

# What is TSC?

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## Technical Background

Unlike metals or ordinary semiconductors, insulators can retain a net space charge for long periods of time, which in some cases may be many weeks, even years. The amorphous or semicrystalline polymers used as insulation in a great variety of electrical systems have very high dc resistivities and are especially prone to accumulate space charge. The presence of space charge can drastically reduce the breakdown strength. It can be very important for the efficient operating of electrets, but it is considered undesirable in electrical insulation. In either case, it is important to be able to characterize a material with regard to its propensity to accumulate space charge.

The charging of a polymer can be measured in several ways. Some new methods just being developed, such as thermal pulse, acoustic pulse, and shock wave analysis, have generated a great deal of excitement. The Thermally Stimulated Current, TSC, (or perhaps more properly, the Thermally Stimulated Discharge Current, TSDC) is a somewhat older method and is most useful for measuring charge concentrations at or close to the surface of the dielectric. However, it also provides a handle on the propensity of an insulating polymer to pick up charge. The background for this technique is covered in this article. It will be followed by examples of application of the TSDC method in a future article.

Historically, the TSC technique was first demonstrated by Frei and Groetzinger in 1936 [1]. They measured the discharge current of an electret between two electrodes connected to an ammeter as a function of temperature. The first theoretical basis for the TSC phenomena was established in 1964 by Bucci and Fieschi based on their work on point defect dipoles in ionic crystals [2]. Since the mid-1970s the TSC technique has become a popular method for studying all the fundamental mechanisms of charge storage and release in semiconductors and insulators [3-6].

When a solid dielectric is subjected to an external electric field, electric charge moves on and within the solid. A number of names are used to designate charges with special properties. *True* or *free* charges are con-

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trasted to *bound* or *polarization* charges. The former can be added to or removed from the dielectric, the latter cannot. *Surface* charge resides on the surface of the dielectric in contrast to *space charge* located within the volume of the material. *Homocharge* is charge located on or very close to the surface of the dielectric adjacent to a polarizing electrode of the same sign as the voltage on the electrode. *Heterocharge* has a sign opposite to the sign of the polarity of the polarizing electrode.

In the simplest case, the effect of the applied field is to polarize the material and thus separate positive and negative charges. Only surface bound heterocharges appear if the applied field is uniform throughout a homogeneous dielectric (plane parallel electrodes with a slab sample) no matter what may be the nature of the polarization (rotation of permanent dipoles, electronic and atomic induced polarization).

If there are ion pairs present in the polymer, the applied field will separate them. If their mobility is very limited, this will simply appear as additional atomic polarizability. However, were one or more of the ion mobilities appreciable, the ion would move toward the electrode of opposite sign. In time it would reach this electrode and its fate would depend upon the electrode characteristics. Were charge exchange impossible, the dielectric would accumulate a surface heterocharge. To the contrary, the ion might be neutralized and the dielectric would have picked up excess true charge when there was no compensating reaction at the other electrode.

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The applied field may also transfer free charges onto and into the dielectric. Townsend breakdowns in the surrounding atmosphere (for imperfect electrode-dielectric contact) and corona discharges can deposit both ions and electrons on the surface. Ion and electron irradiation can similarly add charge to the dielectric. Ions, even very energetic ions, are unlikely to have much range in solids and so will almost always constitute free surface charges. Energetic electrons, on the other hand, can penetrate far into the dielectric and become trapped as a free space charge.

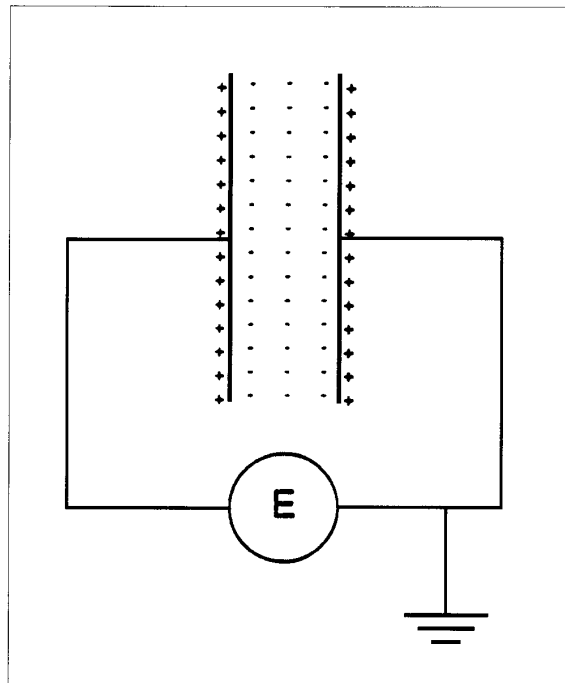
In electrical insulation the most important source of excess charge is undoubtedly that due to hole and/or electron injection at the electrode-dielectric interface. The injection currents may be due either to quantum mechanical tunneling or the thermally assisted Schottky emission. In either case one does not expect any true voltage threshold. The injection currents are typically exponential in the applied voltage and are, therefore, extremely small for normal operating voltages in electrical insulations. However, the voltages are applied for very long times, and appreciable space charge can accumulate in the insulating dielectric. This can be true even for ac voltages if the electrodes are not symmetric. Under conditions of injection, the charge carrier concentrations may greatly exceed the equilibrium concentrations. Charge carrier trapping on localized states may therefore proceed quite rapidly. The trapping states may be associated with the amorphous state of the polymers or with imperfections and impurities or with the presence of interfaces in heterogeneous materials [7]. The release of the trapped charge is almost always thermally activated and at the temperature of injection may be extremely slow. In this way, an immobile free, space charge is built up in the dielectric. This charge, under favorable conditions, may be of the same order of magnitude as the charge located on the polarizing electrodes. In this case, the electric field within the dielectric will become highly non-uniform with the result that the ordinary dielectric polarization also becomes non-uniform.

The objective of the TSC measurements is to ascertain the state of charge of the dielectric produced by an applied electric field. The sample is usually prepared in the form of a thin film. Metal electrodes are attached to the large plane surfaces. Evaporated metal electrodes are to be preferred. Pressed electrodes can be successfully used if a thin film of grease or oil is used to eliminate air gaps between the metal-dielectric contact. *Silver paint* is always to be avoided since the organic carriers of the metal particles may attack the polymer.

Generally the experimental procedure involves the following steps [8].

1. Applying a dc voltage,  $V_p$ , at a starting temperature,  $T_p$  (the sample is said to be poled);
2. Cooling under this voltage to some lower temperature,  $T_0$ ;
3. Holding the sample at  $T_0$  for some time to eliminate transients;
4. Changing the voltage at  $T_0$  to another voltage,  $V_d$  (which may be zero);
5. Placing an electrometer, set to measure small currents, in series with the sample;
6. Measurement of the current generated by the relaxation of the charged dielectric as a function of temperature, which is programmed to rise linearly in time.

In the first step the dielectric is charged. In the second step the charges are frozen to prevent relaxation. In the last step, the charged dielectric relaxes as the temperature increases. Relaxation processes that become possible at various temperatures are evidenced by peaks in the discharge current. It is important to remember that the TSC measurement does not directly measure the charges on and within the dielectric. As the charged state of the dielectric relaxes, the compensating charges held on the electrodes by the charges on, and in, the dielectric move from the electrodes and may pass



**Fig. 1. The discharge of a uniform distribution of injected space charge during a TSC measurement. In this case the electrometer, E, will indicate zero current at all temperatures no matter how large the initial concentration of space charge might have been.**

through the electrometer and be recorded. Fig. 1 shows a dielectric uniformly charged with an excess negative free space charge. If the electrodes are exactly the same, as this charge relaxes, equal amounts of negative charge will move to the two electrodes and no current will pass through the electrometer. Thus the interpretation of TSC results can be quite complicated. Systematic variation of the poling voltage, poling time, and poling temperature will be required if the true state of the charged dielectric is to be determined.

By adjusting the bias voltage, two different types of TSC techniques are obtained: Thermally Stimulated Depolarization Current (TSDC) and Thermally Stimulated Polarization Current (TSPC). In TSDC,  $V_p$  is not zero and  $V_d$  is zero, so that the current peaks are observed during the thermally activated transition from the polarized state to the equilibrium state. Most of the TSC data reported have been obtained by this technique. In TSPC, however,  $V_p$  is zero and  $V_d$  is not zero, so that the current peaks superimposed onto the normal dc conduction current are obtained as a result of the opposite process, i.e. thermally activated transition from the equilibrium state to the polarized state. In general, where both  $V_p$  and  $V_d$  are unequal to zero, the current observed is obviously governed by the combined effects of polarization and depolarization mechanisms.

The principal concern of TSC research is to study the charge decay as a function of temperature. In the process of heating a polarized sample up to or above the polarization temperature, the release of charges takes place as a function of temperature and the attendant discharge becomes measurable and gives rise in the external circuit to a current which first increases with temperature, and then decays when the supply of charges is depleted. A current peak thus will be obtained at a temperature where dipolar orientation, ionic migration or carrier release from traps is activated. As the total polarization usually arises from a combination of several individual effects with various relaxation times, a complete picture of the temperature-dependent relaxations will, in principle, be obtained.

In the case of polymers, the release of charges can occur by thermal motions of polymer molecules and/or chains, so that the peaks in a TSC thermogram can be considered the same as those measured by mechanical or dielectric relaxation techniques. However, because of different experimental principles associated with each of these techniques, the direct comparison of the TSC thermogram with the dielectric or mechanical thermogram can't be accomplished unless the latter are obtained at a very low frequency corresponding to the so-called "equivalent frequency" of the TSC method. The equivalent frequency of TSC measurements represents the frequency at which AC experiments should be

performed in order to obtain a loss peak having the same peak maximum temperature as the TSC method, and can be estimated by correlating the heating rate and AC frequency [9]. For an Arrhenius-type relaxation involving a constant activation energy, the equivalent frequency can be expressed as Eq (1).

$$f_e = \frac{\omega}{2\pi} = \left( \frac{1}{2\pi} \right) \left( \frac{R_h E}{k T_m^2} \right) \quad (1)$$

while, for a WLF type relaxation,

$$f_e = \left( \frac{1}{2\pi} \right) \frac{R_h U_1 U_2}{(U_2 + T_m - T_g)^2} \quad (2)$$

where  $f_e$  = equivalent frequency

$\omega$  = angular velocity (rad/sec)

$R_h$  = heating rate (K/sec)

$E$  = activation energy (eV)

$k$  = Boltzmann constant (eV/K)

$T_m$  = maximal temperature (K)

$U_1, U_2$  = universal constants (K)

$T_g$  = glass transition temperature (K)

Substituting the typical values of the TSC parameters, these equations lead to  $10^{-2}$ – $10^{-4}$  Hz. In the case of polyethylene, the equivalent frequency,  $f_e$ , is about  $10^{-3}$  Hz with  $R_h = 0.07$  K/sec. A TSC method, therefore, leads to a better resolution of the different relaxation processes than the dielectric loss method ( $1 - 10^{12}$  Hz), and is considered to be well suited to the study of the relaxation of polymers [10].

As mentioned, the polymer sample becomes an electret by the poling and subsequent cooling processes. The dipole moment is the sum of molecular dipoles produced by displaced charge that is intrinsic to the polymer and the electrons and/or holes injected into the polymer from the electrodes. Compensating charges are present on the metal electrodes. As the temperature is raised the dipoles and the charges in the polymer become free to move. Correspondingly, the compensating charge on the electrodes also moves. If this charge passes from one electrode to the other, it passes through the electrometer and is recorded as the TSC. In this case, the direction and amount of charge flow determine the polarity and magnitude of the resulting TSC. The positive polarity of the TSC is defined as the direction in which the electrons are injected from the electrode (measuring electrode side) to the sample.

The negative polarity is defined as the direction that the electrons are released from the sample through the electrode (again measuring electrode side) to the electrometer. Generally, the positive polarity is defined as a charging direction and the negative polarity as a

discharging direction. Large thermally stimulated currents reflect large readjustments of charge within the polymer.

Not all space charge motion within the polymer will give rise to a TSC. For example, an injected electron may simply move back to the electrode from which it was injected, cancel the compensating positive charge on this electrode and never produce any signal in the electrometer connected between the electrodes. Thus the measured TSCs do not always correlate in a characteristic way to the internal charges (which reside in the bulk of polymer). Often a single TSC result does not provide enough information to predict the internal charges in the polymer. Therefore, a series of experiments varying the experimental variables is required for understanding the internal charges. Qualitatively one is certain that large thermally stimulated currents are indicative of large readjustments in the positions of charges in the polymers.

### Effect of Metal Contacts

Generally the TSC is affected by the nature of the metal polymer contacts which, in two extremes, may be ohmic or blocking. Relative work functions and affinities may, therefore, play a role in shaping the  $i$  vs  $T$  curve. The work function of a metal is defined as the energy required to remove an electron from the metal. The presence of oxides and other impurities at the interfaces can also be important since they will influence the surface charge distribution. Differences in the TSC results using different metals are expected. The transfer of electrons or holes from a metal to an insulator depends on the work function of the metal. This difference is probably the reason that electrical tree initiation in polyethylene has been observed to be a function of the electrode material [11]. It has also been reported that the nature of the TSC depends on the metal used for the electrode [12]. Because true work functions are obtainable only under carefully controlled conditions, the differences observed for TSC measurements can probably be only approximately correlated by the work functions found in the literature for the metal used.

The amount of injected electrons and thus the magnitude of TSC peaks associated with the electron injection will be governed by the work function. The electrode metal with the lower work function results in the injection of more electrons into the sample. It is generally believed that the peak current increases linearly with decrease in work functions and the peak temperature is more or less independent of the work function. On the other hand, the magnitude of TSCs of the peaks associated with the dipolar orientation is independent of the work function simply because it does not involve the injection of electrons.

### Transitions in Polymers

Amorphous polymers undergo several transitions, which include the glass transition from a glassy state to a rubbery state, and the secondary relaxations in the glassy state. In measurements of mechanical loss tan-

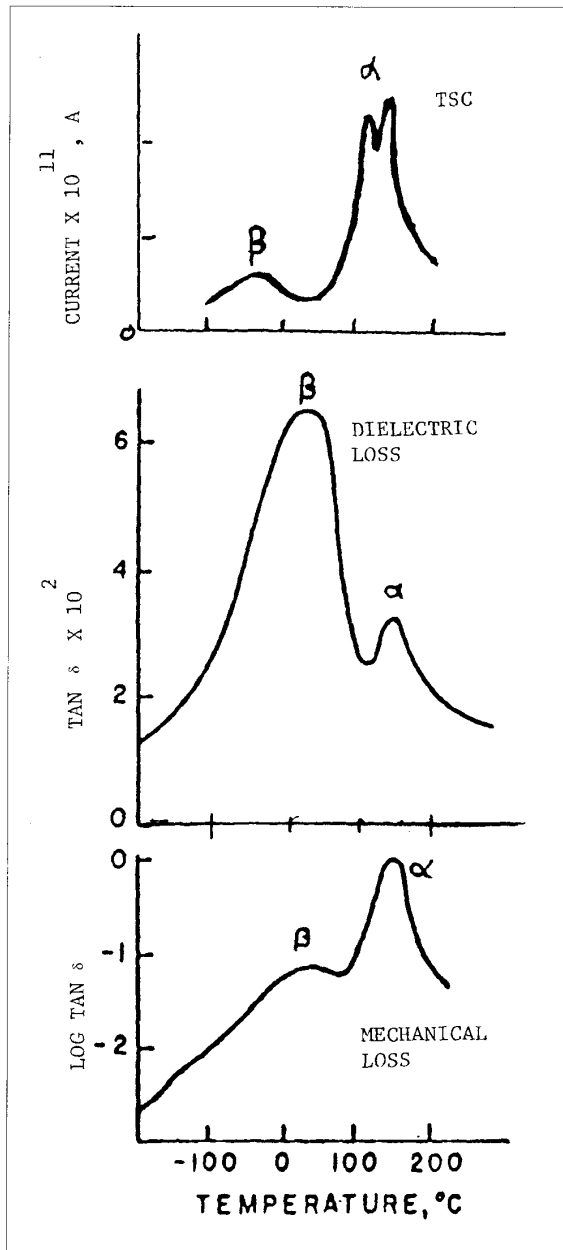


Fig. 2. A comparison of dielectric, mechanical loss tangents, and thermally stimulated currents of syndiotactic PMMA. The curves describing mechanical and dielectric loss were taken from Aklonis and MacKnight [40]; the TSC results are those of Gourari et al. [41].

gent, dielectric loss tangent and TSC, these transitions appear as peaks. The peaks, following a conventional scheme, are labeled by  $\alpha$ ,  $\beta$ ,  $\gamma$  and so on in order of decreasing temperature. In amorphous polymers, the  $\alpha$  peak corresponds to the glass transition ( $T_g$ ), arising from the micro-Brownian motion of the whole main chain, and characterizes the mechanical properties of polymers. The  $\beta$  peak, which arises from the secondary relaxation in a glassy state, is inherently broad. The mechanism of a  $\beta$  relaxation may be one of several different types depending on the nature of the dipole group concerned and its position on the polymer chain. Among the most important mechanisms are the rotation of a side group about a C—C bond, conformational flip of a cyclic unit, and local motion of a segment of the main chain.

A typical dynamic relaxation phenomena for an amorphous polymer is that for poly(methyl methacrylate) (PMMA). Fig. 2 shows a comparison between the dielectric loss tangent and mechanical loss tangent in PMMA as a function of temperature. Over the temperature range of  $-200$  to  $160^\circ\text{C}$ , the mechanical and dielectric loss tangent shows two relaxation peaks labeled by  $\alpha$  and  $\beta$ , respectively. The peaks are located at almost the same temperature for both methods, at about  $50^\circ\text{C}$  for the  $\beta$  process and at about  $130^\circ\text{C}$  for the  $\alpha$  process. As described in an earlier section, the  $\alpha$  peak corresponds to the glass transition and is associated with the conformational motions of the whole main chain. The  $\beta$  peak, a secondary relaxation in a glassy state, has generally been associated with the motions of sections of the main chain or of a side group. The presence of a polar group determines the peak magnitude of the dielectric properties. Since PMMA has a predominantly nonpolar backbone with flexible polar side groups, the dielectric  $\beta$  relaxation is of much greater magnitude than the mechanical  $\beta$  relaxation, as shown in Fig. 2.

A TSC thermogram, on the other hand, shows somewhat different trends. First of all, owing to the low equivalent frequency, TSC peaks appear at much lower temperatures than usually found in dielectric and mechanical loss tangents. For example, TSC peaks have maximum temperatures of about  $-35^\circ\text{C}$  for the  $\beta$  process and about  $90^\circ\text{C}$  for the  $\alpha$  process, whereas mechanical and dielectric relaxation peaks occur at about  $50^\circ\text{C}$  for the  $\beta$  process and about  $130^\circ\text{C}$  for the  $\alpha$  process. Secondly, an additional peak, designated by  $\rho$ , appears in a TSC thermogram and is assigned to the motion of space charges. This peak can be observed above  $T_g$  in many polymers [7, 13-16]. In dielectric measurements the  $\rho$  peak replaces the conduction losses, which derive from the oscillatory motion of the carriers in the applied ac field. Naturally these losses do not show a peak but increase exponentially with

temperature. In a short-circuited TSC, the charges migrate in their own internal field. This self-motion of charges gives rise to a peak, because the number of charges stored is eventually exhausted.

That the  $\rho$  peak arises from the motion of space charges can be argued on the basis of several observations. One of these is the activation energy of the  $\rho$  peak. The activation energy of  $\rho$  peak agrees well with that of dc conduction. Another significant piece of evidence is that the  $\rho$  peak is strongly dependent on the electrode materials. Different electrodes probably cause different degrees of blocking owing to differences in their work functions. Generally it is believed that a metal with a low work function produces a high TSC.

The presence of nonpolymeric components, such as plasticizers or absorbed water, also may induce secondary transitions. A secondary transition peak due to absorbed water was detected using the TSC technique at about  $-120^\circ\text{C}$ , labeled by  $\gamma$  (Fig. 3).

In a partially crystalline polymer like polyethylene, where crystalline and amorphous phases coexist in the solid, the relaxation spectrum becomes more complicated. Apart from orientational processes of dipoles taking part entirely in the amorphous region, there are different mechanisms operating inside the crystalline domains and at their boundaries. Also, semicrystalline polymers exhibit secondary transitions above and below the glass transition temperature, whereas amorphous polymers exhibit them below the glass transition temperature. Those transitions observed above  $T_g$  in semicrystalline polymers are thought to be associated either with the motion of folded chains or with the motion of structural defects in the crystalline region. The same labeling can be applied to semicrystalline polymers. However, there is no correspondence of the identification of peaks between crystalline and amorphous polymers. Generally the peak identification should change with the structure.

It is usually possible to decide whether a given loss peak belongs to the amorphous phase or is connected with crystals by varying the crystallinity. Thus reducing the crystallinity, by rapid quenching from the melt, enhances the intensity of the peak assigned to a relaxation process originating in the amorphous phase. In the case of Nylon 6, the  $\gamma$  and  $\beta$  peaks remain with only minor changes, but the  $\alpha$  peak shows a big change with degree of crystallinity. Generally the peak temperature increases and the peak height increases with an increasing degree of crystallinity.

## TSC of Polyethylene

Polyethylene can be classified, depending on its density and chain structure, into four categories; Low Density Polyethylene (LDPE), High Molecular Weight

Polyethylene (HMWPE), High Density Polyethylene (HDPE), and Linear Low Density Polyethylene (LLDPE). Each type of polyethylene has a different density and chain structure and consequently different physical properties and uses. Each also is prepared by different polymerization techniques.

Dynamic properties of various polyethylenes are somewhat different because of differences in physicochemical variables such as density, molecular weight, branching, etc. Also, the interpretation of dynamic properties of polyethylene is quite controversial [15, 17-18]. Not only the interpretation of dynamic behavior but also the published data differ because of differences in instrumentation, experimental conditions, sample history, etc. It is, however, believed that polyethylene shows three relaxation or damping peaks over the temperature range of -140 to 100°C. As shown in Figs. 3 and 4, these are labeled by  $\alpha$ ,  $\beta$  and  $\gamma$  peaks in order of decreasing temperature. Fig. 3 shows dynamic mechanical loss tangents of various polyethylenes and Fig. 4 the TSC results of LDPE. As previously mentioned, the TSC technique gives the lowest peak temperatures; i.e., -180 vs. -110°C for  $\gamma$  peak, -25 vs. -20°C for  $\beta$  peak and 30 vs. 70°C for  $\alpha$  peak.

As shown in Figs. 3 and 4, dynamic properties of polyethylene by the TSC method are very similar to those by the mechanical method.

It is generally agreed that the  $\alpha$  peak, occurring above room temperature, is representative of the crystalline phase and originates from some type of motion in the crystals [19-25]. For example, the chains in the crystal are mobilized by chain rotation, translation, and/or twist. On the basis of the model compound ( $C_{94}H_{190}$ ) and its single crystals [22, 27], it has been demonstrated

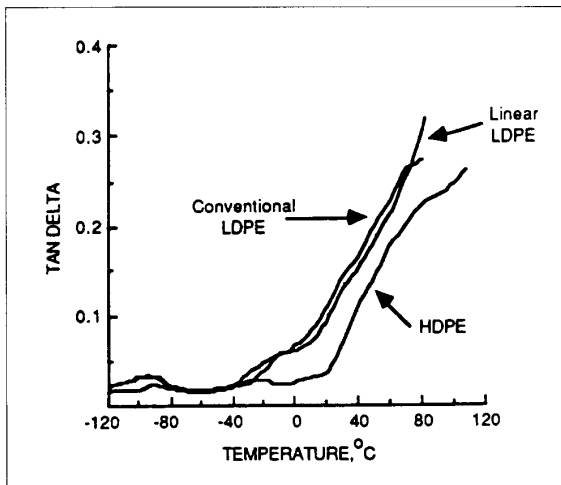


Fig. 3. Dynamic mechanical loss tangents of various polyethylenes [20]. Conventional low density polyethylene, high density polyethylene, and linear low density polyethylene as labeled.

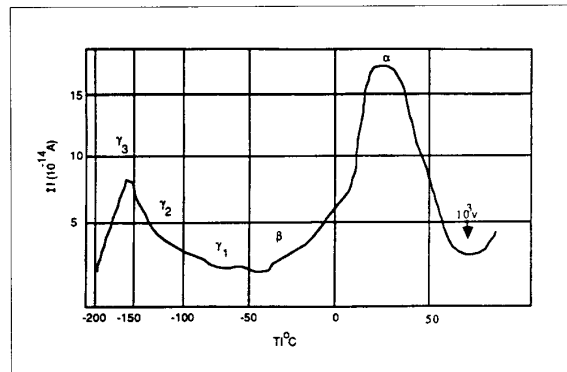


Fig. 4. Thermally stimulated currents of low density polyethylene [26]. Polarization condition: 2 min at 70°C (arrow), electric field strength  $10^3$  V/mm.  $\alpha$ ,  $\beta$ ,  $\gamma_1$ ,  $\gamma_2$  and  $\gamma_3$  designate the relaxation mode.

that the perfect crystal itself would not lead to an  $\alpha$  relaxation and that the fold surface is necessary for the occurrence of the  $\alpha$  process. However, the  $\alpha$  peak temperature does depend on the crystallite thickness, thicker lamellae having higher  $\alpha$  temperatures. Boyd [28] therefore proposed that the mechanical  $\alpha$  process occurs in the amorphous phase but involves the motion of the crystals. Specifically, the  $\alpha$  relaxation is due to the softening of the amorphous phase with a resulting increase in the crystallite mobility. Other models modify this picture slightly by associating the relaxation with the deformation of the interfacial regions (chain folds, loops, tie molecules) rather than the bulk amorphous phase. Many authors have reported the existence of at least two crystalline dispersion peaks in the  $\alpha$  relaxation region [22-24, 29-30]. The low and high temperature peaks are ascribed to interblock and to interlamella relaxation, respectively. The negative peak in the TSC curves at high temperature is, therefore, associated with the release of homocharges (space charge) and heterocharges from the crystals.

The  $\beta$  peak appears broad over the temperature range from -70 to 0°C. Its peak maximum is generally located near -20°C and its peak current has an order of  $-13$  ( $10^{-13}$  A range).

The true origin of the  $\beta$  relaxation is still unresolved. Usually single crystals of linear polyethylene do not exhibit a  $\beta$  relaxation, whereas a very small  $\beta$  peak is observed in bulk linear polyethylene containing an amorphous phase [22-23]. Also, the  $\beta$  peak is strongly dependent on the degree of branches in the polyethylene chain [31]. Therefore, the  $\beta$  relaxation is associated with the motion of the backbone, the branch points or crosslinks being fixed tie points for the chains in the amorphous matrix [29, 32, 33]. Also, polar groups such as C=O formed by oxidation are known to contribute to the formation of the  $\beta$  peak in polyethylene [34].

In addition to the debates on the mechanisms for the molecular relaxation, it has been a subject of controversy whether the glass transition temperature ( $T_g$ ) of polyethylene is equal to the  $\beta$  relaxation temperature [35]. In the past, the  $T_g$  of polyethylene was believed to be below  $-100^\circ\text{C}$  [36] at which the  $\gamma$  relaxation occurs. Recently the influence of physicochemical parameters on the  $\beta$  relaxation was explained in terms of  $T_g$ . In the case of polyethylene, the intensity of the  $\beta$  peak tends to increase with amorphous volume (e.g., by quenching and/or branching), and the temperature of the  $\beta$  peak increases with increasing molecular weight and is influenced by the type and amount of branching. These phenomena can't be explained if the  $\gamma$  relaxation temperature is considered to be equal to  $T_g$ , because the  $\gamma$  relaxation is associated with only short polymer segments. As previously mentioned, the glass transition is associated with the micro-Brownian motion of the whole chain in amorphous polymers. Also on the basis of the quantitative evaluation of the difference in heat capacity between crystalline and amorphous polyethylene, Wunderlich [37] proposed a  $T_g$  of  $-36^\circ\text{C}$ , which agrees well with the  $\beta$  relaxation temperature.

The  $\gamma$  peak appears as a broad peak over the temperature range of 5 to  $150^\circ\text{K}$ , with the  $\gamma$  peak maximum located near  $-93^\circ\text{C}$  with a peak current on the order of  $-14 (10^{-14} \text{ A range})$ , (about 10 times smaller than that of the  $\beta$  peak). The  $\gamma$  peak observed by the TSC technique is very complicated because it is composed of several small peaks, the origins of which are not yet known [37-39].

Usually the  $\gamma$  relaxation in polyethylene occurs below  $-100^\circ\text{C}$ . It has been generally agreed that the  $\gamma$  relaxation is associated with the motion of a short segment of three to four  $\text{CH}_2$  units in the amorphous phase and explained using a "crankshaft" mechanism, and that any polymer that has a series of at least three  $\text{CH}_2$  units may display a transition below  $-100^\circ\text{C}$ . Some controversy, however, exists about the origin of the  $\gamma$  relaxation. Illers [39] has argued that the  $\gamma$  peak is due to the amorphous fraction while Sinnott [22] and Hoffman et al. [23] propose that it is strictly due to the defects in the crystalline phase. The mechanism of Sinnott and Hoffman et al. is based on the similar occurrence of a  $\gamma$  relaxation in single crystals of linear HDPE and is assigned to the reorientation of loose chain ends (defects) in the polymer crystal. Also the  $\gamma$  relaxation temperature increases with the number of carbon atoms between the surfaces of the crystal, i.e., the fold length. Thus, thicker crystals of HDPE tend to raise the relaxation temperature relative to the thinner crystals of branched LDPE.

## Summary

TSC measurements can be used to study polarization and space charge injection in polymeric insulation. A dielectric sample is first polled and then allowed to relax by slowly raising its temperature. The currents released by these relaxations can be interpreted to provide information about the initial charged state and various relaxation phenomena in polymers. These results supplement those provided by mechanical and dielectric spectroscopy.

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**Dwight Damon** obtained his undergraduate training in physics from Amherst College. He received the M.A. and Ph.D. in physics from Purdue University, the latter degree in 1961. After nine years as a research scientist at Westinghouse Research Laboratories in Pittsburgh, Damon joined the physics faculty at the University of Connecticut. His research interests have been in solid state physics, specifically in the transport properties of solids at low temperatures and the electrical conduction in polymers.

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