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Non-Linear Electrical Characteristics of Composite Layers Conductor-Dielectric

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A current limiting phenomenon has been observed in a composite material graphite-polyethylene and was accompanied by the peak of current on the current-voltage characteristic. From the investigation of current on time and current on temperature relations one can see thermal nature of the phenomenon. Possible explanation of the effect is a destruction of some parallel conductive paths because of joule heating of them and, consequently, thermal bulk expansion of polyethylene. A simple quantitative model confirms the presence of current peak on voltage-current characteristic.

Keywords: conductor-dielectric composite, current limiting, non-ohm conduction, electrical conduction, and percolation.

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I. Introduction

The investigation of the conduction mechanism of strongly inhomogeneous solid state materials is a matter of great concern for the development fundamental notion and searching for possible practical implementations.

While electronic equipment is in use there are situations when current value becomes too high and may cause destructive effect. On this regard quite perspective can be studying of elements with non-linear current-voltage characteristic (VCC) and current limiting area [1-5]. The preparation of the materials with such electrical properties is quite actual. The usage of conductor-dielectric composites based on polymer with high values of bulk thermal expansion coefficient would be reasonable [6,7]. However systems based on graphite as a conductive phase are not well studied. Electrical properties of composite material graphite-polyethylene have been studied in this work.

II. Experimental details

The thick films of composite material were prepared by mixing of melted polyethylene with electrotechnical graphite. The amount of graphite is varied within 30-70 % by weight. The samples copper-polyethylene were also obtained and studied as well.

Electrodes were prepared by deposition of graphite onto sample surface and by embedding copper rods. The characteristics of the samples were similar for both electrodes types. An uniform distribution of conductive impurities in the bulk of the sample has been controlled indirectly by estimating of the value of electrical conduction of samples were obtained from different parts of initial bar.

III. Results and discussion

In Fig.1 one can see VCC of the samples have been investigated. At the concentration of graphite lower then 30 % the conduction

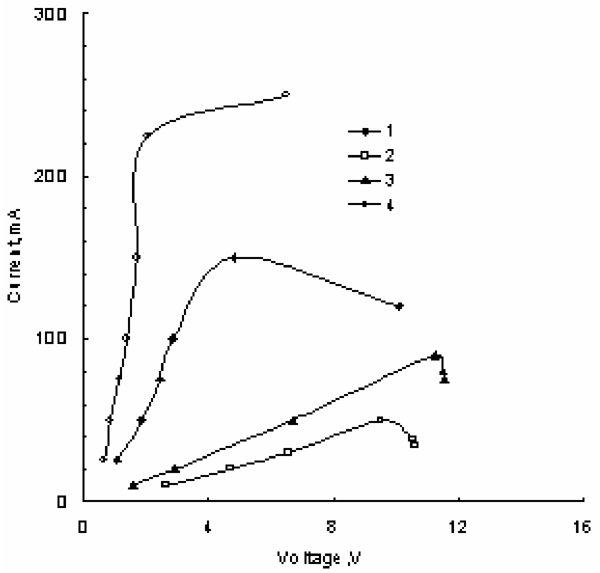

Fig. 1. Current-voltage characteristics of the samples with different graphite concentration.

becomes too low, its magnitude is controlled by dielectric component of the material (polyethylene). When the amount of conductive component exceeded 30% the conductance of the samples becomes quite high. Conductor-dielectric composites are an example of percolation system. It is well known that percolation in three-dimensional system arises when the concentration of conductive phase approaches ~ 25 % [8]. This magnitude of percolation threshold corresponds to that one was found experimentally.

In weak electric fields, with the increasing of amount of the graphite in composite material the conductance increases too (Fig. 1 curves 1-3). Deviation in geometry of the samples was negligible and did not affect on the shown dependencies. For the sample copper-polyethylene a higher conductance has been attained, however in this case because of the difference in densities of copper and polyethylene the samples were extremely inhomogeneous.

In pre-threshold electric fields VCCs were linear. So it is obvious, there are no potential barriers at phase boundaries in this material. The rise of conductance with the growth of the amount of graphite can be explained, probably, by increasing of the number of parallel percolation paths between electrodes.

It is revealed, that magnitude of the threshold current I_{th} increases with the growth of graphite concentration. The peak of the current can be observed on VCC. Further increasing of the voltage invokes decreasing of the current (Fig.1 curves 1-3).

The most likely, the cause of current limiting property is a joule heating of conductive paths followed by the heating of polyethylene nearby. Thermal expansion of polyethylene is a reason of the destruction of conductive paths. As a result the decreasing of conduction occurs.

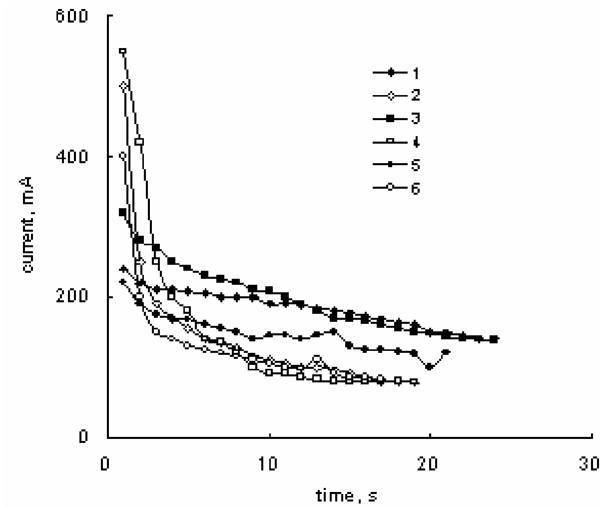

Fig. 2. The dependence of current on time with two voltage values U=9V and U=18V.

Relations of current to time with two fixed values of voltage shown on Fig. 2 can serve as a confirmation for this assumption. When the voltage U=9 V rather weak decreasing of current on time takes place for the account of low heating and, consequently, low thermal expansion of polyethylene. When the voltage value is higher (U=18 V) the heating significantly increases and abrupt decreasing of current can be observed owing to destruction of great number of conductive channels. Then the slanting decrease of current occurs.

The significant inertia of a sample's response to the increasing of applied voltage confirms thermal nature of the observed processes one more time. We can make a conclusion about satisfactory reproducibility of the curves I(t).

The dependence of the resistance of a sample in weak electric field on ambient temperature is shown at Fig. 3. While such indirect heating occurs and ambient temperature below T~340 K the resistance of the sample smoothly increases. Further increasing of ambient temperature T causes destruction of a large number of conductive paths so the steep rises of the resistance take place. Similar results have been obtained for copper-polyethylene sample (Fig. 3 curve 4).

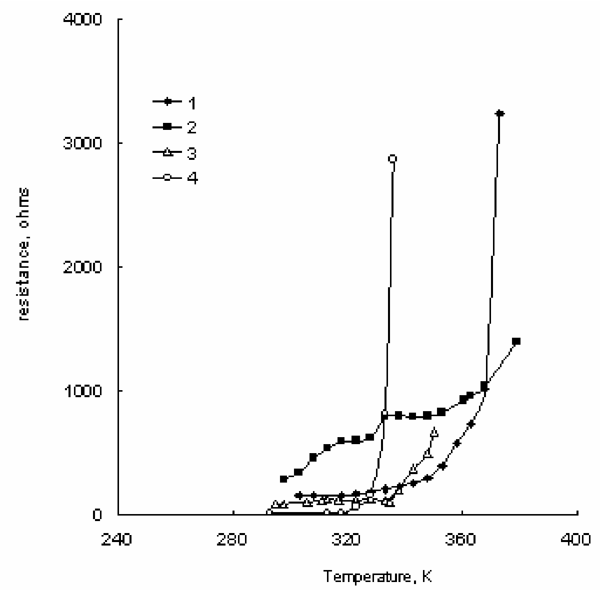

Fig. 3. The dependence of the resistance on temperature for the samples with different graphite concentration. 30% (curve 1), 40% (curve 2), 50% (curve 3). Curve 4 is a dependence for the sample copper-polyethylen.

Let us consider a model of current limiting process in the samples graphite-polyethylene.

The sample is represented by N_0 parallel percolation paths. Each of them has average resistance R_1. In weak electric fields joule power $P_1=U^2/R_1$ is negligible and temperature of particular conductive path is equal to ambient temperature. With the increasing of voltage the power increases too. Insufficient thermal outflow leads to overheating of this path. Thermal expansion of polyethylene occurs. The path is breaking. The destruction of this path leads to the decreasing of the number of non-destructed paths and appropriate increasing of the resistance of a sample.

With increasing of the voltage from *U* to *U+dU* the destruction of *dN* paths occurs. So we can assume that *dN* is proportional to the number of non-destructed paths and to the increment of voltage:

$$dN = -\gamma N dU, \qquad (1)$$

where γ - dimensional factor, that becomes distinct from zero starting from the voltage U_1, when significant joule heating is exhibited. Minus shows decreasing of the number of parallel paths with the increasing of voltage (*dU*>0). By integrating of equation (1), the dependence of the number of non-destructed paths on voltage can be obtained:

$$N = N_0 e^{-\gamma U}. \qquad (2)$$

Thus, current-voltage relation of the sample can be presented as follows:

$$I = \frac{N_0}{R_1} U e^{-\gamma U}. \qquad (3)$$

At low voltages $\gamma U \ll 1$ there is no overheating and VCC linear:

$$I = \frac{N_0}{R_1} U. \qquad (4)$$

At higher voltages the exponential factor in (3) becomes dominant, the peak of current appears on VCC. It is confirmed by experimental results shown on Fig. 1.

IV. Conclusions

It is revealed current limiting property in structures based on composite material graphite-polyethylene. Experimental results can be explained by the model that assumes decreasing of a number of parallel conductive paths in the sample owing to joule heating and thermal expansion of polyethylene.

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В композиційному матеріалі графіт-полиетилен спостерігалося явище граничного струму, яке продемонстроване піком струму на вольт-амперній характеристиці. Дослідження залежностей струму від часу та струму від температури дали можливість побачити теплову природу явища. Можливе пояснення ефекту – руйнація деяких паралельних провідних доріжок через теплоту Джоуля та через теплове об’ємне розширення поліетилену. Проста кількісна модель підтверджує наявність піку струму на вольт-амперній характеристиці.