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ORIGINAL PAPER

The Effect of the External Magnetic Field on the Wide Band Gap Polymer Conductivity

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Abstract The polydiphenylenephtalide (PDP) films of submicron thickness can reversibly switch their conductivity from dielectric to quasi-metallic state with changing their boundary conditions. The intermediate conductivity state "semi-conducting" can also be obtained. The metallic conductivity is characterized by quasi-one-dimensional conductive channels with diameters of 10–100 nm. PDP molecule contains only C, H, and O atoms. The behavior of PDP films out-of-plane conductivity with in-plane magnetic field is studied with current-voltage characteristics (CVC) method. In dielectric state, the films have some volumetric conductivity, so the magnetic field suppresses the conductivity, as it must be because of the Hall effect. When the boundary conditions are changed to provide the "semi-conductive" state, some quasi-one-dimensional conducting channels are partially switching on. So the Hall effect is being suppressed in these sectors, and the previously trapped electrons become free just enlarging conductivity with the magnetic field enhancement. When the film is shifted to quasi-metallic state with linear CVC, the processes of enlarging the conductivity with the magnetic field enhancement become prevailing.

Keywords Polymer electronics · Magneto transport · Spintronics · Thin films · Nanotechnology

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1 Introduction

The interaction between the weak external magnetic field and organic polymers' conductance is surely detected now in many cases [1, 2]. Organic magnetoresistance (OMAR) has a few mechanisms and can be tuned with the change of the molecular structure [2]. The molecules that are sensitive to weak external magnetic fields may include in their structure the phenylene component, so as polydiphenylenephtalide (PDP) has. The heterostructures that are containing the PDP layer may interact with the external magnetic field sharply. Non-ferromagnetic PDP layers show conductivity switching of 6–8 orders of magnitude while they are casted on the ferromagnetic substrates [3, 4]. The nature of this effect seems to be the same as for the paramagnetic nanoparticles' huge magnetoresistance [5]. It is the appearance of the additional electric potential that is provided by the external static magnetic field [6]. This potential pushes off the charge carriers (electrons) and the allowed paths (narrow channels in the polymer layer). Up to now, there was no disjunction for PDP between the effects of magnetic field on the ferromagnet/polymer interface and the proper polymer film magnetoresistance. This paper is dedicated to study of the interaction between the PDP film and magnetic field.

2 Experimental

In order to explore the properties of polymer film without ferromagnetic electrodes, the structures of Cu/PDP (thickness of films ∼800 nm) were obtained. PDP film was deposited by spin coating from the polymer solution onto Cu surface. Cyclohexanone was used as a solvent. Current-voltage characteristics (CVC) of the structure

Cu/PDP/Cu were studied. CVC were obtained for increasing voltage and for decreasing one with magnetic field of 0–250 mT with the step of 50 mT. While obtaining each CVC curve, the magnetic field remained steady. The measurements of the current were done by Agilent 34401A voltmeter through the measurement of the voltage on the resistor of 2 kOhm, inserted in series with the Cu/PDP/Cu structure. Switching over of electric polarity and repeated CVC measurement were done at every magnetic field fixed value in order to exclude the inaccuracy connected with the real asymmetry of heterostructure. The experimental conditions were room temperature and air atmosphere.

3 Results and Discussion

The geometry of the experiment intends for the current suppression by magnetic field—the current flow was normal to the magnetic field direction. But when the current and magnetic field become substantial enough, the magnetic field helps to enlarge the current (Fig. 1).

So with the magnetic field increase, one can see two oppugning processes for all the combinations of mutual orientation of current and magnetic field, and the current enforcement prevails when current is more than 1 mA and magnetic field is 0.25 T. The PDP films have the positive electron affinity energy, so they always have the captured electrons. The role of lateral fragments of molecule (containing the paramagnetic oxygen) for the electron transport in polymer film have just been emphasized [7]. The explanation that the magnetic field initiates the liberation of trapped electrons is confirmed by the fact that the CVC for decreasing bias voltage are disposed higher, than ones for the increasing bias voltage.

In order to consider the role of magnetic field in the processes of capture and emission of charge carriers by the traps in the polymer layer the CVC curves were plotted in Poole-Frenkel (PF) coordinates ln (I/U) vs $E^{1/2}$, where E is the applied electric field, I is current, and U is bias voltage (Fig. 2). The current in the PF model is described by the expression [8] $I \propto E \cdot \exp[(-e\phi_B + \beta_{PF}E^{1/2})/kT]$, where ϕ_B is the potential barrier height, e is the elementary charge, k is Boltzmann's constant, and T is temperature. β_{PF} is the PF parameter, its theoretical value is $[e^3/(\pi \cdot \varepsilon \cdot \varepsilon_0)]^{1/2}$. Here ε is the relative dielectric constant and ε_0 is the permittivity of vacuum. According to [9] the calculated value for $\varepsilon = 3.4$ is $\beta_{PF} = 4.17 \times 10^{-4}$ eV(cm/V)$^{1/2}$, experimental values in [9] vary in the range of $\beta_{PF} = (1.3 \div 2.8) \times 10^{-4}$ eV(cm/V)$^{1/2}$.

In Fig. 2 one can see two CVC curves in PF coordinates. The linear segments can be eliminated: for example the segment 2 is marked out for bias voltage of 4–20 V (this corresponds to electric field across the polymer film to be 5–25 kV/cm) It is possible to estimate the PF parameter for linear segments. PF parameter changes as a function vs external magnetic field value for all cases and all segments. These cases are as follows: dielectric state, bias voltage increases; dielectric state, bias voltage decreases; semiconductive state, bias voltage increases; and semiconductive state, bias voltage decreases. The separation of increasing and decreasing bias voltage is necessary in order to divide the processes of population and vacation of traps. In Fig. 3 the variation of β_{PF} parameter vs external magnetic field is shown for the case of dielectric state and increasing bias voltage, calculation interval 4–20 V is marked as 2 in Fig. 2.

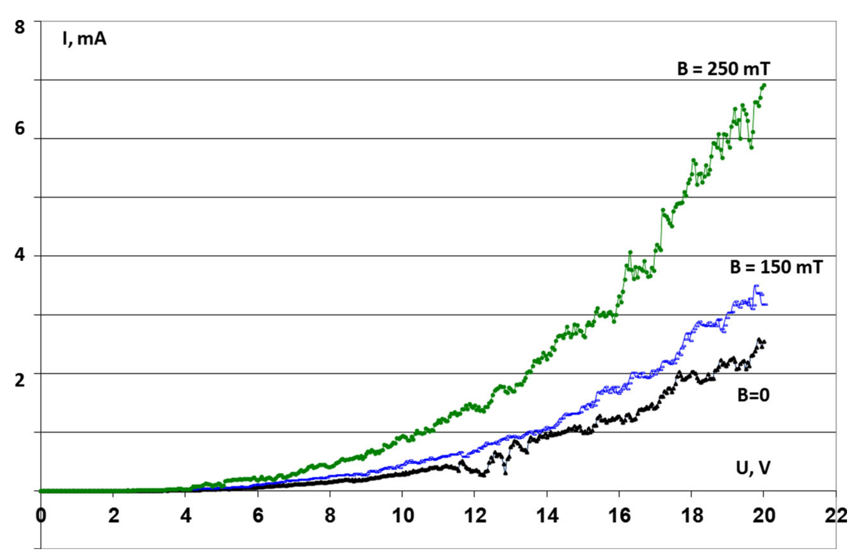

Fig. 1 CVC series for Cu/PDP/Cu heterostructure in external magnetic field (semiconductive state, bias voltage decreases)

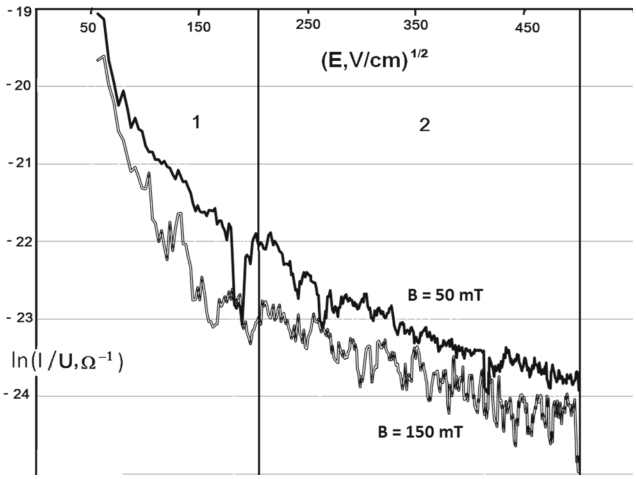

Fig. 2 CVC curves for Cu/PDP/Cu heterostructure in external magnetic field (dielectric state, bias voltage increases). PF coordinates

The variation of β_{PF} is possible when ε varies, as it can be for PDP films [10]. In [10] the variation of dielectric permittivity of PDP films vs external pressure is considered. The occasion of this process is the charge injection from electrodes resulting finally to the change of the type of basic charge carriers from holes (dielectric state) to electrons (high-conductive, quasi-metallic state). The results of current work show that the weak external magnetic field also can contribute to these processes. All dependencies for β_{PF} vs external magnetic field have nonmonotonic character. This means that systematic errors connected with method and equipment do not have the determinative significance. The location and nature of the extreme points demand for the additional research.

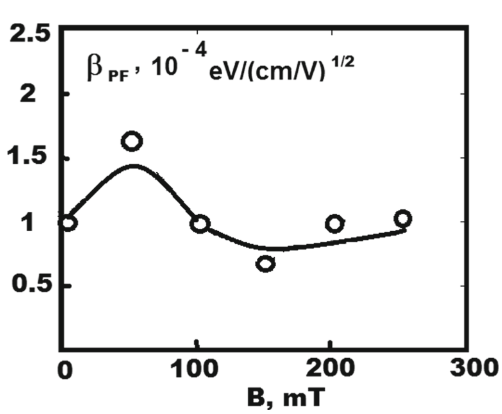

Fig. 3 PF parameter vs external magnetic field. The calculation interval corresponds to the segment 2 marked out in Fig. 2

4 Conclusions

The results of the study of CVC curves for the Cu/PDP/Cu system (out-of-plane geometry) give evidence that quasi-one-dimensional charge transport is prevailing comparatively with the volume conductivity even for the dielectric state. The calculated PF parameters are in good accordance with the previous research [9], and the variation of β_{PF} means the variation of dielectric permittivity. The external magnetic field really effect on the charge injection and hopping processes. Also the traps in PDP are mainly the functional molecular groups with paramagnetic oxygen and their charge catching capacity also changes in the magnetic field. These processes in turn change the mobility of molecular polarized parts and consequently the electric permittivity. As a result one sees the functional dependence of β_{PF} on the external magnetic field value.

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