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SPACE CHARGE AND ITS IMPACT ON DC BREAKDOWN OF POLYMERIC MATERIALS

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Abstract: The presence of space charge will lead to distortion of electric field distribution within the dielectric material, resulting electric field enhancement in certain region of the dielectric. The electric field enhancement could cause material degradation, even premature failure. In this paper the simulation of charge dynamics in polyethylene based on the observed negative differential mobility has been carried out using the bipolar charge injection model. Assuming that the maximum electric field governs the breakdown event in the material, the simulation results show that the applied electric breakdown strength is thickness dependent during a ramping breakdown test. The thickness dependent breakdown strength has been experimentally observed and widely reported in literatures but the mechanisms have never been fully explained. Our model indicates that the space charge formation and its movement within the material are responsible for the effect of sample thickness on electric breakdown. Accumulation of positive charge in the region near to the anode leads to a local high field, which may initiate the breakdown when it reaches the breakdown strength of the material. Our recent experimental observations of space charge dynamics up to breakdown in different thick samples strongly support the influence of space charge on electric breakdown.

1 INTRODUCTION

The effect of space charge on electrical performance of dielectric materials has been recognised for many years. The presence of space charge will lead to distortion of electric field distribution within the dielectric material, resulting electric field enhancement in certain region of the dielectric. The electric field enhancement could cause material degradation, even premature failure. The research on space charge has been intensified recently due to renewed interests in high voltage dc system. On the other hand, many observed anomalous phenomena [1] at high fields have been associated with the presence of space charge and its dynamics. Although the mechanisms of charge formation and its dynamics are still not fully understood, progress in space charge mapping in solid dielectrics over last three decades has revealed bipolar charge injection at high electric fields and the effect of charge dynamics on electric breakdown.

Zhou et al [2] have realized the importance of charge dynamics in the process of breakdown and proposed a dynamic electron trapping-detraping process in the material under the application of an electric field. It has been proposed that the conductive path (breakdown) occurs when a critical electron trap density is reached. This can only happens when the trapping rate exceeds detrapping rate. The model also predicts a threshold thickness below which no breakdown should take place because the electron detrapping rate is greater than trapping rate. However, there is not enough experimental evidence to support the existence of the threshold thickness.

Recently, characteristics of charge trapping and detrapping have been linked to the long term electrical performance of polymeric materials [3-4]. By assuming the existence of two trapping levels, it has been found that after ageing there are increases in both trap depth and number of traps. The increased trap depth is associated with chemical changes brought by ageing while a number of traps are related to the extent of the chemical change.

It is also clear from the literature review that thickness dependent dielectric breakdown is a common phenomenon when examining the short term electrical performance but the detailed mechanisms are poorly understood. Although attempts have been made to understand the phenomenon, all the proposed models lack creditable experimental support, therefore, are difficulty to relate to physical processes taking place in the material under higher electric fields.

2 NEW EXPERIMENTAL EVIDANCE FROM SPACE CHARGE MEASUREMENTS

Following significant progress in the development of techniques to measure space charge in solid dielectric, experimental data on charge dynamics in many materials under various field and temperature conditions are now available. The analysis of these results has helped us to get an insight of charge behaviours in terms of formation, transport, trapping/ detrapping.

2.1 Space charge injection

Charge formation in polymeric dielectrics has been generally considered from two sources, (i) ionisation due to additives/impurities, and (ii) charge injection from electrodes. Ionisation has been observed in crosslinked polyethylene, epoxy resin and some nanocomposites where by-products and impurities dissociate into either positive/negative ions or positive ions and electrons under the influence of the electric field. Charge injection occurs when the electric field at the electrode exceeds a critical value. It has been found that at low electric field, ionisation may dominate charge formation process; in the medium field range, both ionisation and charge injection may take place, resulting in a complicated charge dynamics. However, in the high field regime, charge injection from electrode is the main source of space charge in the polymeric materials. Figure 1 shows an example of charge injection in low density polyethylene (LDPE) when it is subjected to an applied electric field of 75 kV/mm.

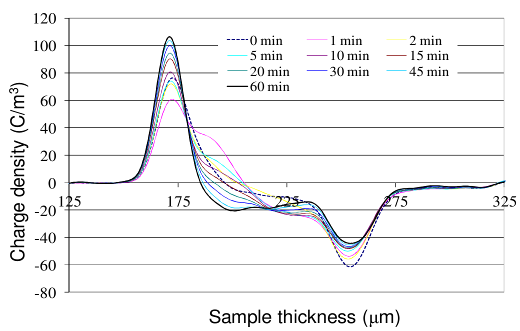


Figure 1: Space charge dynamics at 75 kV/mm in LDPE

It can be seen that charge injection from both electrodes occurs at high electric fields. The unsymmetrical characteristics of negative and positive charge indicate their different trapping/detrapping and transport features.

2.2 Space charge packet and Pre-breakdown

When the applied electric field is further increased, there is a possibility that charges may form a packet which moves across the sample towards the opposite electrode. A typical example is shown in Figure 2, where a positive charge packet is formed at the anode due to sufficient charge injection from the electrode to LDPE. The charge packet moves towards the cathode under the influence of the electric field. When it reaches the cathode the charge packet can move further into the electrode and the second charge packet develops. The latter is strongly dependent on the material and electrode. It has been confirmed [xx] that the formation of positive charge packet is caused by the negatively differential charge mobility.

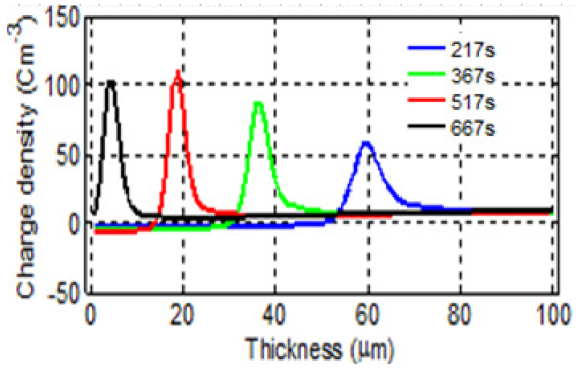


Figure 2: Charge packet and its dynamics in LDPE at 80 kV/mm

The electric breakdown has been linked with charge packets formed in the polymeric materials. One of them clearly demonstrates the space charge and breakdown as shown in Figure 3 [5].

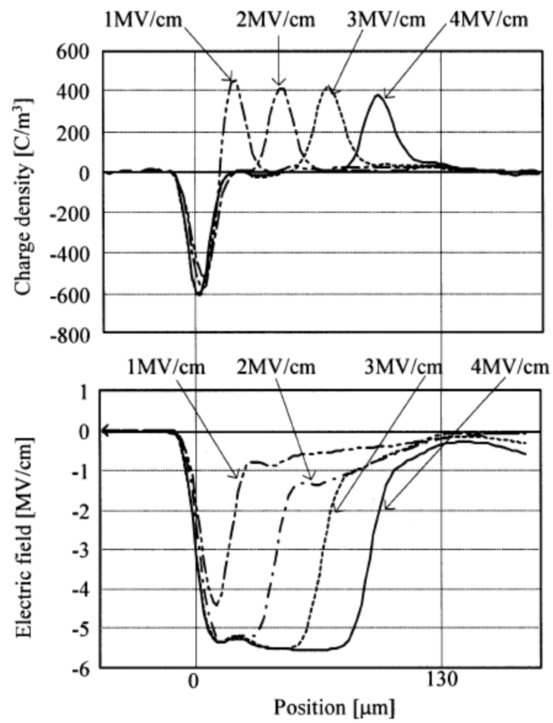


Figure 3: Space charge distribution (top) and its corresponding electric field distribution in LDPE at different applied fields [5].

Several constant high electric fields have been applied across LDPE samples. Positive charge packets have been formed and moved towards the cathode. However, it has been observed in this particular case, the packet charge stops at a different position in the LDPE film depending on the electric field applied. The higher the applied electric field, the shorter the distance that the charge packet travels before the breakdown occurs. This is clearly demonstrated in space charge distribution as shown in Figure 3. Another important observation is when the breakdown occurs the maximum electric field in the sample is almost same as shown in Figure 3 (bottom). There is no breakdown at an applied electric field of 100 kV/mm.

3 SPACE CHARGE BASED BREAKDOWN MODEL

3.1 Bipolar charge injection model

The bipolar charge injection model is commonly employed to simulate space charge dynamics. The charge transportation in an insulating material is essentially governed by the set of basic equations below. These equations describe the behaviour of charge carriers in the bulk over time and the position dependent total flux $j_C(x,t)$ without charge diffusion.

$$j_C(x,t) = \mu n(x,t)E(x,t) \quad (1)$$

$$\frac{\partial n(x,t)}{\partial t} + \frac{\partial j(x,t)}{\partial x} = s \quad (2)$$

$$\frac{\partial E(x,t)}{\partial x} = \frac{\rho(x,t)}{\varepsilon} \quad (3)$$

where μ is the mobility of the carriers, n is the density of the mobile species, j is the current density, x is the position coordinate in the thickness direction, t is time, s is the source term, ε is the permittivity, and ρ is the net charge density.

In this bipolar charge model, the charge carriers are injected from the electrodes by either Schotthky mechanism or tunnelling mechanism, and consequently the charge carriers overcome/through the potential barrier at the interface between the electrode and the sample. After injection into the bulk, carriers travel to the counter electrode with an effective mobility by the local field, which consists of the applied field and the field produced by space charge. Because some carriers are trapped in the deep trap center without de-trapping, the total amount of mobile carriers decreases. Both positive and negative carriers may be prone to recombination with their opposite carriers.

3.2 Space charge based breakdown model

Based on these strong experimental evidences, we propose the following electric breakdown model. The breakdown under dc conditions is governed by space charge and the injected charges are responsible for electric field enhancement in the bulk and once the local field reaches the "intrinsic breakdown strength" of the material breakdown occurs. The bipolar charge injection at the two electrodes is governed by the Schottky injection process. Once injected, they can be described by the bipolar charge transport process with trapping and recombination in the material [6], i.e. governed by equations (1) to (3).

The dynamics of charge will influence the electric field distribution. The local electric field can be considered coming from the two components, i.e. the applied electric field and contribution from space charge.

$$E_{loc} = E_{appl} + E_{sc} \quad (4)$$

Once this local field reaches the "intrinsic breakdown strength" of the material, the dielectric will break down. Based on the results from [5] E_{loc} is set to 550kV/mm for low density polyethylene.

4 SIMULATION RESULTS

To simulate bipolar charge injection and charge dynamics in LDPE, the model proposed in [6] is used. The details are shown in Figure 4.

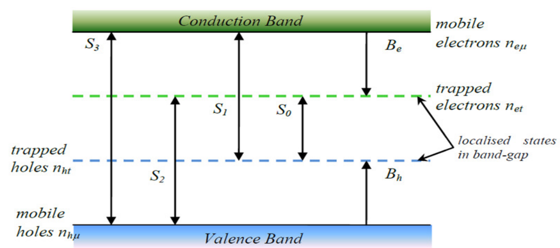


Figure 4: Schematic diagram of the conduction, trapping and recombination [6]

The boundary condition is defined by the Schottky injection [ref] at both electrodes,

$$j_e(0,t) = AT^2 \exp\left(-\frac{e w_{ei}}{kT}\right) \exp\left(\frac{e}{kT}\sqrt{\frac{eE(0,t)}{4\pi\varepsilon}}\right) \quad (5)$$

$$j_h(d,t) = AT^2 \exp\left(-\frac{e w_{hi}}{kT}\right) \exp\left(\frac{e}{kT}\sqrt{\frac{eE(d,t)}{4\pi\varepsilon}}\right) \quad (6)$$

where $j_e(0,t)$ and $j_h(d,t)$ are the fluxes of electrons and holes at the cathode and anode respectively; T is the temperature; $A = 1.2 \times 10^6 Am^{-1}K^{-2}$ is the Richardson constant; w_{ei} and w_{hi} are the injection barrier for the electrons and holes.

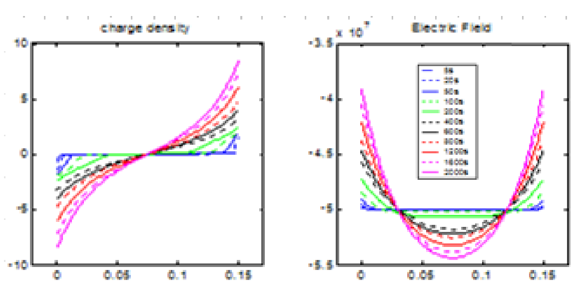


Figure 5: Space charge and electric field distribution in LDPE at an applied voltage of 7.5 kV

In our initial attempt, the parameters from our previous simulation [7] were adopted as shown in Table 1. Figure 5 shows the initial simulation result when the mobility for both electron and hole is set as $9 \times 10^{-15}\ m^2V^{-1}s^{-1}$. The more detail about the simulation can be found in [7].

Table 1: Parameters for space charge simulation

Symbol	Description	Value	Unit
dx	width of every element	1e-6	m
ε	permittivity of sample	2.3x8.854e-12	F/m
m	number of element	100	
d	width of sample	100e-6	m
V	applied voltage	Depends	V
e	the elementary charge	1.602e-19	C
ω_{pi}	injection barrier of holes	1.14	eV
ω_{ni}	injection barrier of electron	1.15	eV
k_B	Blotzmann's constant	1.3807e-23	J/K
T	temperature	295	K
A	Richardson-Dushman constant for free electors	1.2e6	A $m^{-1}K^{-2}$
$n_{h\mu}$	charge density of mobile holes		C/m^3
$n_{e\mu}$	charge density of mobile electrons		C/m^3
n_{ht}	charge density of trapped holes		C/m^3
n_{et}	charge density of trapped electrons		C/m^3
S_0	coefficient of trapped holes and trapped electrons	4e-3	$m^3s^{-1}C^{-}$
S_1	coefficient of trapped holes and mobile electrons	4e-3	$m^3s^{-1}C^{-}$
S_2	coefficient of mobile holes and trapped electrons	4e-3	$m^3s^{-1}C^{-}$
S_3	coefficient of mobile holes and mobile electrons	0	$m^3s^{-1}C^{-}$
B_h	coefficient of holes trapping	7e-4	s^{-1}
B_e	coefficient of electrons trapping	7e-3	s^{-1}
n_{0ht}	trap density of holes	10	C/m^3
n_{0et}	trap density of electrons	100	C/m^3

It has been found that charge packet is closely associated with the hole mobility. Recent experiment [8] has revealed that hole velocity is electric field dependent as shown in Figure 6. The hole mobility derived from the relationship shows a negatively differential field dependence. The observed charge packet can be numerically obtained as shown in Figure 7 [9].

For dc electric breakdown, one of the observed phenomena is the breakdown depends on sample thickness, i.e. the thicker the sample the lower the breakdown field. The exact mechanism for this is unknown but the phenomenon has significant impact on insulation design. If the proposed space charge based breakdown model is feasible it should be able to reveal the phenomenon. The simulations below have been performed on low density polyethylene with a thickness range from 100 to 200 μm. To reduce the simulation time we set the breakdown strength of the material to 300 kV/mm, i.e. when the internal local field in the material reaches 300 kV/mm, the simulation stops. Then the applied electric field is obtained based on the applied voltage for a particular sample thickness.

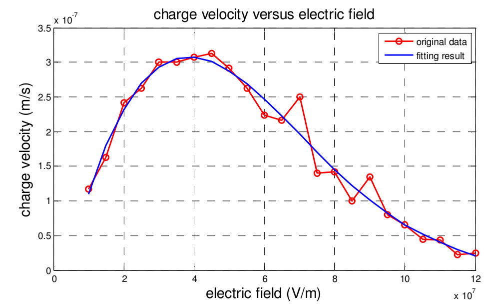


Figure 6: Field dependent velocity of positive charge carriers.

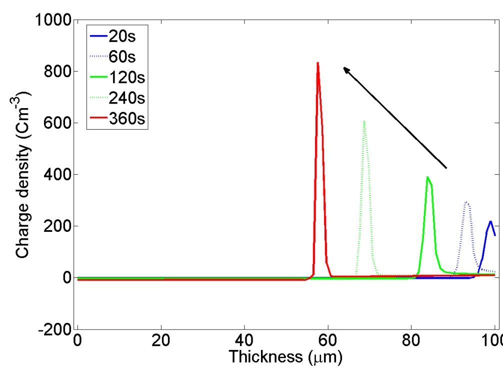


Figure 7: Simulated space charge profiles at an applied electric field of 100 kV/mm

Figure 8 shows the simulated results when the applied voltage is raised at a ramping rate of 200 V/s. It is obvious that the breakdown strength decreases with sample thickness. It is also noticed that the reduction depends on a number of factors such as the onset electric field, charge carrier velocity, trapping/detrapping coefficients, voltage rise rate etc. Figures 9 and 10 show the influence of the predefined local electric field and voltage rising rate on the applied breakdown strength.

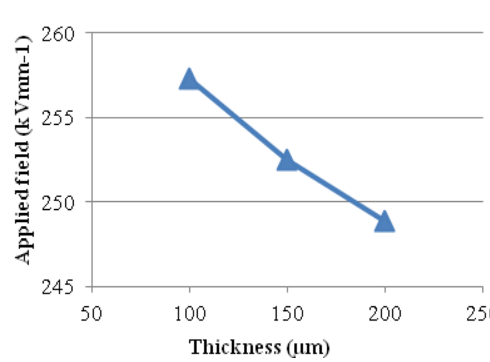


Figure 8: Effect of sample thickness on electric breakdown strength of polyethylene.

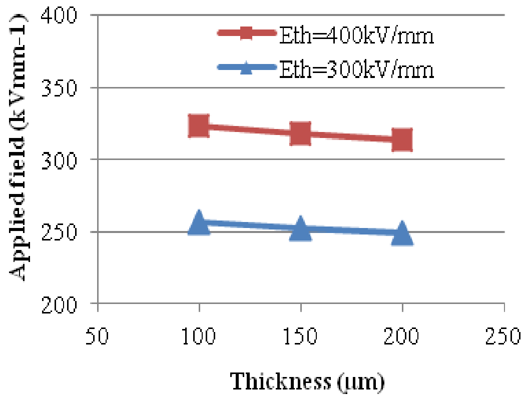


Figure 9: Influence of the predefined local breakdown strength

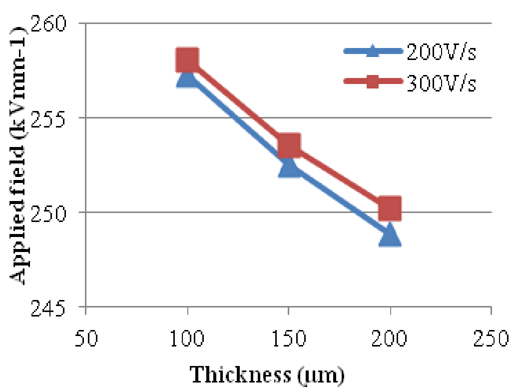
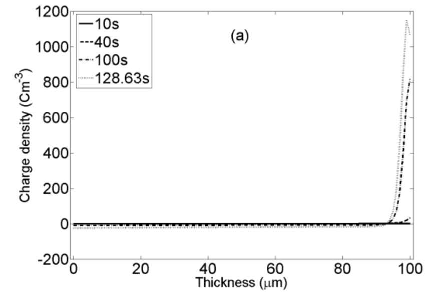


Figure 10: Influence of voltage rising rate

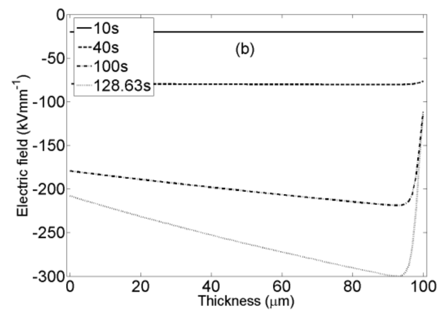
In addition to the correct simulation of thickness dependent dielectric breakdown, the new model also provides charge dynamics and electric field distribution in the material during and up to breakdown as shown in Figure 11 [10]. This type of detailed information can not be obtained through the experimental techniques at the moment but is critical for the understanding of electrical breakdown mechanisms. It is anticipated that if there are more experimental evidences on charge dynamics in the material, the accuracy of the above model can be further improved.

5 EXPERIMENTAL VERIFICATION

To verify the space charge based breakdown model, space charge measurements under ramping dc conditions have been performed up to breakdown on low polyethylene (LDPE) film with a thickness of about 0.10 or 0.18 mm respectively. Figure 12(a) shows the electrode configuration to measure the space charge distribution up to the breakdown. A 10 mm diameter gold electrode was formed on both sides of the LDPE film. An acrylic frame adhered to the film surface on one side. A semi-conducting electrode and a steel ball were installed on the gold electrode, and these were fixed using an epoxy resin to prevent a surface flashover.



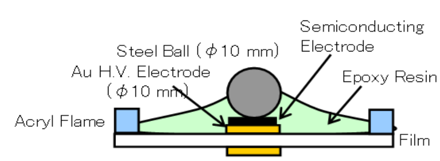
(a) Charge dynamics up to breakdown



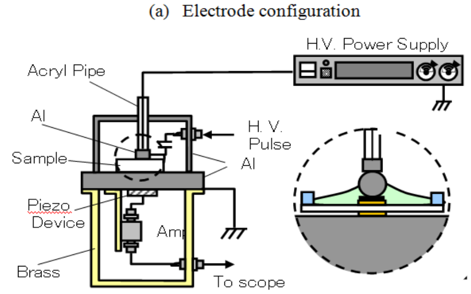
(b) Electric field distribution up to breakdown

Figure 11: Charge dynamics and electric field distribution in 100µm thick polyethylene during voltage rising stage [10]

Figure 12(b) shows the experimental setup for the space charge measurements. The sample was subjected to an increasing dc ramp voltage at a rate of 300 V/s, which corresponded to that of about 3.00 kV/(m·s) for the 0.10 mm thick sample and 1.67 kV/(m·s) for the 0.18 mm thick sample. The space charge up to the breakdown or the surface flashover under a dc ramp was measured at 1s intervals at room temperature using the pulsed electroacoustic (PEA) method.



(a) Electrode configuration



(b) Experimental setup

Figure 12: Sample configuration and experimental setup

Figure 13 shows charge distribution at different voltages in 100μm and 180μm LDPE samples [11]. As the measurements were made during ramping process charge packet is not obvious. However, charge injection from the two electrodes is obvious.

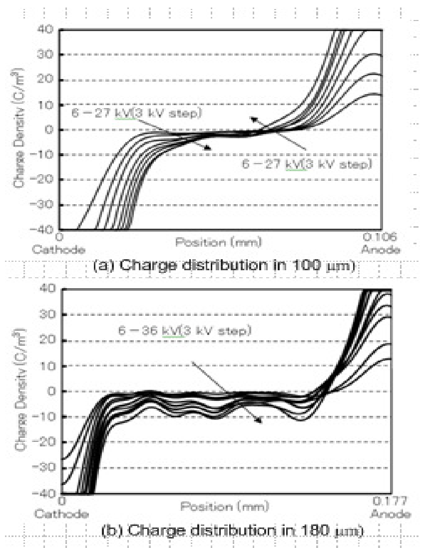


Figure 13: Charge distribution at different voltages in 100μm and 180μm LDPE samples [11]

The maximum electric filed can be calculated from space charge distributions for the two samples and the electric field enhancement, defined as the difference between the maximum field and the applied field, is shown in Figure 14 [11].

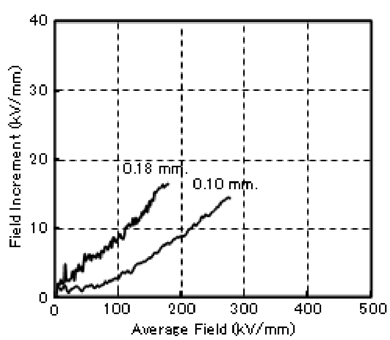


Figure 14: Electric field enhancement in LDPE with different thicknesses [11]

It can be seen that the field enhancement is much greater in the thicker sample. This suggests that the thicker sample will breakdown at a lower applied electric field. The result strongly supports our proposed model.

6 CONCLUSIONS

The new space charge based breakdown model is based on strong experimental evidence of bipolar charge injection and the formation of charge packet under higher electric fields. From the simulation it is clear that the thickness dependent dielectric breakdown is the result of charge dynamics in the material. In addition, the model also shows correctly the relationship between the dielectric breakdown strength and dc voltage rising rate. The new model also provides the information of charge dynamics and electric field distribution in the material up to breakdown

New experimental evidence from space charge measurements up to breakdown strongly indicates the electric field enhancement is much stronger in the thicker sample than in the thinner sample, indicating that space charge is the origin of thickness breakdown dependence.

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