Electrets

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Magnets – bodies possessing long-lasting magnetization – established their place in science and industry a long time ago and are now familiar to practically everyone. But not many people know that there are also bodies possessing long-lasting electrization,* called *electrets.* A search for such bodies started more than 200 years ago. Yet only since about 1920 has one discovered reliable methods for their production, and only within the last 10 years have they been used on an appreciable scale for scientific and industrial applications.

In this article we shall give a brief account of the history of electrets, shall describe how they can be made in a small laboratory, shall summarize their uses, and shall suggest some interesting projects and experiments with them.

History of electrets

Stephen Gray, best known for his discovery of electric conduction, wrote in 1732 his "enquiry whether there might not be a way found to make the property of electrical attraction more permanent in bodies."[1] He melted various dielectric materials (rosin, shellac, beeswax, sulfur, etc.) in iron or glass vessels, allowed them to cool and solidify, slightly reheated the vessel to separate the dielectrics from the sides and the bottom of the vessels, and then removed the dielectrics. He found that the dielectrics so treated, when they were cooled once again, became strongly electrized. He also found that when sulfur was cast in a glass vessel, both the sulfur and the vessel became electrized. Gray also discovered that the electrization of his dielectric bodies could be preserved for months, if the bodies were kept wrapped in paper or cloth.

There is an element of mystery in Gray's experiments. We know now that placing two different bodies in close contact (such as between the melt and the mold), and then separating them, causes an appearance of surface charges ("molding charges") on the two bodies. The phenomenon is basically the same as when two bodies are charged by friction.[2] But Gray said that he remelted the

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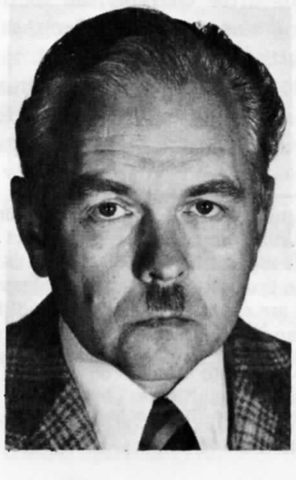
*We use the term "electrization" to describe a state of a dielectric (insulating) body characterized by the presence of an electric field outside or inside the body not caused by sources external to the body. We shall use the verb "electrize" to describe any action (friction, charge injection, polarization, etc.) that produces an electrization of a dielectric.



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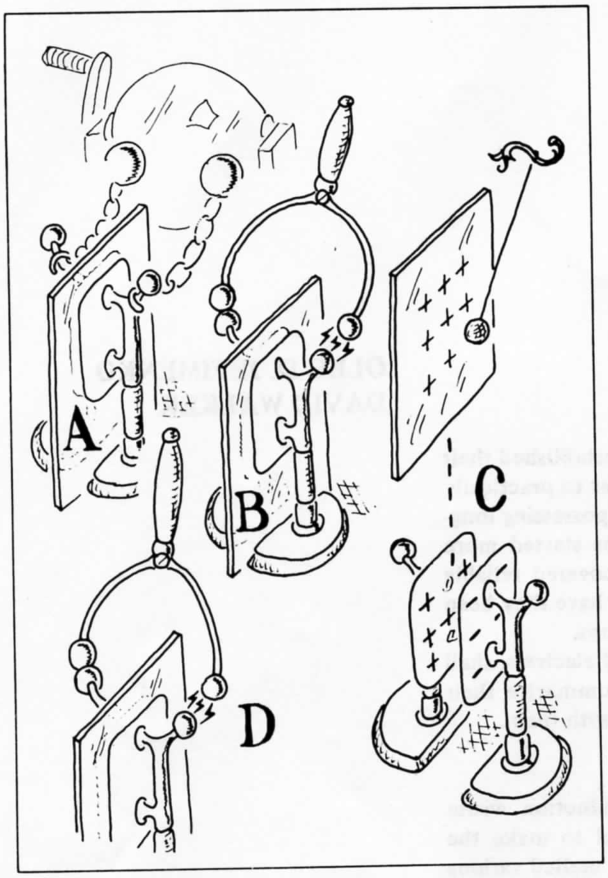

Fig. 1. Benjamin Franklin's "dissectible capacitor" experiment is the prototype of the modern "electroelectret" forming procedure. (A) The capacitor is charged from a high-voltage source. (B) The capacitor is discharged. (C) The dielectric plate is withdrawn from the capacitor. It has acquired a residual electrization (has become an electret), manifested here by the fact that it deflects a pith-ball pendulum. (D) In the further continuation of the experiment the capacitor is discharged once again, and the plate is reinserted into the capacitor. It induces charges on the capacitor plates, so that a spark can be again drawn from the capacitor even though the capacitor was just discharged.

surface of his dielectrics before taking them out of the mold. No surface charges should appear on the dielectrics in this case, so that the long-lasting electrization discovered by Gray was caused by effects not easily explained. It may be that the electrization was due to the appearance of electric charges on the interface between the liquid and the solid phase of a dielectric; such an effect was described in 1950 by J. Costa Ribeiro, who named it the "thermodielectric effect."[3] It may also be that Gray's description of his experiments was incomplete.

Whatever the truth about Gray's experiments may be, his discovery has a direct bearing on the making of modern "thermoelectrets," as we shall see later.

Benjamin Franklin, in 1748, wanted to determine whether the seat of electric "power" of a Leyden jar was in the metallic coatings or in the glass.[4] For this purpose he constructed what is now known as the "dissectible capacitor" (Fig. 1). His capacitor consisted of a glass plate laid between two smaller plates of lead. He charged the capacitor with his electrostatic machine, discharged it, removed the lead plates from the glass plate, and examined the glass plate for the presence of electrization. He found that the plate was strongly electrized, and that, if it was once again placed between the lead plates, a strong spark could be extracted from the lead plates while shorting them with a conductor. From these experiments Franklin concluded that the "power" of a Leyden jar resided mainly in the glass rather than in the coatings, and that the electric charges in a charged Leyden jar were "imbibed" in the "pores" of the glass.*

The phenomenon of the residual electrization of a dielectric in a capacitor became later known as the "dielectric absorption," and was studied by several eminent scientists in the 19th century.

Michael Faraday, in 1837, investigated dielectric absorption by using a spherical dissectible capacitor containing a hemispherical shell of shellac as the dielectric.[5] He found that after the capacitor was charged, the dielectric first exhibited an electrization of a polarity opposite to that applied to the capacitor during charging; that is, the surface of the dielectric that had been in contact with the positive conductor during charging exhibited a negative charge, and the surface that had been in contact with the negative conductor exhibited a positive charge.** However, the dielectric soon reversed its polarity all by itself, so that the surface in contact with the positive conductor during charging became positive, and the surface in contact with the negative conductor during charging became negative.† After the polarity reversal the electrization of the dielectric lasted for a considerable time.

Faraday interpreted these results as a superposition of two effects: (a) polarization (alignment of molecular dipoles) by induction and (b) conduction of electric charges from the capacitor plates into the dielectric. According to him the reversal of polarity was caused by the variation of the relative depth at which the dipoles and the charges that penetrated the dielectric were located at different times after the capacitor was charged.

The polarity reversal discovered by Faraday is an important effect encountered in modern electrets. We shall explain it in greater detail at the end of this section.

The Italian physicist Carlo Matteucci, in 1849, described several experiments on dielectric absorption.[6] He placed one end of a sulfur rod in contact with a charged conductor for a fixed duration and measured the charge distribution along the rod. He found that electric charges penetrated only a short distance into the rod. He then performed a similar experiment by using a compound dielectric made of a large number of mica sheets. By examining the individual sheets after charging, he found that if the duration of charging was sufficiently long, the sheets acquired charges from the conductor; but if the charging was short, the sheets exhibited only a residual polarization while their net charge remained zero. Matteucci also charged sulfur rods first positively, and then nega-

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*One should not downgrade the significance of Franklin's discovery because of his somewhat strange 18th century language. The fact is that his description of the residual electrization of the glass is precisely the same as used today on the best 20th century evidence, except that we now say "charges are *captured* in the *traps* within the glass," thus using the more imposing (but not more revealing) words "captured" instead of Franklin's "imbibed," and "traps" instead of Franklin's "pores."

**We now call this type of electrization the "heterocharge" state.

†We now call this type of electrization the "homocharge" state.

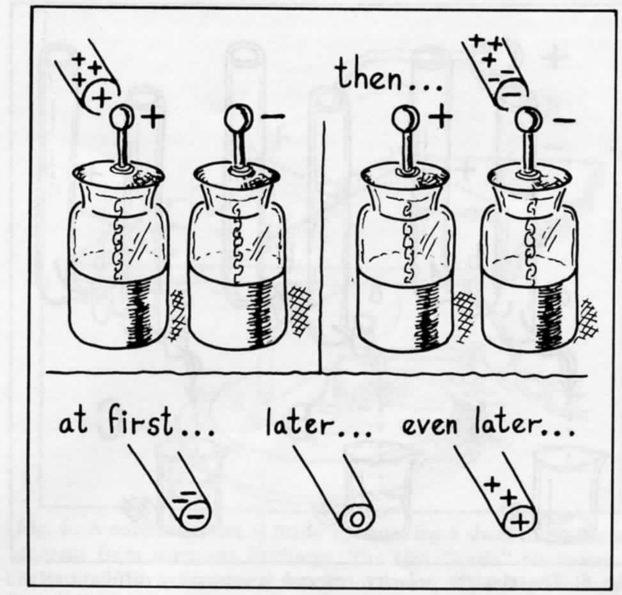

Fig. 2. Carlo Matteucci charged sulfur rods in alternation positively and negatively by touching them to charged Lyden jars. After the charging the rods exhibited several polarity changes corresponding to the charging sequence in reverse. This mode of charging is now called "step charging." It can be used to produce electrets with programmed polarity changes.

tively (Fig. 2). The observed polarity of the resulting electrization was negative right after the charging, then it became positive. Finally he found that the electrization of a dielectric could undergo several polarity reversals if the dielectric was charged in alternation positively and negatively.

In spite of the experimental evidence for the penetration of electric charges into the dielectric obtained by Franklin, Faraday, and Matteucci, the mechanism of the penetration was far from clear. Indeed, all solid bodies have many minute surface irregularities, and therefore a conductor could come in contact with only a few points of a dielectric during charging. Therefore only a very small charge could possibly pass into the dielectric from the conductor. But the observed electrization of the dielectrics was frequently very strong.

New experiments gave a partial answer to this paradox. It was found that if the charging conductor was at a sufficiently high potential (high voltage), electric breakdown took place in the air gap between the conductor and the dielectric, and the charges from the conductor were then transferred to the dielectric by minute electric sparks.* The points where the sparks entered the dielectric could be made visible by sprinkling the electrized dielectric with some fine nonconducting powder as shown in Fig. 3. The powder adhered to the charges on the dielectric, forming the so-called Lichtenberg figures** (the technique was eventually refined and is now used in electrostatic copying machines).

Many experiments indicated, however, that dielectric absorption could take place also at low potentials (voltages), when the breakdown could not occur (a breakdown is practically impossible for voltages below about 5000 V).

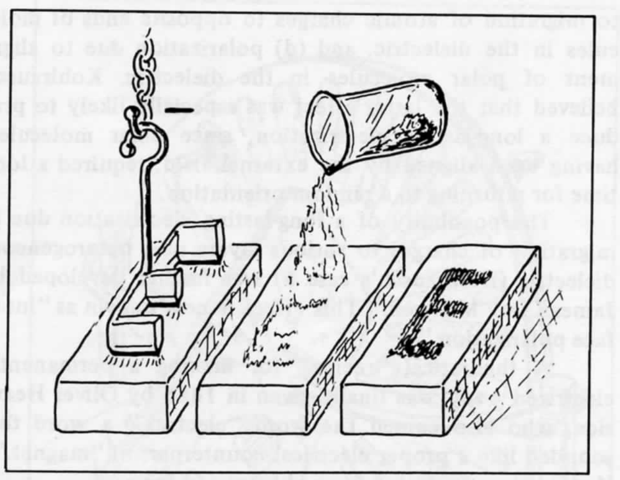

Fig. 3. When a dielectric is electrized by the corona charging method, electric charges are injected into the dielectric by minute sparks emanating from an electrode attached to a high-voltage source. The injected charges produce a long-lasting electrization of the parts of the dielectric corresponding to the shape of the electrode. The latent electric image so produced can be made visible by sprinkling the dielectric with some "developing powder" such as a very dry mixture of red lead and flowers of sulfur. The red lead will adhere to negative charges in the image, the sulfur to positive. This developing technique is now frequently used to study surface-charge distributions on all types of electrets, whether made by corona charging or otherwise.

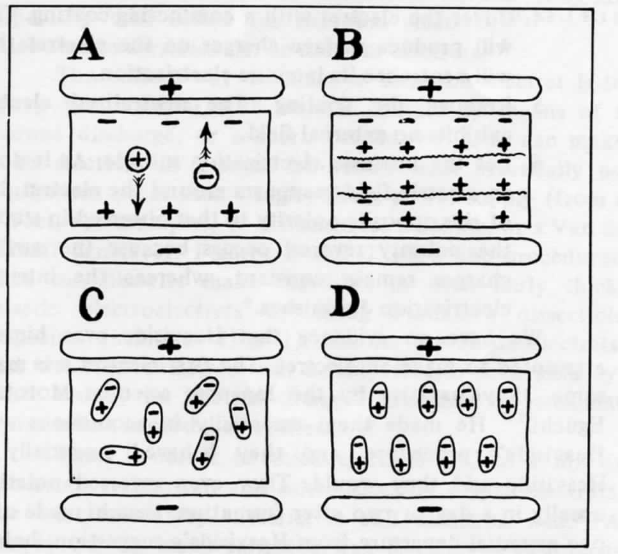

Fig. 4. Kohlrausch showed that an electrization of a dielectric can be produced by four effects without any charge transfer from the electrodes: (A) Migration of internal charges to the surfaces of the dielectric. (B) Migration of internal charges to the various layers of the dielectric. (C) Migration of charges within molecules of the dielectric. (D) Orientation of molecular dipoles within the dielectric. It is now known that all these effects as well as charge injection, formation of molding charges, and formation of contact (friction) charges may take place in the production of modern electrets.

The theoretical possibility of dielectric absorption without a breakdown was investigated in 1854 by the German physicist R. Kohlrausch.[7] He suggested that a dielectric body could acquire a residual electrization without a charge transfer from external sources by the following four effects (Fig. 4): (a) polarization due to migration of internal charges to the surface of the dielectric, (b) polarization due to migration of internal charges to various layers within the dielectric, (c) polarization due

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*This type of charging is now called "corona charging" and is widely used for making electrets.

**Georg Lichtenberg was the German physicist who discovered the electric figures in 1777.

to migration of atomic charges to opposite ends of molecules in the dielectric, and (d) polarization due to alignment of polar molecules in the dielectric. Kohlrausch believed that the latter effect was especially likely to produce a long-lasting electrization, since polar molecules, having been aligned by the external field, required a long time for returning to a random orientation.

The possibility of a long-lasting electrization due to migration of charges to various layers of a heterogeneous dielectric (Kohlrausch's case *b*) was further developed by James Clerk Maxwell.[8] This effect is now known as "interface polarization."

A theoretical "recipe" for making a permanently electrized body was finally given in 1885 by Oliver Heaviside, who also coined the word "electret," a word that sounded like a proper electrical counterpart of "magnet."[9] Here is his prescription in an abbreviated form:

1. Place a well-absorbing dielectric into an electric field.
2. Keep the dielectric in the field for as long as is needed for an absorption to take place.
3. Remove the dielectric from the field. If the dielectric is such that the absorption results in a long-lasting (slowly subsiding) electrization, the dielectric has become an electret: it now produces its own electric field similar to the magnetic field produced by a similarly shaped magnet.
4. Cover the electret with a conducting coating. This will produce surface charges on the electret that will neutralize its intrinsic electrization.
5. Remove the coating. The neutralized electret exhibits no external field.
6. Let the intrinsic electrization subside. As it does, an electric field reappears around the electret, but of the opposite polarity to that observed in step 3; the polarity reversal occurs because the surface charges remain constant, whereas the intrinsic electrization diminishes.*

We have no evidence that Heaviside ever himself attempted to make an electret. The first electret was made some 35 years later by the Japanese scientist Mototaro Eguchi.[10] He made them essentially in accordance with Heaviside's procedure, and they behaved essentially as Heaviside said they would. They even reversed polarity, usually in a day or two after formation. Eguchi made only one essential departure from Heaviside's suggestion: before placing his dielectrics into an electric field he melted them. Then he let them solidify in the field, thereby "freezing" all the various charge accumulations and field-oriented molecular dipoles in the dielectric. Eguchi's technique was thus a combination of that of Gray and Heaviside. The material for Eguchi's electrets was a mixture of carnauba wax, beeswax, and rosin. This mixture still remains the classical laboratory electret material.

Eguchi's type electrets are now known as "thermoelectrets" since they involve a thermal treatment of the dielectric.**

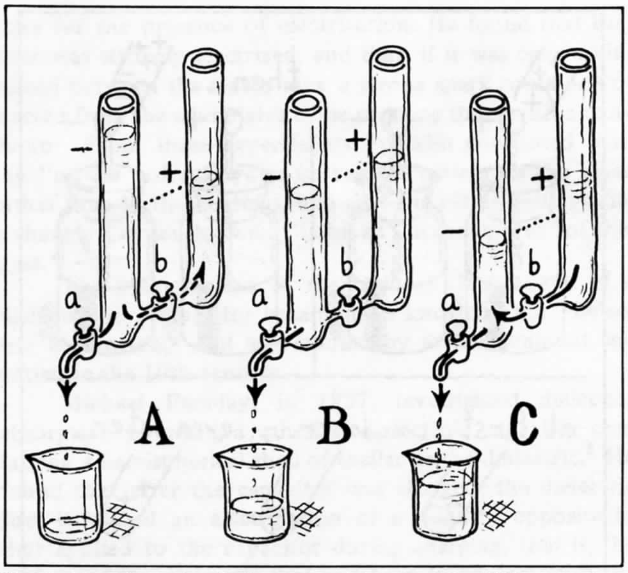

Fig. 5. The electret polarity reversal is caused by different relaxation (dissipation) rates of "hetero-" and "homocharges." It is analogous to the water level reversal in the apparatus shown here. In this apparatus the water level in the front tube corresponds to the heterocharge of an electret, the water level in the back tube corresponds to the homocharge (or polarization), valve *a* (large opening) corresponds to the relaxation mechanism of the heterocharge, and valve *b* (small opening) corresponds to the relaxation mechanism of the homocharge. (A) "Heterocharge state." Initially the water level in the front tube is higher than that in the back tube. However, it rapidly decreases due to the outflux through valve *a* (whose opening is much larger than that of *b*). (B) "Neutral state." The water level in both tubes is now equal. (C) "Homocharge state." The water level in the back tube is now higher than that in the front tube. This is because the outflux through valve *a* is faster than the rate of water transfer from the back to the front tube through valve *b*. The "reversed" water level difference in the two tubes will persist as long as there is water left in the apparatus.

As is clear from the short history of electrets presented above, one of the most intriguing phenomena associated with electrets is the reversal of polarity. Not all electrets reverse their polarity, but most thermoelectrets do. The exact nature of this phenomenon is not yet clear. A quantitative theory of polarity reversal that is thus far in the best (although far from perfect) agreement with experiments was given in 1957 by the Russian physicist Gubkin.[11] According to this theory an electret acquires during forming two different types of charge distributions: the "homocharge," whose polarity is the same as that of the nearest forming electrode, and the "heterocharge," whose polarity is opposite to that of the nearest forming electrode. At first the heterocharge dominates. However, it decreases rather fast, while the homocharge lasts very long. Therefore the electret eventually reverses its polarity. The theory takes into account the internal conductivity of the electret and the effects of storage conditions, but does not specify the physical nature of the processes responsible for the formation of the two types of charges or for the greater longevity of the homocharge. Thus it is only a phenomenological theory. Its basic idea can be nicely illustrated by using the hydrodynamic analogy described in Fig. 5.

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*We now know that in reality, in most electrets, the surface charges subside, whereas the internal electrization remains practically unchanged.

**It is interesting to note that Aguchi claimed in his paper to have independently invented the word "electret" prior to learning of Heaviside's writings or finding the word elsewhere. This is difficult to accept since beginning with about 1900 there appeared a number of well-known textbooks on electricity which not only used the word "electret" but even devoted entire chapters or sections to electrets. For example, in Webster's *Theory of Electricity and Magnetism* (Macmillan, 1897), Section 201 (pp. 389-391) is devoted to electrets; in Barnett's *Elements of Electromagnetic Theory* (Macmillan, 1903), Chapter VI (pp. 176-191) is called *Electric Absorption. Electrets*; etc.

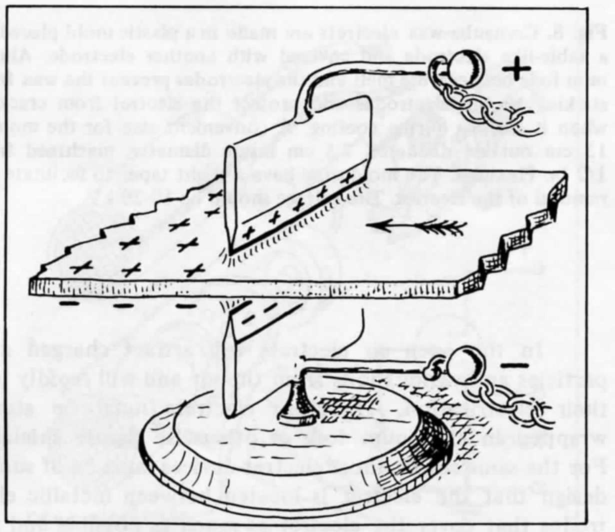

Fig. 6. A coronaelectret is made by spraying a sheet of plastic with charges from a corona discharge. The two "knife" electrodes are connected to a dc power supply or some other high-voltage dc source of 6 kV or higher. The voltage must be, however, low enough not to permit a spark discharge between the two electrodes around the edges of the material.

Although the phenomenon of permanent electrization is not yet completely understood, it is clear that it is caused by the fact that charges and charge complexes within good insulating materials are practically immobile, except when a very strong electric field is applied to the dielectric. When such a field is applied during forming of electrets, it causes a formation of ordered charge accumulations inside the electret, as described in the caption to Fig. 4. One explains the phenomenon qualitatively by saying that the applied field moves the internal and external charges until they fall into some "traps" within the dielectric. When the applied field is removed, the charges remain "captured" in the traps, so that the relaxation of internal charges is extremely slow and the electrization becomes practically permanent. As a rule, an electret that has only surface charges does not last so long as the one that has internal charges.

How electrets are made and measured

As one can see from the previous section, to make an electret one needs to produce long-lasting charge accumulations in a dielectric material, long-lasting polarization of a dielectric material, or both.

Electrets are classified in accordance with the manner in which the material is treated during forming. Electrets made by melting or heating the material before forming are called "thermoelectrets." Electrets made by subjecting the material to radiation are called "radioelectrets." Electrets formed while subjecting the material to a magnetic field are called "magnetoelectrets." Electrets made by exposing certain materials (such as sulfur) to an electric field with simultaneous strong illumination of the material are called "photoelectrets" (photoelectrets retain their electrization only when stored in the dark). If the material is sprayed by charges from a corona discharge the resulting electret is called a "coronaelectret." And if the material is merely subjected to a forming electric field, the electret is called "electroelectret."

There are many materials from which electrets can be made. Carnauba wax is especially convenient for laboratory experiments, but it lacks mechanical stability for reliable industrial applications.* Various plastics (Lucite, Mylar, Teflon, etc.) possess excellent mechanical properties and can be used for electrets in commercial devices. They are especially well suited for thin-film electrets.[12,13,14,15] Also certain ceramics can be used for electrets.[16]

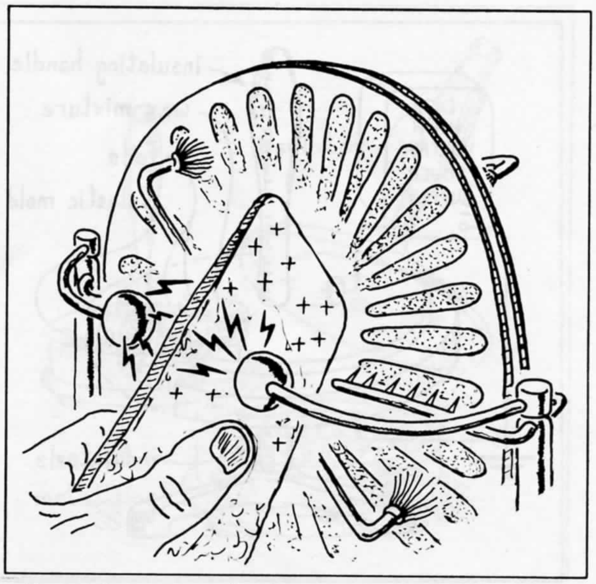

Fig. 7. An electret can also be made by subjecting a dielectric material to spark discharge from a high voltage dc source.

The easiest way to make a thin-film electret is to spray the material with electric charges by means of a corona discharge, or a spark breakdown. One can make such electrets in a small laboratory with practically no equipment other than a high-voltage power supply (from a TV set, for example), or a Wimshurst machine, or a Van de Graaff generator. Figures 6 and 7 show the procedures. One can likewise make thin-film, or even fairly thick, plastic electroelectrets by using Franklin's dissectible capacitor technique (Fig. 1). Neither the coronaelectrets, nor the electroelectrets will usually reverse their polarity, since usually no internal charge distribution or remanent polarization is produced in them.

When it comes to thick electrets (1/2 to 1 in), or spherical, cylindrical, and other specially shaped electrets, the best laboratory material is still carnauba wax.* A simple way to make carnauba wax electrets is as follows (Fig. 8).

A mixture of 45% carnauba wax, 45% colophonium (rosin), and 10% beeswax, measured by weight, is melted at 120-130°C for 30 min or until completely liquified. The melt is poured into a mold resting on a piece of aluminum foil placed on an insulated metal electrode, as shown in Fig. 8. A second piece of aluminum foil is placed on top of the mold containing the wax, and a cover electrode is placed onto the foil. A high voltage is next applied between the two electrodes for about 30 min, or until the wax is completely solid. The voltage is then turned off, and the electret is removed from the mold. The foils can be peeled off any time after forming, but if the electret is to be subjected to some mechanical treatment (such as cutting, for example), the foils should stay on until the treatment is completed in order to protect the surfaces of the electret.

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*Carnauba wax is available from various scientific supply companies, such as Central Scientific, Fisher, etc.

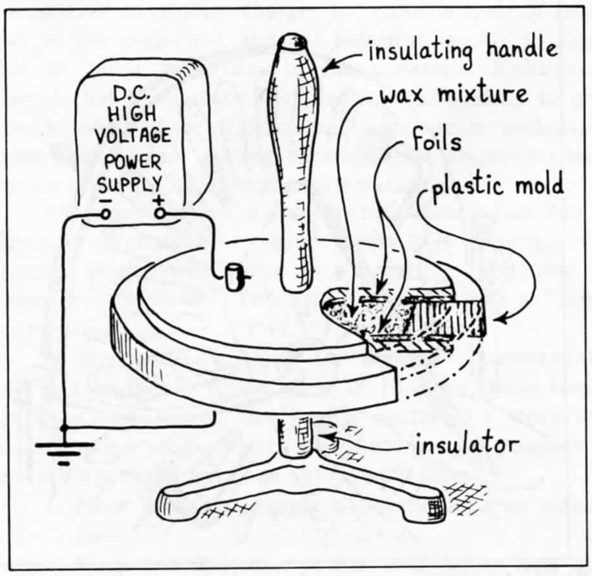


Fig. 8. Carnauba-wax electrets are made in a plastic mold placed on a table-like electrode and covered with another electrode. Aluminum foils between the melt and the electrodes prevent the wax from sticking to the electrodes and protect the electret from cracking when it shrinks during cooling. A convenient size for the mold is 15 cm outside diameter, 7.5 cm inside diameter, machined from 1/2 in. Plexiglas. The mold may have a slight taper to facilitate the removal of the electret. The voltage should be 10-20 kV.

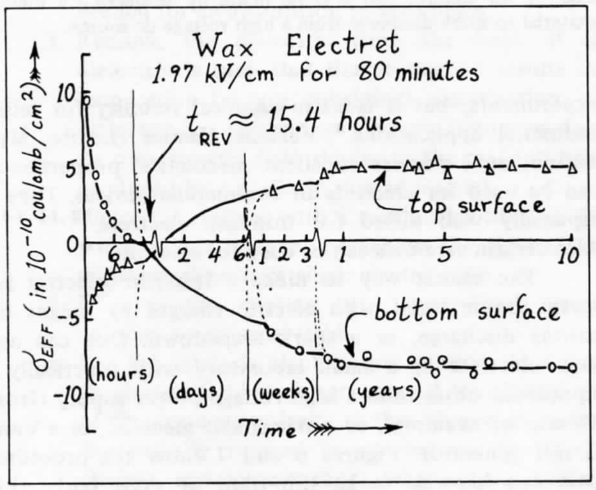
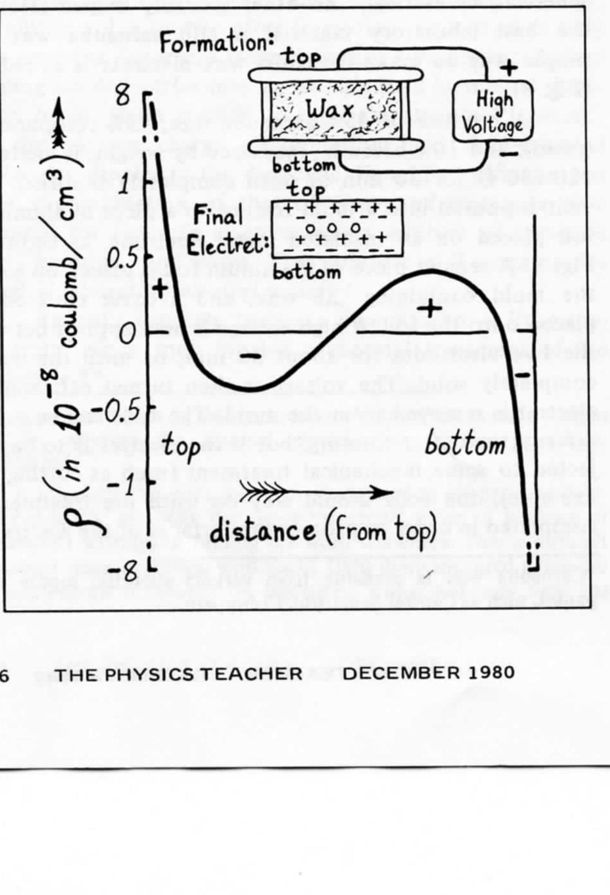


Fig. 9. Effective surface charge density of the two surfaces of a carnauba-wax electret as a function of time showing the polarity reversal from the initial heterocharge state to the final homocharge state. The forming field was 1.97 kV/cm and was applied to the melt for 80 minutes. The reversal occurred 15.4 hours after forming.



In the open air electrets will attract charged dust particles and various ions from the air and will rapidly lose their electrization. Therefore electrets must be stored wrapped in aluminum foil, or otherwise tightly shielded. For the same reason most electret devices must be of such a design that the electret is located between metallic electrodes that cover the electret as much as possible and are also as near to the electret as possible.

The strength of electrets is measured in terms of their "effective surface charge density." This is easily determined by placing a metallic disk supported by an insulated handle (for example, the cover electrode of Fig. 8) onto the electret, temporarily grounding the disk, lifting it, and placing it in contact with a terminal of an electroscope or electrometer.* The charge indicated by the electrometer divided by the surface area of the electret is the effective surface charge density. In a good electret it is about 10^{-9} C/cm^2, which is the maximum charge density that can be sustained in air before a breakdown occurs.

Carnauba-wax thermoelectrets will reverse their polarity usually in several minutes (but sometimes days, months, or even years) after they are made. Once the reversal has occurred, the electret will reach its maximum strength, and if properly shielded, will keep its electrization for many years. An electret made by the senior author in 1954, for example, has not diminished its strength to this day. Figure 9 shows typical electrization curves for the two surfaces of a carnauba-wax electret made in our laboratory in 1967. Figure 10 shows the internal distribution of space charge in such an electret, as measured by a cutting technique developed in our laboratory.[17] It is interesting to note that even when an electret field is neutralized by deposition of opposite charges on its surface (as when an electret is left unshielded) the internal-charge distribution shown in Fig. 10 remains unchanged. In fact, the only way to change this charge distribution is to remelt the electret.

The fact that carnauba-wax electrets have a permanent internal-charge distribution (or polarization) is the characteristic property of highly stable electrets, as compared with other dielectrics possessing a long lasting electrization (surface charge, for example) but no permanent internal-charge distribution. The latter dielectrics lose their electrization in a few days, or months, and are sometimes called "pseudoelectrets." Actually there is no clear demarcation line between true electrets and pseudoelectrets. As a rule of thumb, a true electret, if properly shielded, lasts at least one year; a pseudoelectret lasts less than a year.

Fig. 10. Internal charge distribution in a carnauba-wax electret. The curve represents the variation of charge density (magnitude and polarity) within the electret.

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*Such as a Keithley Model 610.

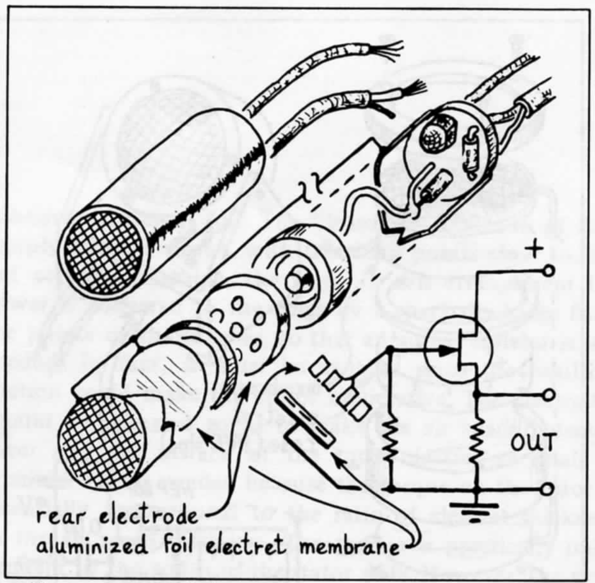

Fig. 11. A commercial electret microphone with a thin-film plastic electret membrane. The membrane has a metallic coating on the outside surface, and the microphone functions essentially as a condensor microphone. The back electrode is insulated from the housing. A source-follower type preamplifier is built into the microphone. The preamplifier is needed to eliminate the capacitance of the long lead-in wires. Without it the capacitance of the wires would be connected in parallel to the microphone capacitance, and, being much larger than the latter, would drastically reduce the sensitivity of the microphone. Also, the preamplifier matches the large output impedance of the microphone to the low input impedance of a conventional amplifier.

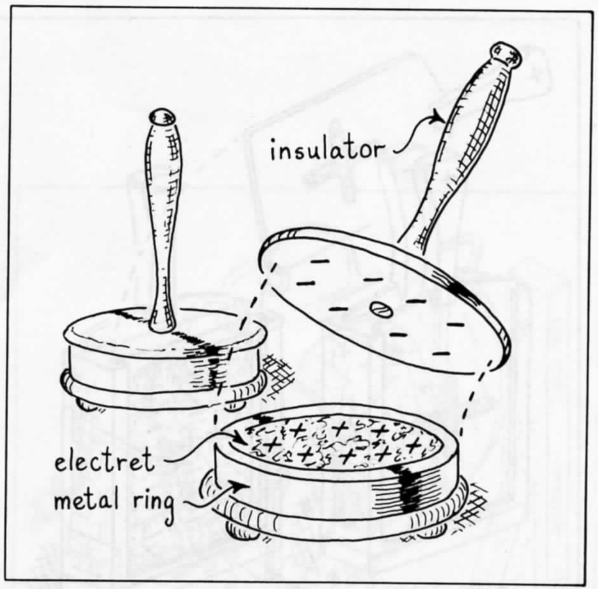

Fig. 12. Automatic electret electrophorus has an electret mounted in a conducting ring and resting on a conducting base. The ring must be slightly higher than the electret, so that the cover comes in contact with it, rather than with the electret. Charge of either polarity can be obtained from this electrophorus by merely inverting the electret on its base. An electrophorus with an electret 7.5 cm in diameter and 1 cm thick delivers about 10^{-8} C to the cover.

Uses of electrets

The earliest use of a dielectric possessing long-lasting electrization was in the charge-dispensing device known as the electrophorus, or more accurately, "perpetual electrophorus," as it was named in 1762 by the Swedish scientist Johannes Wilcke.[18] An electrophorus consists of a dielectric disk, called the "cake," resting on a conducting base, and a conducting cover plate with an insulating handle. The cake is first electrized by friction, which makes it into a pseudoelectret. The cover plate is then placed onto the cake. The cake induces charges on the plate, and when the plate is next grounded by touching it with a finger, the charges of the same polarity as that of the cake are led into the ground, while the charges of the opposite polarity remain on the cover. The cover is then lifted, and its charge is used for some intended purpose. Since the cover plate and the cake touch only at a few points, and since the cake is a nonconductor, only those parts of the cake are discharged which are extremely close to the points of contact. The charge on the remaining surface of the cake remains unchanged. Therefore, the cover plate can be repeatedly charged by induction from the originally electrized cake by merely repeating the covering, grounding, and lifting operations. Observe that the electret measuring operation described earlier is derived from the electrophorus principle. In Projects 1 and 2 we shall describe how to make a permanent automatic electret electrophorus and a charge dispensing cell.

The earliest use of modern electrets was by the Japanese, who used them for some of their military telephones in the Second World War. Electret microphones are now extremely widespread. They are inexpensive, possess excellent electroacoustical characteristics, and can be made extremely small (less than 1 mm thick and less than 5 mm in diameter). Most commerical electret microphones use plastic-sheet electrets for the membrane (Fig. 11). In Project 3 we shall describe how to make a "back electret" microphone with an aluminum-foil membrane.

Many electret devices have been suggested and patented.[19] Among them are radiation detectors, dosimeters, memory storage units, humidity meters, air cleaners, vibration detectors, pressure gauges, relays, electrostatic motors, current and voltage generators, electron beam deflectors, pushbutton keys, etc. Perhaps the most noteworthy electret application was for seismic detectors used on Apollo space missions. One of the newest suggestions for electret applications is an airport security system.[20]

As an illustration of more complex electret devices we shall describe in Project 4 how to make an electrostatic electret motor by utilizing the "slot effect" discovered in our laboratory.[21]

Projects

1. Automatic electrophorus.[22] The electrophorus is illustrated in Fig. 12. It consists of a disk electret mounted in a conducting ring and resting on a conducting base together with a metallic cover plate on an insulating handle. The purpose of the ring is to eliminate the necessity for grounding the cover plate by a finger, as is done in a conventional electrophorus. In our electrophorus the cover need not be grounded at all. Just place it on the electret and lift it; it will acquire its charge completely automatically. We suggest a carnauba wax for the electret. The ring may be made from a brass or aluminum tubing, or simply from an adhesive aluminum tape. The handle of the cover plate should be made of a very good insulator, such as Plexiglas.

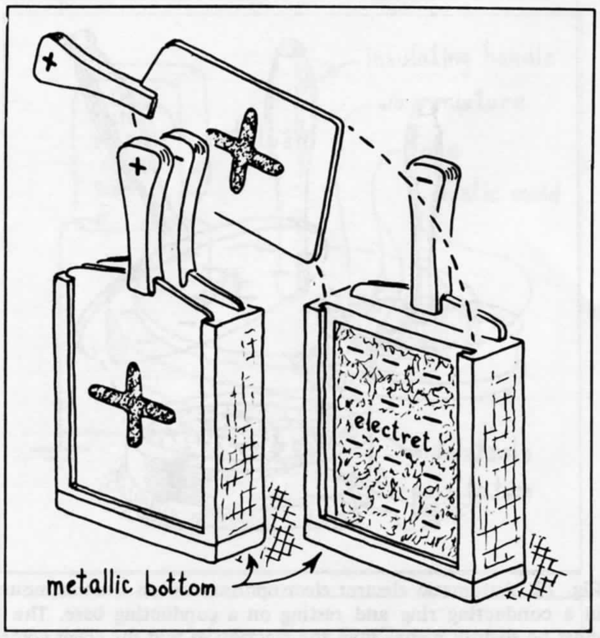

Fig. 13. The electret charge dispensing cell automatically produces charges of either polarity. One of the sliding plates is permanently marked "+," the other "−." They always carry equal charges of the indicated polarity. The plates must be as close to the electret as possible, but must not touch it. With a good electret the cell produces about 10^{-9} C per cm^2 of the electret surface.

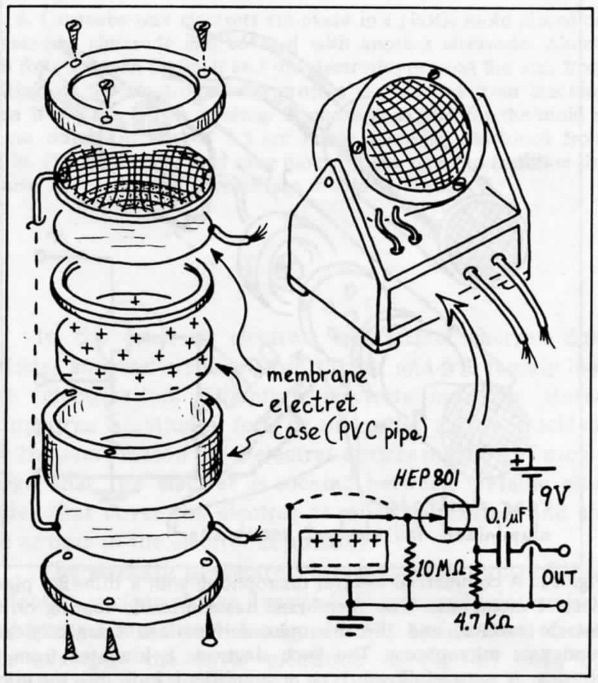

Fig. 14. The electret microphone is a simple device. An excellent microphone can be constructed with a carnauba-wax electret 7.5 cm in diameter and 1 cm thick. The spacer ring between the membrane and the electret should be as thin as possible. The membrane must be well insulated, and the protective metal screen must be mounted on an insulating ring. The preamplifier is needed for reasons mentioned in Fig. 11. The circuit given here will work fine, but there is nothing critical about it.

2. Charge-dispensing cell.[22] This device is merely an improvement on the electrophorus just described. It consists of an electret mounted in a insulating housing with a conducting bottom and two sliding metallic cover plates with insulating handles (Fig. 13). It functions essentially as the electret electrophorus, except that now the charges are produced on the sliding plates. One plate gives positive charge, the other – negative. The metallic bottom has the same function as the conducting ring of the electret electrophorus.

3. Electret microphone. The diagram of the microphone is shown in Fig. 14. The electret is sandwiched between the back electrode and an aluminum foil membrane. The back electrode and the membrane are connected to a preamplifier contained in the base of the microphone. Even if crudely built, this microphone will have an excellent fidelity.*

4. Slot-effect motor.[23,24] The slot effect is a peculiar force action on electrets, illustrated in Fig. 15. If two electrodes forming a slot are placed near an electret, and if a voltage is applied across the slot, a force is exerted on the electret by the electric field of the slot in the direction perpendicular to the slot and parallel to the electrodes. This arrangement combines a nearly perfect shielding of the electret with a force larger than that obtainable with any other presently known electrode arrangements.

The motor, Fig. 16, has two pairs of stator electrodes, and a disk electret rotor consisting of two oppositely polarized half-disks. To build the rotor, an ordinary disk electret is first made. Without peeling off the foils the electret is cut with a saw along a diameter. The two parts are then glued together so that their polarizations are in opposite directions. Next, a central hole is drilled and the rotor is mounted on the axle. Only then, just before placing the rotor between the stator plates, are the foils removed. The motor requires for its operation a dc power supply of 6-10 kV. The power is delivered to the stator plates by means of a commutator made of a good insulator (Plexiglas). The "slip rings" of the commutator can be made of

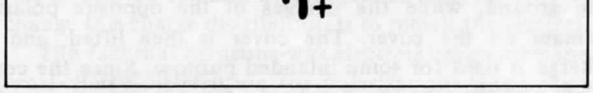

Fig. 15. When an electret is placed between slotted electrodes to which a voltage is applied, the electret experiences a force. This is called the "electret slot effect."

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*In 1964 such a microphone built by a student in our Junior Electricity Laboratory was successfully tried at a Pittsburgh TV station. This was before commercial electret microphones became available.

adhesive aluminum foil. The "brushes" are made of four sharply pointed screws, with the sharp points close to, but not actually touching, the rings. In this arrangement the power is delivered to the rings by a spark discharge from the points of the brushes, so that an actual contact is not needed. In fact, it must be avoided since the resulting friction could make the motor inoperative. The electrodes should be adjusted so as to make the air space between them and the surface of the rotor electret as small as possible. This is needed because the torque on the rotor is essentially proportional to the ratio of electret thickness to the air space thickness. The torque is practically independent of the width of the stator slots. However, the slots should be wide enough to prevent a spark discharge across them. Of all the project devices described here, this motor is the most delicate one and should be built with the precision that one would use in building a fine clockwork.

In conclusion we should like to note that we have deliberately not given rigid or detailed construction plans for the above projects in order to encourage some individual research and invention activity by those working on the projects.

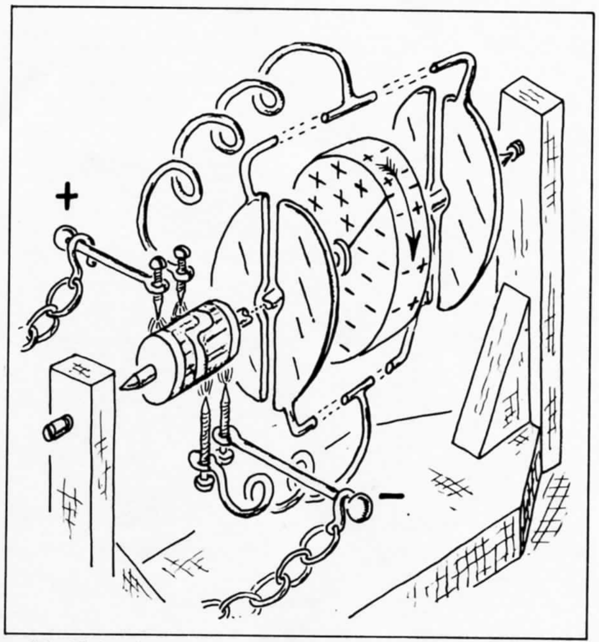

Fig. 16. This electret motor utilizes the slot effect. The stator plates should be as close to the rotor electret as possible without touching it. The commutator is used to switch the voltage when the neutral line of the electret passes the slots.

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