sadakichi Shimizu, Tohoku Univ., Sci. Reports **21**, 29 (1932), see especially p. 48.

[4] Cf. V. Karapetoff, Trans. A. I. E. E. **45**, 124 (1926).

treatment, the heterocharges, with a smaller relaxation time, disappear spontaneously after the system has been shorted, and a pure homoharge remains. The velocity of the transition depends on the degree of dielectric absorption, which in its turn is determined by the duration of the polarization. After a heat treatment, a considerable fraction of the heterocharge is preserved besides the homocharge in the shorted system. The resulting field depends on the values and spacial distribution of both charges; its transitory increase during a later heating is another consequence of the smaller relaxation time of the heterocharges.

In polar substances, the formation of heterocharges is due mainly to dipole orientation. Proportionally to the value of these charges the electric field increases in the interphase dielectric-electrode. With sufficiently high field strengths, conduction currents surge in the interphase and, consequently, ions (or electrons) are fed into the dielectric or extracted from its surface and transferred to the electrodes. Accordingly, homocharges appear, initially in the form of surface charges, later spraying over a certain depth within the dielectric.[5] This process, resulting in a weakening of the field, reduces the conduction currents. With the short circuit, a part of the dielectric polarization, in phase with the electric field, disappears immediately; the rest follows more or less slowly. In consequence of this decay of the heterocharge, the homocharge component begins to prevail in the resulting field. Again conduction currents play a role, now carrying away part of the homocharge. It must be kept in mind that there is no recombination between the two types of charges. Thus, the homocharge is released in the same measure as the heterocharge decays. If a part of the heterocharge is frozen in, the relaxation time for its decay is so long that the homocharge in its turn is conserved over extremely long periods of time. Such an electret possesses really a volume polarization like a magnetized iron bar, but the field becomes disturbed by conduction effects non-existing in magnetism. If an electret with strong homocharges is cut into two pieces of about equal dimensions, both surfaces of the same piece should show charges of the same sign. But conduction currents surge at the newly created surface in contact with metal, the internal field of the electret now playing the same role as previously did the external field. So a change of polarity takes place and each piece becomes a dipole.

The effect, which manifests itself in the appearance of homocharges, must interfere in many problems of dielectric behavior, like increase of dielectric loss at high voltages and rupture. Its closer investigation may reveal further interesting features.

[5] This picture is very similar to that given by M. Faraday, *Experimental Researches in Electricity, Volume I* (Richard and John Edward Taylor, London, 1839), who has already known the existence of homocharges: "The effects appear to be due to an actual penetration of the charge to some distance within the electric, at each of its two surfaces, by what we call *conduction;* so that, to use the ordinary phrase, the electric forces, sustaining the induction, are not upon the metallic surfaces only, but upon and within the dielectric also, extending to a smaller or greater depth from the metal linings." (Art. 1245, p. 390.)

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