'A BRIEF STUDY OF THE ELECTRET'

Shailendra Singh Chauhan,
Principal in Late Bahadur Singh Mahavidhyala,
Madhaugarh (Jalaun)

Abstract: Although the existence of an electrical counterpart to the magnet, the electret, had long been regarded as theoretically possible, the first practical electret was not produced until the 1920s. The electret possesses an electric volume polarization and produces a static electric field that remains constant over many years. Its physical behavior has been explained only in recent years. The road to practical applications has been opened, and the performance of the electret microphones now commercially available equals or exceeds that of the conventional condenser microphone.

Index Terms – Electret, Polarization, Dielectric, Polarity

1. INTRODUCTION

A magnet produces a static magnetic field, an electret produces a static electric field. Oliver Heaviside was the first to speculate about the existence of such a counterpart to the magnet and it was he who first used the term 'electret. Around 1890 he wrote: The study of electrization is in some respects more important than of magnetization, on account of its greater generality it is more instructive' [1]. Thirty years later the Japanese physicist M. Eguchi [2] succeeded in producing bodies with electrical properties analogous to the magnetic properties of permanent magnets. Eguchi, who was unaware of Heaviside's work, re-invented the term electret. His truly remarkable work at first received scant attention. In 1935, more than a decade later. A. Gemant [3] repeated, confirmed, and extended Eguchi's results. But the strange behavior of electrets revealed by the early experiments, reinforced by Gemant's view that for theoretical reasons they should not exist [4], did much to shroud the electret effect in mystery. It took much fundamental research to establish the basic facu and to show that the electret effect, far from being an anomaly, is a general property of solid dielectries, varying in degree rather than in nature. Technical developments have now led to practical applications.

2. HETEROCHARGES AND HOMOCHARGES

Eguchi found that the electrical conductivity of natural waxes increases strongly with temperature and in the liquid state is much higher than in the solid. He concluded that by solidifying a liquid dielectric exposed to a strong electric field it should be possible to freeze-in' displaced or oriented charge carriers in fixed positions and thus to create a dielectric body which produces an electric field of its own even after removal of the electric field that originally was applied to polarize it. Experiments with Carnauba wax (obtained from the Brazilian: wax palm), beeswax, and mixtures of these waxes with rosin confirmed his expectation. Until now Carnauba wax has remained the substance preferred by many investigators. Recently other materials, in particular polymers such as polyurethane, polyethylene, and fluorocarbons, have been found preferable for practical applications. Electrets can also be prepared without raising the temperature beyond the melting point.

When the surfaces of one of Eguchi's electrets were physically cut off the field originating from the residual section was temporarily reduced, but later recovered its original value, thus proving the polarization to be a bulk property. There remained only one disturbing aspect in an otherwise consistent picture: the final surface charges of the electret had in the view of prevailing theories the wrong polarity. Immediately after a sample had been cooled and the polarizing field removed, the surface that had been in contact with the electrode connected to the positive pole of the voltage source was found to carry a negative charge, while the surface in contact with the negative electrode became positively charged This is what can be expected when the field-induced polarization partially persists without an applied field. But these charges, which since Gemant's initial work are called heterocharges, are not stable. They decrease, a polarity: reversal occurs, and after a period of days or weeks an apparent equilibrium is reached and the dielectric carries surface charges which have the same polarity as the corresponding polarizing electrodes and are called homocharges.

3. TYPES OF DIELECTRIC POLARIZATION

A magnetic material contains only magnetic dipoles, never magnetic monopoles. A dielectric material may contain both electric dipoles and electric monopoles, that is single positive and negative charge carriers. This fundamental difference explains why a dielectric can be polarized in more ways than a magnetic material. These forms of polarization will now be briefly discussed.

Application of an electric field always produces a small movement of charges within the atoms of a dielectric, displacing the negative electronic cloud relative to the positive nucleus and thus temporarily generating a small dipole moment and a consequent atomic or 'deformation polarization. This effect occurs within very short times; its time scale cannot be changed from 'outside'. Thus its influence on the persistent polarization of the electret can be disregarded.

Many dielectrics, including polymers, contain molecules that have an electric moment. An applied field tends to align these elementary dipoles along its own direction and thus produces an electric moment of the whole body thus giving rise to dipole polarization, essentially a volume effect.

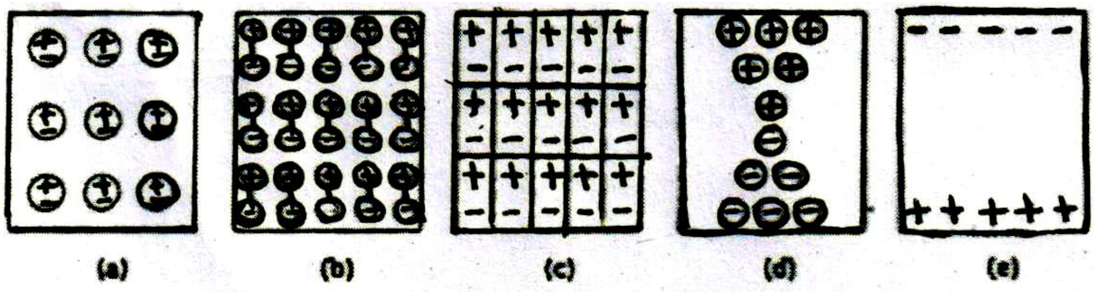

Figure 1 Types of polarization. (a) Atomic polarization; (b) dipole polarization; (c) interfacial or barrier polarization; (d) space-charge polarization; (e) external polarization (charged dielectric).

All dielectrics contain a small number of free charge carriers, ions or electrons or both. An electric field tends to separate positive from negative charges aid to move them toward the electrodes. The structure of many. dielectrics is not homogeneous; there ex.st microscopic domains or grains separated by highly-resistive inter- faces. In this case the charge carriers can move relatively freely only within single grains, piling up along the 'frozen-in'. barriers which they are unable to surmount as they lack the necessary energy. Alternatively, when the dielectric contains many irregularly distributed traps with widely different well depths, carriers might move in the direction of the field until they fall into deep traps from which they do not have enough energy to escape unless re- activated by a temperature increase. Both these inter facial polarization effects constitute again a volume polarization.

Ionic conduction currents in homogeneous dielectrics usually lead to the formation of space-charge clouds in the electrode regions. This effect results in a macroscopic space-charge polarization of the dielectric.

The sources of the internal polarization described so far have been charges originating from and remaining within the dielectric. But a polarization can also be caused by the deposition or injection of charge carriers. from outside. Deposition of equal and opposite charges on opposing surfaces of a dielectric produces an 'external polarization. The distinction between internal and 'external' polarization is due to S. Mikola (5). Charges can also be shot into the dielectric using penetrating electron beams. Such electron-charged dielectrics now are also called electrets, a rather loose use of the term.

Figures 1(a) to 1(e) illustrate these effects. They show that only dipole and interfacial polarization are true volume effects in the sense that the polarization of any section of the electret is the same as that of the electret as a whole.

4. 'FREEZING-IN' THE POLARIZATION

The degree of polarization and its rate of decay depend on the nature of the dielectric and the experimental conditions, in particular the temperature. A dielectric becomes an electret when the rate of decay can be slowed down so much that a significant fraction of the field- induced polarization is preserved long after the polarizing field has been removed.

Dipole orientation is strongly temperature-dependent; at high temperature or in the molten state the forces opposing rotation are lessened. Thus a high degree of polarization can be achieved in a short time by application of an electric field at a high temperature or in the molten state. If the dielectric is coined and the field re- moved only after a low temperature has again been reached, dipoles return to the original disordered state very slowly because rotation is hindered by strong viscous forces. The polarization is thus 'frozen-in'. A similar behavior is found in the case of space-charge and interfacial polarization. The mobility of the charge carrier is very low at room temperature, but increases. strongly with temperature. Thus the previous reasoning, *mutatis mulandis*, applies here too. Space-charge clouds and charges accumulated along interfaces can be ‘frozen-in.

All types of internal polarization lead to surface charges which have the opposite polarity to that of the corresponding polarizing electrodes. Therefore hetero- charge formation should be, and is, a very general effect. 'Freezing' of the polarization is a rate effect which can be illustrated by a hydraulic analogue. Consider a water vessel with a tube through its bottom which serves as inlet when connected to the mains and as outlet when left open. The flow of water through the tube is controlled by a valve operated by a temperature- sensitive device which closes at very low temperature and opens at very high temperature. When the vessel is connected to the mains at room temperature water flows in very slowly and it would take an inordinately long time to fill the vessel completely. To do it rapidly we must raise the temperature until the valve opens fully. If we now wish to keep the vessel filled without keeping it permanently under pressure from the mains we must first reduce the temperature to a sufficiently low value and thus close the valve. Only then can we disconnect the mains and leave the end of the tube open without the risk of quickly losing all the contents.

5. CHARGES, FIELDS, AND CURRENTS

The charges residing in the electret produce an electric field. If the electret is placed between the electrodes of a capacitor, its field induces in the plates image charges which are equal and opposite to the surface charges of the electret. The density of the electrode charge, that is, the number of elementary charges per unit area, is proportional to the field strength and can be calculated from it. To determine the field we measure the charge of the electrode. This is done by lifting the electrode and transferring its charge to a second capacitor. Frequently a 'dissectible' capacitor is used whose upper electrode can be lifted by means of a mechanical or electro- mechanical system. Figure 2(a) shows a polarized dielectric placed within such a capacitor. With the switch S closed the electrode voltage is zero. The electric field is concentrated in the dielectric-electrode interface, the bulk of the dielectric is field-free. In figure 2(b) the switch has been opened and the electrode moved out of the reach of the electret's field which has receded into the bulk of the dielectric. With no field lines terminating in it the lifted electrode no longer contains any charge.

[1]Only an electret with dipole or interfacial polarization or carrying charges deposited from outside has surface charges in the strict sense of the word. In the other cases space charges are distributed unevenly throughout the volume of the dielectric. They can, however, be represented by fictitious surface charges insofar as one is focusing the external electric field. It is in this sense that one can always speak of the surface charges of the electret.

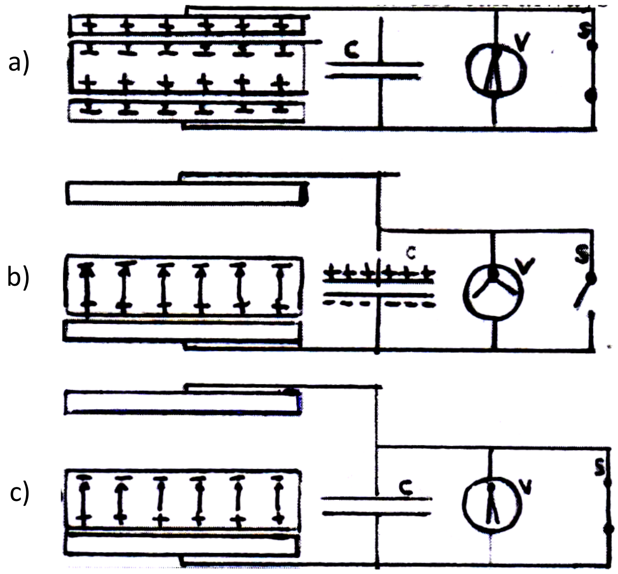

Figure 2 Measurement of surface charge with dissectible capacitor. (C. parallel capacitor, V. electrostatic voltmeter, S, switch) (a) Polarized dielectric between short-circuited capacitor plates. The field of the dielectric induces image charges in the plates.

(b) The switch has been opened and the upper electrode lifted. The induced charge of the electrode has been transferred to the parallel capacitor and charged it to voltage V.

(c) The switch has been closed again and the parallel capacitor discharged. Only the surface charges of the polarized dielectric are left.

Since charge is not lost, it must have been transferred to and charged the parallel capacitor. Its value is given by the product of voltage and capacitance of the system. In figure 2(c) the switch has been closed again and the capacitor discharged. When in this situation the electrode is placed again on top of the dielectric the original situation as shown in figure 2(a) is re-established. This cycle can be repeated indefinitely. The charged capacitor shown in figure 2(b) contains a certain amount of usable electrical energy; this has been generated at the expense of the mechanical work necessary during the lifting of the electrode to overcome the downward pull of the electric field. The stable electret is neither an energy source nor a battery, it merely produces a static electric field. The unstable electret can provide energy, but only at the expense of its polarization.

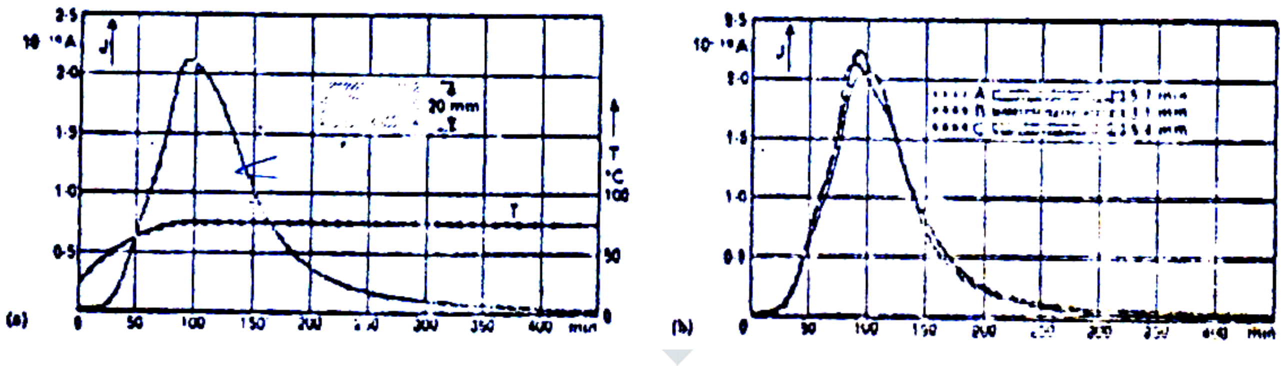

Figure 3- The sectioning experiment. (a) Thermally stimulated current as a function of time for original sample (b: Currents from sections of original sample. 7 indicales temperature. Insets show location and thickness of samples. The grass under the current curves are identical, thus all samples here the seme polenization (9). (Reproduced by courtesy of the American institute of Physics)

Every decrease of the internal polarization due to rotation of dipoles or recombination of ions within the dielectric frees image charges which flow back through the external circuit where a discharge current is recorded. Analogously every increase of polarization gives a charging current. Therefore build-up and dissipation of internal polarization can be investigated by means of current measurements.

Depolarization currents at room temperature are frequently too small to be easily measured. To increase them one must speed up the depolarization process by reheating the electret up to or above the polarization temperature. The ensuing current has been called the thermally stimulated current' since it is produced by heating without an external voltage [6]. Current peaks are observed at temperatures where dipole orientation or carrier release from traps is activated. The analysis of dipole structure and trapping characteristics by the method of thermal activation has developed into a separate area of research (7).

6. POLARIZATION AS A BULK PROPERTY

The bulk properties of the electret are investigated the most directly by the sectioning technique. But planning the surface of a polarized dielectric is a drastic operation. It generates new surface charges by triboelectric and breakdown effects which falsify the results of surface charge measurements made with the dissectible capacitor. Preferable is the measurement of thermally stimulated currents which records only internal polarization effects. The amount of charge transported by the depolarization current is equal to the heterocharge. It is determined by integrating the current time curve from the start of the reheating until the current has become negligible.

An unimpaired electret is reheated until it is completely depolarized; the ensuing current is measured and integrated Subsequently the electret is cut into sections which receive new electrodes and are polarized and measured under the same conditions as the original sample. In the case of a uniform dipole or interfacial polarization cut and uncut samples give the same charge: in the case of a space-charge polarization thinner sections release less charge than thicker ones and still less than the original sample (ef. figure 1). The experiment has been carried out with Carnauba wax (8).
It was found that very thin samples removed from the middle section of an electret gave as much charge as the original specimen, as shown in figure 3. The existence of a volume polarization was thus proved. The method does not distinguish between a dipole and an ionic effect. But Gemant has already pointed out [3] that the dipole moment of Carnauba wax is too small to account for the extremely high values of the electret charge. One must therefore seek the explanation in an ionic effect connected with carrier trapping [9]

An alternative to the sectioning technique is the non- destructive testing method of potential probes by which the distribution of the electric field within the electret is determined. A non-uniform distribution, where the field is high near the electrodes and low in the centre, indicates the existence of space-charge clouds. Evidence for such a distribution has also been reported [10].

7. THE POLARITY REVERSAL

The homocharge is due to surface effects and external polarization. While the electret is polarized the density of the charges facing each other across the dielectric- electrode interface increases steadily. Eventually the electrical field between them becomes high enough to enforce breakdown. Charges are transferred from the electrodes to the surfaces of the dielectric where they are trapped; coming from the polarizing electrodes they constitute the homocharge. This mechanism keeps the interface field below a critical level. After the surface breakdown the dielectric houses charges of opposite polarity which partially compensate each other and whose sum determines the net surface charge [11].

When at the end of the forming period the voltage source has been disconnected and the electrodes short- circuited the heterocharge still prevails over the homo- charge. But the decrease of the internal, dipole or ionic, polarization, which even at low temperature always follows the removal of the polarizing field, reduces the amount of the heterocharge. The net surface charge therefore also decreases; it becomes zero when the heterocharge just balances the homocharge and sub- sequently increases in the opposite direction because now the homocharge predominates. A steady state is finally reached where the electret has a net homocharge. This is shown schematically in figure (4)

8. THE STABILITY OF THE ELECTRET

In the steady state, with short-circuited electrodes, the electric field in the bulk of the dielectric is too small to cause any significant transport of charge carriers, while the interface field is not high enough to enable charge carriers to cross the energy barrier separating dielectric and electrodes.

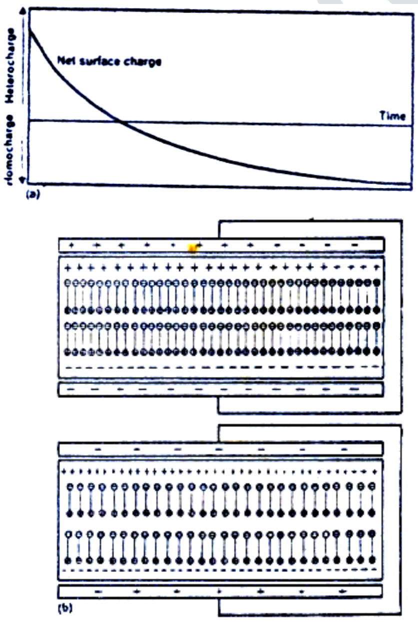

Figure 4 (a) Polarity reversal: Net surface charge of an electret as a function of time. (Al zero time the electrodes were short-circuited).

(b) Polarity reverset: Charge distribution for slectret with dipole polarization before (top) and after (bottom) polarity reversal.

To simplify one might say that the charge carriers constituting the homocharge stick to the surface of the dielectric because they cannot do otherwise. The situation is changed when one of the electrodes is re- moved and the electret left uncovered. The field disappears outside, reappears inside, and polarizes the dielectric ancw. Produced by a net homocharge it has the same direction as the original polarizing field and therefore builds up a heterocharge which reduces the net surface charge. The effect is reversible; if the site- trode is brought back into place and the short-circuit re-established, the internal field and the field-induced polarization disappear again and the surface charge recovers. The net charge of an uncovered electret is therefore always smaller than that of a shielded electret.

9. MAXIMUM CHARGE

All practical applications of the electret depend on the use of the electric field between the surface of th: dielec tric and an electrode. The field decreases with increasing gap width, falling off rapidly when the latter exceeds the thickness of the dielectric. Figure 5 gives the field strength as a function of gap width for some plastic foil electrets. (The decrease of the external field corresponds to an increase of the internal field.) The breakdown strength of air and other gases varies with electrode distance and configuration and with pressure; it is shown in figure 5 as a function of gap width for air at atmospheric pressure, assuming plane-parallel electrodes (Paschen curve). The curves 1-3 of figure 5 are every- where below the Paschen curve and are therefore stable. But curve 4 intersects it at two points; between them the field strength is not given by curve 4 but is equal to or lower than the values of Paschen's curve. The limitation of the field is brought about by breakdown which reduces the net surface charge of the dielectric. Using Paschen's curve it is possible to calculate the theoretical maximum values of charges and external fields for electrets of given dimensions. Since breakdown strength increases with pressure, hieher values ran be obtained by placing the electret in a pre chamber .

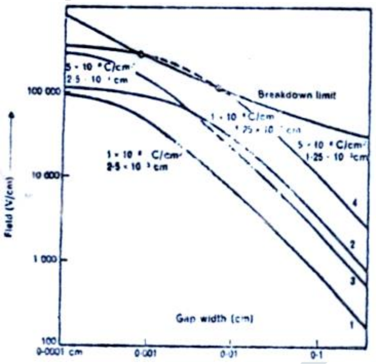

Figure 5 Breakdown Bmit (Paschan curve) and field as functions of gap width for various fel electrts with different surface charge densities (in C/cm) and thicknesses (in cm).

The thickness of the samples used in early work varied from a few millimetres to centimetres. Recent work with plastic electrets has been mostly done with foils less than 0.1 mm thick. Forming fields of 1o kV/ cm give surface charge densities up to 10^{-7} coulonih/ cem', corresponding to about 10^{+12} elementary charges on cach square Centimeter. About one moiceuk in to must then be charged. How well the electest kreps its charge depends very much on storage conditins. An unshielded electret kept in a hot atmosphere with a high moisture content performs worse than one kept dry at low temperature, between short-circuited electrodes, it has been estimated that the same plastic electret which completely un- shielded at 25°C and low buniciity would keep its charge for 200 years, might Inse it in two years at 50°C and 99 per cent relative humidity. These are not ultimate values. Improved materials now allow the manufacture of electreis whose durability under service conditions fulfils all practical requirements.

10. APPLICATIONS

Many proposals have been made for the use of electrets in electrostatic measuring instruments, electrostatic voltage generators, piezoelectric devices, air filters, radiation dosemeters, electrophotography, prosthetic devices, memory devices, and microphones. Electret microphones are now commerciaily produced by the Sony Corporation in Japan. Hasic research and develop ment work has also been dout at Bell Research Labora tories in the USA and Northern Electric, Canada and elsewhere.

The performance of the electrect microphone as a high- Edelity instrument is as good or better than that of the condenser microphone. it does not need tie separate battery of about 140 V necessary to energize the latter. The small dimensions of the microphone cartridge, >5 mm in any direction, and use of integrated circuitry facilitate miniaturization of the equipment. The low internal and mechanical noise level enables the micro- phone to be incorporated in the chassis of tape recorder.

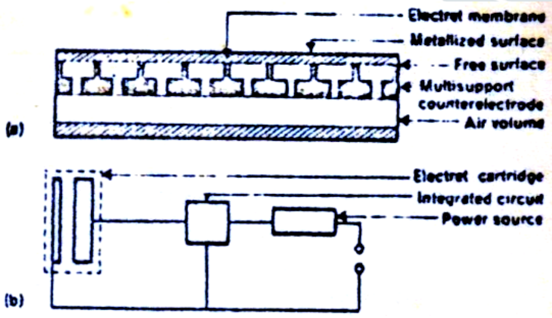

Figure 6 (a) Electret microphone;

(b) block diagram of circuit

An electret microphone is shown schematically in figure 6(a). The sound-sensitive element is an externally metallized and grounded plastic electret membrane about o.o1 mm thick. The oscillations of the electric field paralleling the vibrations of the membrane induce signals on the back-plate which are amplified. The same system, operating in the reverse sense, functions as a loudspeaker. Figure 6(b) shows a block diagram.

Attempts have been made to use electrified polymer as blood-compatible materials in prosthetic devices (12). The blood components which are likely to cause clotting in contact with the plastic tubing used to replace arteries, in particular the platelets, are negatively charged. For platelets charge densities of about $5x\ 10^{12}$ electronic charges/cm^2 have been reported; similar values can be obtained with electrets(13). A negative surface charge of the inner walls of the tubes which are used as inserts and are in contact with the blood flow should prevent or at least reduce platelet deposition and thus help to prevent clotting. Experiments in vitro have been inconclusive, but in vice experiments have given encouraging results [14]. Thus a wide and rewarding area of research remains.

11. REFERENCES

[1] Heaviside, Oliver. Electrical Papers, 1. p. 488. Macmillan. London, 1892.
[2] Eguchi, M. Proc. phys-moth. Soc. Japan, 1, 326, 1919: Phil. Meg-49. 179. 1925.
[3] Gemant, A. Phil. Mag. 30, 999. 1935.
[4] Idem. Physics Today, 1, No. 3. 8. 1949.
[5] Mikois, 5. 2. Pl. 33, 475- 1925.
[6] Bucci, C. and Fieschi, R. Phys. Rev. Lett., 13, 16, 1964.
[7] Mascarenhas, S. Radiat. Ef (G.B.). 4. 263, 1970.
[8] Grow. B. and de Moraes, R. J. J. chem. Phis.. 34. 2001, 1962.
[9] Gerson, R. and Rohrbaugh, J. H. Aid.. 33. 1381, 1955.
[10] Antenen, K. 2. angen. Math. Phys., . 478, 1955.
[11] Gros, B. Phys. Rer, 66, 26, 1944: J. Chem. Ph., 17, 866, 1949.
[12] Donelan J.M., LiQ., Naingv., Hoffer J.A., Weber D.J., and Kuq A.D., B Biomechanical energy harvesting : Generating electricity during walking with minimal user effect [Science, Vol, 319, pp.807-810] (2008).
[13] Bush S.B. Power source Scandenges from environment, electrow, weekly, p.3, Feb. 9 (2005).
[14] Zhong J., Zhong Q., Fan F., Zhang Y., Wang S, Hu.B., Lin wang Z., and Zhou, J., Finger typing driving turboelectric Nano generator and its use for instantaneously lighting up lads. Nano energy (2012).