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The Field of Electrets in the Presence of Gaseous Ions

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It is shown by computation that the field of electrets ought to be completely shielded by the ions present in the atmosphere. Experimental evidence available at this time is in apparent contradiction with this conclusion. Some points that might help in clarifying this difficulty are discussed. In view of the fact that the electret field persists in spite of the ions present, the use of electrets in discharge tubes or in any case in high vacuum tubes is suggested. In order to achieve this purpose, the making of electrets of relatively high softening point appears to be the next necessary step in research.

SECTION 1. INTRODUCTION

ALTHOUGH some recent researches have been carried out on electrets,[1–3] one of the chief characteristics is still not understood from a physical standpoint. This is the polarity of the electret. The surface of the electret that has been in contact with, say, the positive polarizing plate is negative during the first few days only, and afterwards changes positive. This reversal is against all expectations, as both ionic and dipolar polarization should be of a sign opposite to that of the polarizing surface.

Several tentative explanations have been suggested in the published researches but none is definitely established by experimental facts. The author, for instance, thought that the final charge was not the direct result of polarization, but rather a secondary piezoelectric effect maintained by the internal stresses in the material. No experimental work has as yet been carried out in an attempt to support this idea.

It should be pointed out, however, that this circumstance did not prove a serious handicap in trying to make use of electrets in electrical appliances.[4] The situation is about the same as with permanent magnets; a thorough understanding of their physical characteristics and the application of them in machinery are two different matters.

In the following pages another question regarding electrets will be discussed, and it will be shown that, although it, too, cannot be answered satisfactorily, it immediately leads to a further suggestion concerning a new application.

This question is: How will the electric field of the electret be affected by the free ions present in the atmosphere? It will be shown that the answer to this question, as it can be derived from simple theoretical considerations, is in apparent contradiction to experimental findings. This contradictory situation is published here in order to stimulate further thought and research on electrets. Besides, considerations along these lines will lead to a discussion of the possibility of the application of electrets in discharge tubes.

SECTION 2. THEORY OF SHIELDING BY IONS

In this section a brief mathematical analysis of the field of an electret in a space of finite ion concentration will be given. The calculation is based on the type of double-layer as first conceived by Gouy[5] for electrolytic solutions. It can be applied to this case as well.

It will not be necessary to reproduce the details of the theory that are available in the original. The basic idea is that ions of a charge opposite to a given charged surface will accumulate in the neighborhood, while ions of the same charge will be repelled. When equilibrium is reached, the ions are acted upon by electrical and diffusion forces of equal magnitude and opposite direction. Thus, for a positive electret surface, negative ions will accumulate near the surface, shielding the field outside the double layer formed by the positive electret charge and the negative ionic charge.

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[1] Andrew Gemant, Phil. Mag. **20**, 929 (1935).

[2] G. Groetzinger and H. Kretsch, Zeits. f. Physik **103**, 337 (1936).

[3] W. M. Good and J. D. Stranathan, Phys. Rev. **56**, 810 (1939).

[4] A. Gemant, Rev. Sci. Inst. **11**, 65 (1940).

[5] G. Gouy, J. de phys. et rad. [4] **9**, 457 (1910).

The computation for the one-dimensional case (radius of curvature of surface larger than the thickness of the double layer) yields the potential distribution φ (Fig. 1) as a function of the distance x from the surface:

$$\tanh(\alpha\varphi/4)=Ae^{-\beta x}. \tag{1}$$

Here $\alpha=z\epsilon/kT$ and $\beta=(a\alpha)^{\frac{1}{2}}$ with $a=8\pi z\epsilon n$, where z = number of elementary charge units carried by one ion (for sake of simplification assumed to be the same for both positive and negative ions), ϵ = electronic charge, k = Boltzmann constant, T = temperature in degrees K, n = number of ionic pairs per cm^3. The constant A is connected with the potential φ_0 at the electrode surface ($x=0$) by the relation

$$\tanh(\alpha\varphi_0/4)=A. \tag{2}$$

φ_0 on the other hand is a function of the specific charge, q, of the electret:

$$q=\frac{1}{2\pi}\left(\frac{a}{\alpha}\right)^{\frac{1}{2}}\sinh\frac{\alpha\varphi_0}{2}. \tag{3}$$

For numerical data,[6] n should be taken 10^4, z as unity, and q is known to be about 5 e.s.u. Then $\alpha=1.2\times10^4$, $a=1.2\times10^{-4}$ and $\varphi_0=2.2\times10^{-3}$ abs. $=0.66$ volt.

We now require the thickness of the double layer. The following relation gives the variation of the field intensity with x:

$$\frac{d\varphi}{dx}=\frac{4A\beta}{\alpha}e^{-\beta x}\frac{1}{1-A^2e^{-2\beta x}} \tag{4}$$

and we now ask for that value of x (designated by δ) for which the field intensity has dropped in the ratio 1 : e. This value will be small compared with unity, as we may infer from the high field intensity (20,000 volts/cm) at the surface and the small value of the total potential (0.66 volt). Thus, the term $e^{-\beta x}$ will remain practically unity, and only the denominator in (4) will change appreciably. As to A, its value is known from (2); since the argument $\alpha\varphi_0/4=y$ has a value 6.6 and changes only very slowly even with large variations in n, the hyperbolic function can be simplified and we have for the denominator in Eq. (4):

$$1-(1-4e^{-2y})e^{-2\beta x}.$$

With the definition as given above for δ, we have the equation

$$4e^{-2y+1}=1-(1-4e^{-2y})e^{-2\beta\delta}. \tag{5}$$

Writing $1-2\beta\delta$ for the last exponential we have in good approximation

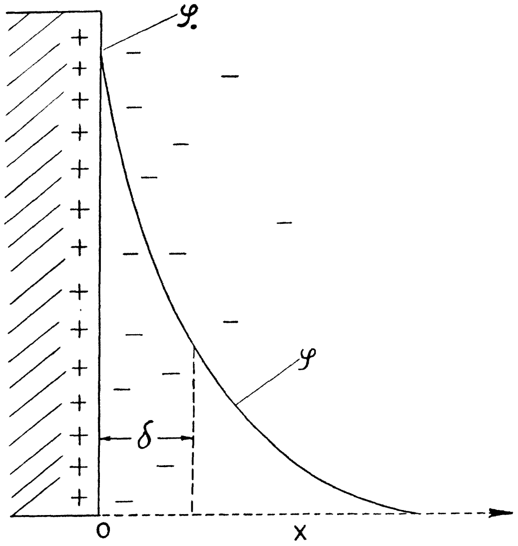

FIG. 1. Diagram of accumulation of ions near electret surface. Potential distribution curve is superimposed. Electret at the left, space charge at the right.

$$\delta=(1/\beta)2(e-1)e^{-2y}. \tag{6}$$

Again from Eq. (3), since the argument is larger than unity, we have

$$e^{-2y}=\frac{1}{4\pi q}\left(\frac{a}{\alpha}\right)^{\frac{1}{2}}$$

and hence from (6)

$$\delta=(e-1)/2\pi\alpha q. \tag{7}$$

It is interesting to point out that this result is entirely different from the expression usually given as the thickness of the Gouy double layer, namely $1/\beta$. Equation (6) is a more general formula from which it can be seen that δ becomes $1/\beta$ (we disregard the numerical factor) if $\alpha\varphi_0\ll1$, and the exponential is near unity.

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[6] G. R. Wait and O. W. Torreson, Terr. Mag. **40**, 425 (1935).

This is the usual approximation made, but it really holds only for voltages below 50 mv.

For voltages larger than 100 mv, on the other hand, Eq. (7) will hold. The usual expression $1/\beta$ contains $1/\sqrt{n}$ as a factor, indicating an increasing thickness with decreasing number of ions; it is, however, independent of the total charge. The thickness as given by Eq. (7) is independent of n, but increases with decreasing charge q. For $q=5$, δ is 4.5×10^{-6} cm, and is thus of submicroscopic dimension.

It should be recalled that the foregoing formulas refer to the one-dimensional case. They will hold well for the center parts of an electret, but will have to be modified at the edges.

It is now possible to compare our theoretical result with experimental observations.

SECTION 3. EXPERIMENTAL FACTS ABOUT THE ELECTRET FIELD

Experience with electrets shows a behavior not in agreement with the expectations derived in the previous sections. However, considering that even the basic properties of electrets are not easily explainable at this time, one may expect to encounter other difficulties.

Briefly, the chief conclusion from the last section, as expressed by Eq. (7), is that outside of a layer of submicroscopic dimensions the electric field of an electret ought to be almost completely shielded owing to the ions present in the atmosphere. This is, however, by no means the case, as can be seen if the author's data on the application of electrets[4] are consulted. Figure 3 of the paper quoted gives the electric field as a function of the distance from the electret, and it appears that at a distance of 5 mm the field drops to about 20 percent of its surface value; thus, is quite appreciable. Besides, this drop could easily be explained on the basis that the field is by no means parallel.

One could object to the interpretation of these particular data by saying that they do not correspond to an equilibrium, a supposition underlying the deduction of Section 2. This may be true; however, for another arrangement, the vibration electrometer, conditions for an equilibrium were much more favorable. In that instrument the field between two parallel electrets in a distance of about 8 mm was about 1500 volts/cm. This intensity was maintained during several weeks; it varied with the temperature in a reversible manner.

While an explanation of the presence of high field intensities in spite of the ion content of the atmosphere cannot be given, a few points that might help to clarify the situation can be mentioned. A definitive solution of the problem will be reached only if more experimental material on this subject accumulates. For the present it should then suffice to point out the following:

(1) It is still possible that, for some reason or other, real equilibrium has not been reached in experimental cases dealing with electrets, not even in the vibration electrometer discussed above. Let us make a numerical estimate. The amount of ions required to neutralize the electret can be computed easily. The specific charge is 5 e.s.u., corresponding to $5/(4.8\times 10^{-10})\sim 10^{10}$ monovalent ions, and for a surface of say 10 cm^2, the total number is 10^{11}.

Now the concentration of ions in the atmosphere[7] is a varying figure. Small ions are present everywhere, as they are formed by means of a penetrating radiation. Besides, there are large ions present in rooms occupied by people, originating partly from the breath, partly from an addition of small ions to tobacco smoke particles. The number of small ions varies around 500 per cm^3, that of the large ones in rooms occupied by people varies around 10^4 per cm^3. Taking this latter figure as representative, as has been done in Section 2, we have 10^{10} ion pairs per m^3. It seems that ten m^3 of air might be easily available for the electrets, unless they were enclosed hermetically. This was not the case with the vibration electrometer, which was placed under a glass jar, but by no means under air-tight conditions.

Thus it can be concluded that conditions for reaching an equilibrium are generally favorable. Still, it might be that the process takes place slowly, and that for this reason the field remains appreciable. It also has to be considered that the spread of data in measurements of this type is of the order of 10 percent; therefore a

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[7] D. H. Gish in *Physics of the Earth*, Vol. VIII (McGraw-Hill, New York, 1939).

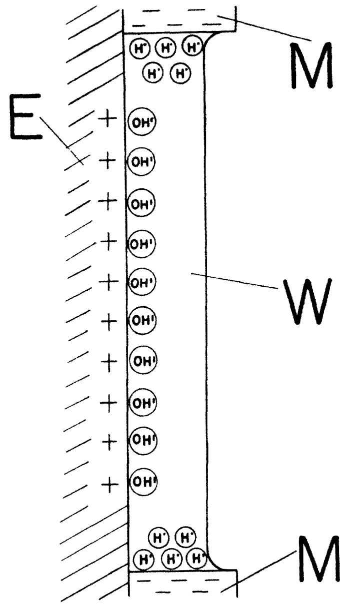

FIG. 2. Diagram of shielding effect on the electret field of adsorbed water layer.

decrease of the total charge within this limit would not be easy to detect.

(2) Another point of interest in this connection is the fact that the atmospheric ions are held near the electret surface only by electrostatic forces but not by any process that might lead to irreversible saturation of the surface. The ions that accumulate near the surface are removed easily by a suitable mechanical process. This statement is best illustrated by the effect of moisture on electrets. If an electret is brought into a room with a fairly high humidity, the field disappears very pronouncedly. Figure 2 shows diagramatically how this happens. *E* is the free positive electret surface, *M* is the nearest free edge of the metallic casing carrying an opposite charge. If a thin layer of water *W* deposits on the surface some of the OH^- ions will neutralize the electret charge, the corresponding H^+ ions accumulating near the metal edge. Although an adsorption of ions undoubtedly takes place in this case, yet the process is fully reversible. If the electret is placed in a dry chamber the water evaporates and removes all ions, restoring the free charge with the same intensity as before. This experiment clearly shows that the inorganic ions, even if attracted by the electric field, are not retained definitely but can be removed by a suitable process. Thus, even if neutralization according to the mechanism as outlined in Section 2 should take place, the process will be easily reversible.

(3) In case later experiments should show that the finite field intensity at a measurable distance from the electret is a true equilibrium, evidently the deduction presented in Section 2 will have to be modified, although how that will be done is not yet clear. One of the possibilities is to replace the Boltzmann statistics underlying Eq. (1) by one of the quantum statistics that might hold for the fairly high ion concentration near the surface. The order of the concentration is 10^{16} per cm^3.

Whichever explanation is established in the future, the fact of a definite charge in the presence of finite ionic concentration remains. And this fact allows certain conclusions regarding the technical applications of electrets to be drawn.

SECTION 4. USE OF ELECTRETS IN DISCHARGE TUBES

It was shown in the last section that the field of electrets is appreciable even in the presence of gaseous ions. Still it is quite likely that this field will diminish with increasing concentration of the ions. Experiments will have to establish the relation, field *vs.* ion concentration.

When this relation is known, the electret in combination with a suitable measuring device might be used as a quantitative indicator for the ion concentration of the atmosphere or any closed space. Because of the light weight of electrets such a device would be particularly suitable for upper atmospheric measurements.

Another possibility that suggests itself is the use of electrets in gas-filled or vacuum discharge tubes. Since the grid bias voltage has no work to do, and acts only on an electrostatic basis, it is generally possible to utilize electrets in tubes, wherever an electrostatic control is required. They may be used in any type of tubes, such as amplifiers, cathode-ray tubes, phototubes, electrometer tubes, and so on.

Among the conceivable advantages in this connection, simplicity of the construction and light weight may be mentioned. This latter advantage will be of particular value in devices built for airplanes or upper atmospheric recording balloons. Another factor is the possibility of producing special field effects. The direction of the field depends upon the procedure followed in making the electrets and not, as with metal electrodes, upon the shape of the free surface. Thus, field distribution and shape of the surface are here independent variables.

In certain cases where the controlling field is parallel to the current it will be advisable to use perforated electrets although such an arrangement might present certain difficulties. If the two directions form a right angle, solid electrets can be used.

Recalling what has been said in the previous section, it is to be expected that the field will be shielded in the presence of a high ion concentration. If the latter is below a certain limit, the field might still persist. Even in this case the free charge of the electret surface will depend to a certain extent upon the ion concentration in its neighborhood. This would be an unusual property to be reckoned with in designing the tube. But—as generally happens in such cases—such a change in conditions is not a disadvantage; designers probably will learn very soon to make particular use of it.

It is possible, however, that in a completely closed space the conditions underlying the deduction made in Section 2 will be fulfilled, so that the field will be thoroughly shielded, even for low values of ion concentration. In this case the use of electrets will have to be restricted to high vacuum tubes in which only electrons are present and the use of negative electrets which will repel the electrons.[8]

The different applications in discharge tubes are handicapped at this time by the relatively low softening point of electrets. It certainly would not be an easy matter to incorporate the electrets in the tubes and to perform the process of evacuation in the customary manner. It might be possible, of course, to devise a method by means of which this difficulty could be avoided, but it is felt that generally all applications mentioned above will be considerably promoted when electrets of a higher softening point have been found.

The next step in the development is, therefore, to attempt the making of electrets of other materials than those used today. This attempt will present many difficulties since we do not know what are the necessary conditions for a material to become an electret. Dipolar constituents seem to be necessary, also a high degree of hardness at room temperature in order that an attained orientation should not be lost too fast. Thus, it is possible to make an electret by adding carnauba wax to paraffin wax, but the life of such electrets is rather short, because of the softness of the product. However, it is not certain whether these two conditions, orientability and hardness, are sufficient, although they are certainly necessary.

Two possibilities will have to be tried. The one is the making of electrets by using some of the synthetic plastics produced today and possessing a relatively high softening point. Both thermoplastic and thermosetting plastics could be tried. The other field is that of glasses, especially those of high electrical resistivity, such as are used in the manufacture of fiber glass for electrical purposes. The technique of making the electrets will have to be adapted at least to the temperatures at which these glasses are soft, if not to temperatures at which they are fluid.

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[8] In a recent note G. E. Sheppard and J. D. Stranathan, Phys. Rev. **60**, 360 (1941), observed a decrease of the surface charge of electrets with decreasing pressure, corresponding to the breakdown strength of the gas. Thus the field of electrets will assume low values in gas discharge tubes, but high values in high vacuum tubes.