Cost: $0-100 [About These Ratings]	Difficulty: ■■□□□	Danger 4: (POSSIBLY LETHAL!!)	Utility: 😎

How to Make an Electret: the Device That Permanently Maintains an Electric Charge

by C. L. Stong
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THE HISTORY OF SCIENCE IS A TREASURE house for the amateur experimenter. For example, many devices invented by early workers in electricity and magnetism attract little attention today because they have no practical application, yet these devices remain fascinating in themselves. Consider the so-called electret. This device is a small cake of specially prepared wax that has the property of permanently maintaining an electric field; it is the electrical analogue of a permanent magnet. No one knows in precise detail how an electret works, nor does it presently have a significant task to perform. George O. Smith, an electronics specialist of Rumson, N.J., points out, however, that this is no obstacle to the enjoyment of the electret by the amateur. Moreover, the amateur with access to a source of high-voltage current can make an electret at virtually no cost.

"For more than 2,000 years," writes Smith, "it was suspected that the magnetic attraction of the lodestone and the electrostatic attraction of the electrophorus were different manifestations of the same phenomenon. This suspicion persisted from the time of Thales of Miletus (600 B.C.) to that of William Gilbert (A.D. 1600). After the publication of Gilbert's treatise De Magnete, the suspicion graduated into a theory that was supported by many experiments conducted to show that for every magnetic effect there was an electric analogue, and vice versa.

"In 1339 Michael Faraday suggested that it should be possible to polarize a dielectric material so as to produce 'a Dielectric Body which retains an electric moment after the externally-applied electric field has been reduced to zero.' In Faraday's time, however, other workers were so busy with such ideas as the telegraph and the arc light that they paid little attention to his device. An exception was Oliver Heaviside, who discusses it in his *Electrical Papers*. Finding Faraday's 19-word description a bit cumbersome, Heaviside coined the word 'electret,' by analogy to 'magnet.' Adorned with this name, the electret remained no more than a scientific concept until 1922, when the first electrets were produced by Mototaro Eguchi, professor of physics at the Higher Naval College of Tokyo.

"The analogy between the magnet and the electret is striking, and this includes the way in which they are fabricated. For example, a magnet can be made 'cold,' but the strength and permanence of its magnetism is enhanced if the material is placed in a magnetic field while it is in the liquid state and is then allowed to cool while the field is maintained. The same is true of the electret, though of course the effect and the field are electrical.

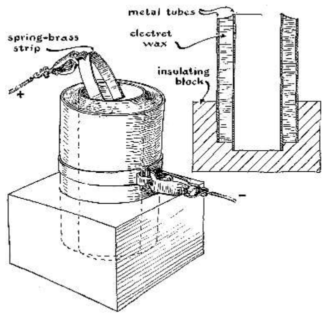

Figure 1: An electret devised by E. P. Adams of Princeton University

"One form of electret is made by melting a mixture of waxes and permitting the batch to cool slowly between a pair of electrodes charged to a direct-current potential of several thousand volts. When the wax has cooled to room temperature and is removed from the field, it will retain a charge. The strength of the charge depends on a number of factors, including the composition of the wax and the rate of cooling. However, even crudely made electrets can maintain a charge of several hundred volts. Just as some magnetic materials have a higher permeability than others, certain waxes make better electrets. One of the more efficient formulas for electret material is: carnauba wax, 45 per cent; water-white rosin, 45 per cent; white beeswax, 10 per cent.

"In the present state of the art this formula is subject to imponderables of the sort that make horse-racing popular: It is more a matter of opinion than of certainty. Some experimenters advocate the substitution of 'halowax' for the water-white rosin. Others who agree go on to point out that if halowax is substituted for the rosin, the beeswax may be omitted. The beeswax is added only to reduce the brittleness of the final electret, and equal parts of halowax and carnauba wax do a fine job. The carnauba-halowax mixture gives the finished product a creamy, ivory texture with a nicely polished surface, and it shrinks sufficiently upon cooling to come easily out of the mold. On the other hand, halowax is somewhat hygroscopic, and electrets containing it must be protected against humidity.

"Some experimenters claim that good electrets cannot be made unless the mixture contains at least a trace of carnauba wax. Others insist that any wax that cools to a fairly hard, shiny surface will accept the electric charge and develop an external electric field. One explanation in support of the carnauba-wax view suggests that the relatively large shrinkage of carnauba wax places an additional stress on the finished electret, which adds a piezoelectric effect to the over-all static charge. In recent years, however, this view has been refuted. When the ceramics industry undertook the development of dielectrics, a whole special class of materials was created. Starting with ceramic capacitors, piezoelectric ceramics were developed for hydrophones, microphones and phonograph pickups. Ceramic magnetic materials appeared, and finally ceramic electrets. A ceramic electret made of barium titanate contradicts the notion that electrets do not work without carnauba wax.

"A major problem in the manufacture of electrets stems from the cussedness of wax dielectrics in general. The insulating property of waxes decreases as the temperature increases. This is a smooth and well-established relationship. When the wax enters the liquid phase, however, the insulation resistance begins to drop sharply. This effect can expose the experimenter to hazard. If a high-voltage supply with low internal impedance is used to provide the polarizing electric field, it is possible that the supply will deliver enough current through the melted dielectric wax to add to the temperature of the mass. Because the internal resistance drops with increasing temperature, the process becomes explosive. Ultimately enough current follows along one channel to provide a flash-arc path that can splatter flaming wax in a dangerous manner.

"On the other hand, a 'safe' high-voltage power supply (one that includes an internal resistance on the order of 50 megohms, say) will deliver only a fraction of its available voltage to the electret-forming terminals, because its ratio of internal impedance to external impedance acts to divide the voltage. The external load resistance also goes up as the electret cools and the strength of the polarizing electric field increases.

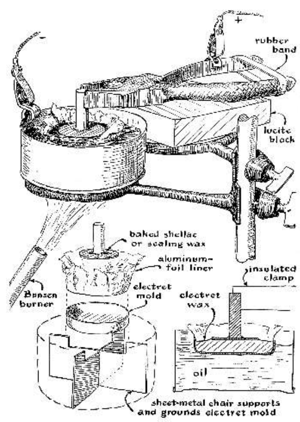

Figure 2: An electret devised by W. M. Cood and J. D. Stranathan of the University of Kansas

"The reason that the electret acquires a charge is fairly obvious. The molecules of the wax are electrically polarized, and they align themselves with the electric field just as the 'domains' of a magnetic material line up with a magnetic field. As the wax cools and solidifies, this alignment is maintained. Unlike metallic substances, however, waxes have no sharp melting point. Even when the wax is highly purified there is a span of many degrees between the solid state and the state in which the wax flows as a liquid. A mixture of waxes usually exhibits an even wider range of temperatures between the semiplastic and semifluid states.

"The current-carrying mechanism in waxes consists of a migration of polar molecules from one electrode to the other, of the delivery of electrons from cathode to anode by true physical movement. The positive end of a polar molecule picks up an electron from the cathode; this causes a local neutralization of the positive end, but destroys the neutrality of the molecule, making it act as if it were a negative ion (anion). Conversely, the negative end of the polar molecule can lose an electron to the anode, causing a local neutralization of the negative end and a loss of over-all molecular neutrality. This molecule now behaves as if it were a positive ion (cation). Both processes can occur in a single molecule, resulting in a restoration of molecular neutrality but the loss of dipolar features. The partially neutralized dipoles exhibit only half as much tendency to align themselves with the electric field, and the neutralized molecules none at all. Add these conditions to the lowered electric-field intensity caused by the current, and to the molecular vibrations caused by the temperature of the material, and it is not hard to understand why electrets that are cooled quickly during manufacture exhibit fields of lower intensity than those that are cooled slowly. Slow, deliberate cooling enables the vibrating molecules in the electret to come to rest in alignments that result in the maximum subsequent field strength.

"A simple form of the electret was devised some years ago by Edwin P. Adams of Princeton University. It consists of concentric metal cylinders sealed at the bottom by an insulating base and containing a cylinder of wax, as shown in the accompanying illustration [*above*]. In 1939 W. M. Good and J. D. Stranathan of the University of Kansas devised the improved version depicted in the second illustration [Figure 2]. The large oil bath shown in this illustration provides a mass to retard the rate of cooling. Good and Stranathan also added electric heaters and an automatic temperature-control to lower the temperature gradually through the semiplastic state over a period of many days. This refinement is scarcely needed unless you embark on a program of meticulous research. When the oil bath is heated to the temperature that will cause a true fluidity of the electret material in the mold, it will cool slowly enough to give rise to an effective electret.

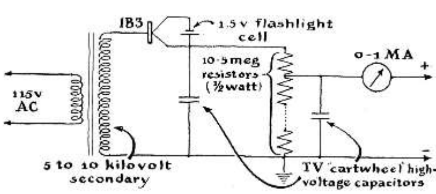

Figure 3: Circuit diagram of a power supply to polarize and charge an electret

"Any high-voltage supply can be used; if the one at hand chances to be capable of delivering more than a milliampere, it can be rendered safe by adding resistors in series between the supply-terminals and the electret plates. This can best be accomplished by connecting the necessary number of two-, three- or five-megohm resistors in series for a total of 50 megohms. The resistors should preferably be of the two-watt size; they should not be smaller than the one-watt size. I concede that 1,000 volts across a five-megohm resistor dissipates only .2 watt. We are not concerned with the wattage, but rather with the voltage gradient across the resistor itself. The physical size of the larger resistors eliminates the high voltage-gradient and attendant internal electrostatic effects that cause fusing of the carbon granules. This process can cause a major change in the resistance value of small carbon resistors. The use of a string of two-, three- or five-megohm resistors also enables you to make a rough adjustment of the output voltage by coupling the output leads to intermediate points in the string.

"Sparking across the surface of the wax can be reduced or eliminated by increasing the series resistance. A meter of some sort should be connected in the load circuit so that you can observe the process. A zero-to-one milliammeter will prove far more informative than a volt meter that merely indicates the total polarizing field.

"The polarizing field should be maintained at a maximum. The current flowing through the melted electret wax should never be permitted to rise above .5 milliampere. At the dielectric material's most conductive phase the series resistance should be adjusted to limit the current to about .1 milliampere. It will not be necessary to readjust the resistance as the wax cools, because the internal resistance will rise to a safe limiting value. Simultaneously the polarizing voltage across the wax will increase to the maximum value.

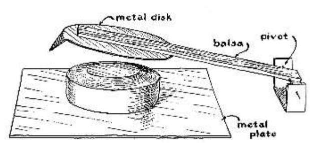

Figure 4: A simple device for testing an electret

"In computing the output voltage of your power supply, such as the one illustrated in the accompanying circuit diagram, remember that the voltage shown on the nameplate of the transformer must be multiplied by 1.414. This is because in this application the load current is so low that the delivered voltage practically reaches the peak value, and the rated output of the transformer is always given as the root mean square value.

"In processing electrets the oil bath should be raised to operating temperature first, or at least started so that it will be at operating temperature by the time the electret formula is mixed. Melt and mix the waxes in a separate pan, stirring frequently to drive out air bubbles and moisture. Keep the electret-mix temperature well above the boiling point of water for at least half an hour. Be wary of touching tiny bubbles that cling to the walls of the container. These may be water droplets. Touching them with a stirring rod breaks the surface tension that has prevented the water from boiling into steam. When the tension is broken, the water explodes into steam with sufficient violence to splatter the hot wax.

"In the meantime line the mold with aluminum foil and smooth it out to remove as many of the wrinkles as possible. Tapering the mold slightly will facilitate the subsequent removal of the foil-encased wax. Next pour the melted mix into the mold. (The size of the finished electret is optional. A disk two or three inches in diameter and about half an inch thick is convenient.) The top plate should just touch the top surface of the electret material. This plate should be heated, too, by the way. When the wax wets the top plate, the high-voltage supply can be turned on. The electrostatic stress should cause an abrupt jump in the annular meniscus of the wax surface between the center plate and the mold walls. If sparks appear on the molten wax, turn off the power and connect the output leads for lower voltage. Then reapply power, turn off the oil-bath heater and permit the assembly to cool to room temperature. Observe the temperature with a thermometer, not by feel. *Stay away from any part of the apparatus when the high-voltage supply is in operation!*

"When the oil reaches room temperature, turn off the power supply and remove the electret. Immediately fold the aluminum foil forward over the surface in contact with the top plate, short-circuiting the electret. The foil acts as a 'keeper' and is analogous to the soft-iron bar placed across the open jaws of a horseshoe magnet to preserve the magnetic flux. Electrets properly short-circuited have kept for longer than five years without noticeable loss of charge.

"Now comes the puzzler that stumps the experts. If the electret's polarity is measured directly after its manufacture, its charge will be just what theory predicts it should be. The negative surface of the electret will be that which made contact with the positively charged polarizing electrode, and vice versa. This agrees with the north-south polarity of a bar of steel magnetized by contact with a permanent magnet. In contrast with the behavior of a magnet, however, the charge on the electret begins to diminish immediately, and in about a week it will have fallen to zero. The charge then begins to build up *in opposite polarity* to a final value that may be several times as large as the original charge. This may take as long as three months. The negative surface of the stabilized electret will be the face that made contact with the negatively charged polarizing electrode. In other words, the charge will correspond in sign to the polarity of the high-voltage field. Just why this reversal takes place has never been satisfactorily explained.

"Measurement of the electrostatic field that surrounds an electret requires a sensitive electrostatic meter, an instrument actuated by electrostatic attraction or repulsion rather than by the passage of current. The magnitude of the surface charge may be measured by passing a metal plate of known area at a known rate into the field until contact is made with the electret surface, the plate being connected to an electrostatic voltmeter. A voltmeter of this type can be made inexpensively by using an electrometer tube (essentially a vacuum tube designed for service in vacuum-tube voltmeters). The instrument will absorb substantially no power and can be calibrated by using a conventional voltmeter as a reference.

"For simple checks a gold-leaf electroscope will do an admirable job of measuring polarity. The polarity of the electret can be determined by charging the gold-leaf electroscope with a current of known polarity and observing whether the electret's approach adds to the charge (by causing the gold-leaf vanes to separate more) or subtract from the charge (by permitting them to fall closer together).

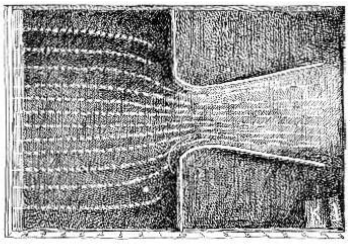

Figure 5: Pattern of smoke pulses passing through a nozzle in a homemade smoke tunnel

"Finally, at least one simple but spectacular test can be made. A metal disk with a point at the rim is cut just large enough to cover the electret. The disk is fastened to an insulating arm that is hinged to a metal base-plate as shown in the accompanying illustration [*Figure 4*]. The metal point should be bent so that when the disk rests on the electret, a sheet of writing paper (.003 to .005 inch thick) will just drag a bit when passed between the point and the metal base-plate. The insulating arm may be made of lucite, or of dry wood (such as a length of model-airplane balsa) that has been boiled in paraffin or impregnated in oil until a fresh-cut surface will repel water. The arm is pivoted at the end to allow the plate to fall through the electrostatic field of the electret. If your hand is steady and your aim unerring, you can omit the lever assembly and merely drop the plate onto the electret surface! The falling plate picks up a charge from the field? and the charge is dissipated in a small but brilliant spark discharge between the point and the bottom plate. Try this with both surfaces of the electret. For some reason electrets are not symmetrical. One surface will deliver more energy than the other.

"The electret has not been entirely without practical application. It has been used to replace the high-voltage polarizing network employed for energizing some types of condenser microphones. The growth of radio broadcasting in the early 1920's, with its need for a microphone that worked on some principle other than the compression of carbon particles, seems to have spurred the original investigation of the electret. For some reason the condenser microphone grew up and passed into obsolescence without ever meeting an electret. But in 1935 Andrew Germant made an electret condenser-microphone for the engineering laboratory of the University of Oxford. Subsequently condenser microphones employing electrets were taken into the field by the Japanese army.

"The electret found another application a few years ago when the television industry was seeking a simple method for focusing picture tubes. Early picture tubes were focused by a magnetic coil that was adjusted by means of a costly power-potentiometer. Eventually the arrangement was replaced by a permanent-magnet focusing device adjusted by changing the magnetic gap. During one brief period, however, the picture tubes were made with an electrostatic lens, the focal length of which was adjusted by a potentiometer. At this point someone remembered the electret and reasoned that, if the electromagnetic focusing-coil could be replaced by a permanent magnet shunted by a mechanically adjusted gap, perhaps the permanent electret could similarly be put to work. Before the idea could be exploited, the development of the self-focusing electron gun solved the focusing problem and once again reduced the permanent electret to the status of a scientific waif.

Dillard Jacobs, associate professor of mechanical engineering at Vanderbilt University, has developed a novel accessory for extending the usefulness of aerodynamic smoke tunnels of the type described in this department [see SCIENTIFIC AMERICAN, May, 1955]. The pattern of air flow in such apparatus is made visible by a grating of smoke streamers admitted to the tunnel through a "rake" of small tubes near the inlet. The lines of smoke bend around test objects placed downstream, and: enable the experimenter to approximate the distribution of forces acting on the object.

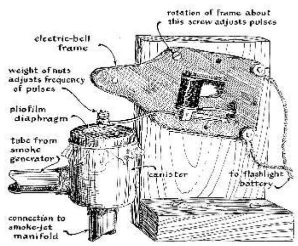

Figure 6: A simple device for pulsing the streams of smoke in a smoke tunnel

"Following your description of the smoke tunnel," writes Jacobs, "I promptly built one and can attest to the suitability of its design. The tunnel has been used extensively to produce photographs of fluid-flow phenomena for use in my classes. Some months ago I added a gadget to the tunnel which considerably broadens its utility as a scientific tool. This consists simply of an electric doorbell (with the gong removed) and a chamber with a diaphragm inserted in the smoke circuit just ahead of the 'rake.' When properly adjusted, the doorbell-and-diaphragm assembly acts as a chopper to send the smoke out into the tunnel in small puffs or pulses instead of in a continuous stream. I was able to measure the frequency of these pulses (780 per minute). With the pulse frequency known, one has only to measure the distance between puffs on test photographs to calculate velocities precisely. When an obstruction such as a divergent nozzle is placed in the tunnel, the increase in velocity through various regions of the constriction show clearly [*see illustration below*].

"The modified doorbell is supported by a wooden bracket as shown in the

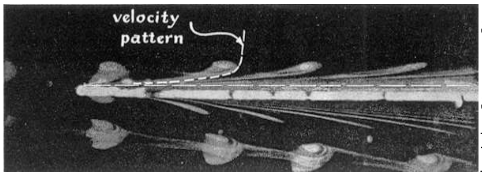

Figure 7: How pulsed smoke streams were used to investigate shearing in the boundary layer

accompanying illustration [*above*]. This provides an adjustment for altering the impact of the clapper on the pliofilm diaphragm, thereby controlling the amplitude of the smoke puffs. If the diaphragm action is too strong, the smoke pulses become smoke rings, an interesting but unsatisfactory effect. Although the bell was originally designed to operate from a six-volt battery, in this device it works best on a volt and a half. "I used an electronic stroboscope for timing the frequency of the pulses. This consists of a variable oscillator that triggers a high-speed gas-discharge lamp. The speed of the flashing lamp is varied until the smoke puffs appear to stand still. The flash rate is then read from a calibrated scale on the oscillator. If an experimenter does not have access to such apparatus, a motor-driven stopcock designed to operate at a known speed could be inserted in the smoke line.

"Among the interesting phenomena opened to investigation by the pulsed smoke tunnel is the shearing action in the boundary layer between the fluid and a solid surface, as shown in the accompanying photograph [*below*]. Both the thickness of the boundary layer and the velocity distribution through it can be determined with fair precision. In this case the smoke velocity beyond the boundary layer is .79 foot per second. The transverse Reynolds number is 960."

Bibliography

FUNDAMENTALS IN THE BEHAVIOR OF ELECTRETS. W. E. G. Swann in *Journal of The Franklin Institute*, Vol. 255, pages 513-530; June, 1953.

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