SCIENTIFIC BULLETIN OF THE LODZ UNIVERSITY OF TECHNOLOGY
No. 1210 Physics, Vol. 37 2016

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ELIMINATION OF THE IMPACT OF RC CONSTANT ON TRANSIENT PHOTOCURRENTS MEASURED IN ORGANIC LAYERS

We present a calculation method for elimination of the effect of the RC constant of the measuring circuit in the time-of-flight (TOF) measurements where a pulse generation of the photocurrent in a thin layer of low-molecular organic material is exploited. Presented method allows to eliminate the influence of the component of displacement current related to dielectric losses and obtaining the actual conduction current time dependence. The method was tested on the thin layers of 1,5-dihydroxynaphthalene.

Keywords: organic electronics, circuit time constant, carrier mobility, drift transport, 1,5-dihydroxynaphthalene, TOF measurements, electric characterization, SCLC.

1. INTRODUCTION

Measurement of charge transport properties in organic semiconductors is very effective using the experimental system designed for the time of flight method (TOF). The principle of operation of this method is based on usage of the fast flash of UV light passing through the semitransparent electrode attached to the layer under study. It causes the separation of the electron-hole pairs followed by their transport to the adequate electrode due to the electric field created inside the layer. The advantage of this method is a possibility of direct measurement of the mobility of carriers without impact of surface states [1]. TOF measurements are applicable to thin layers of such organic structures as polymers or low molecular weight organic materials [2]. In TOF experiment we use generation of charge carrier pairs inside the measured layer with use of UV light. The depth of penetration *L* of this light is reciprocal of the absorption coefficient α of the UV light.

$$L = \frac{1}{\alpha} \tag{1}$$

A major limitation of TOF measurements is related to the difficulty of application of the method to layers thinner then inverse of absorption coefficient of absorbed light (1). This problem is related to low values of transient currents. This is a reason that the TOF experiments require relatively thicker layers compare to the layers used in a steady state (*I*-*U*) measurements. Unfortunately, the technology for organic electronics mainly exploits the layers not thicker than 1 μm [3-6]. For this reason, the extension of the measuring range for TOF method towards thinner layers should allow wider application of this kind of measurements. TOF method development, in mentioned above direction, should also reduce costs by using the same sample for two types of measurements, i.e. for the measurement of transient currents and steady state currents.

In this work we propose additional numerical analysis of the experimental data obtained with use of TOF, allows to separate conductivity component and displacement component from the total current value. This allows to obtain the correct value of the transit times or life times for charge carriers registered in the TOF measurements, when the measured transit times or life times are near the RC constant of the experimental set up.

2. EXPERIMENTAL

The set-up used for measurements of transient currents is presented in Fig. 1. The UV light pulse (1) short in comparison to the duration of the obtained measured transition time separates the charge carriers (electrons and holes) in the proximity of the semitransparent electrode (3). The transporting electric field, *E* is created due to the polarization voltage U_B supplied to the measuring cell by the means of the low-noise battery supplier (2). This field, *E*, forces ordering of the carriers movement inside the studied layer (4) of organic material. The total current flown through the electrode (5) forces the formation of the potential drop in the resistance *R* (6). This potential drop is measured by a digital oscilloscope (7) and then recorded by the computer (8) controlling the acquisition of the signal.

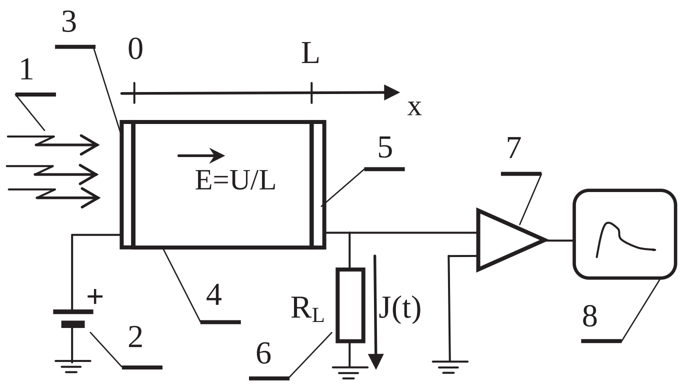


Fig. 1. Set-up used for the study of the transient currents density ($J(t)$): 1 – UV light pulse, 2 – DC battery supplier, 3 – front electrode (semitransparent), 4 – the layer of the organic material under study, 5 – back electrode, 6 – load resistance, 7 – oscilloscope, 8 – computer controlling the acquisition of the signal

Commercially available 1,5-dihydroxynaphthalene (purity 97%, Aldrich) were used for experiments. The "sandwich" type measuring cell consisted of the Au electrode deposited in the vacuum on the glass substrate and top vacuum deposited semitransparent Al electrode. Deposition of all of the layers took place in the vacuum of order of 10^{-5} Tr. The surface area of the electrodes used in experiment was equal to 0.15 cm^2.

3. ANALYTICAL MODEL

The transient photocurrent method with generation of carrier pairs with use of UV light pulses, using the set-up designed for the TOF measurements, gives the opportunity to direct determination of either the time of flight for the carriers or the life time of carriers [8]. The fundamental limitation of the range of measured times of flight or life times is a time constant *RC* of the measuring apparatus. Its impact is noticeable for studied waveforms of transient currents running faster than the value of *RC* [9,10]. The measurements of transient photocurrents in the high resistive organic materials require larger surfaces of the measuring cell electrodes in order to obtain measurable current created by absorption of UV radiation. This condition implies that the capacity of the measuring cell, proportional to the electrode surface S may not be less than:

$$C = \frac{\varepsilon\varepsilon_0 S}{L}, \tag{2}$$

where ε – relative dielectric permittivity, $\varepsilon_0 = 8.85 \cdot 10^{-12}$F/m, L – thickness of the measured layer.

The capacitance of the measuring cell is ordinarily within the range of 10 to 500 pF. Taking into account that a typical thickness of the organic sample is usually in the order of several or a few dozens of micrometer, with the relative dielectric constant of the investigated layer of $\varepsilon = 3$, when the electrode surface is equal to 0.15 cm^2. The load resistor of a typical value of $R_L = 10^6\ \Omega$ is used in the input of digital oscilloscope (see Fig. 1). Its presence enables obtaining the measurable values of voltage signal forced by a flow of transient current $I(t)$. The magnitude of load resistance could not be lower because of the noise to the signal ratio. Resultant RC constant for a typical experimental set-up is between 10 μs and 500 μs. The value of RC, for examined transients, is a restriction on the possibility to make a measurement of the time constant of current extinction, τ, which is interpreted either as the life-time for carriers or the time of flight. The circuit RC constant also limits the range of reliable measured mobility obtained with use of TOF method. The threshold limit of the mobility calculated for the $L = 10$ μm, $\tau = 10$ μs, $E = 10^4$ V/cm, is of the order of $\mu = 10^{-4}$ $cm^2/(Vs)$. The numerical separation of the displacement current component $I_d(t)$ and conduction current component $I_c(t)$ from the total registered current is solving this problem.

For theoretical analysis we have applied the electronic circuit presented in Fig. 2. The measuring cell is represented as parallel electronic circuit composed of capacitor and resistor. Capacity of capacitor is associated with relative dielectric constant of material, ε. The capacity is responsible for appearance of displacement current. The resistance $R - r(t)$ is connected with conduction current component. We have assumed that the time dependent resistance component, i.e. $r(t)$ is negligible in comparison to the constant value of R. Further, we assumed that the value of U_B, i.e. the voltage polarising the layer is constant. This assumption is connected with our observation that the voltage drop, on the clamps of an applied low-noise supply battery during carrying a pulse of the current through studied layer, do not exceed the 5% of total value of U_B.

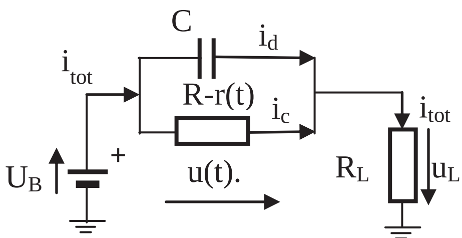


Fig. 2. Electronic circuit of the measurement system

Therefore, the total current, i_{tot}, supplied from the battery to the layer under investigation can be described as:

$$i_{tot}(t) = i_c(t) - i_d(t), \tag{3}$$

where: i_{tot} – total current, i_c – conductivity component of the current, i_d – displacement component of the current.

On the basis of above assumptions, the battery is regarded as a current source with infinite efficiency. Therefore, the interested for us, conductivity component of the current can be derived from (3) and determined as:

$$i_c(t) = i_{tot}(t) + i_d(t) \tag{4}$$

Displacement current i_d can be determined from undermentioned dependences:

$$i_d = C\frac{\mathrm{d}u(t)}{\mathrm{d}t} = C\left(\frac{\mathrm{d}\log u(t)}{\mathrm{d}\log t}\right)\cdot\left(\frac{u(t)}{tR_L}\right) = R_L C\left(\frac{\mathrm{d}i_{tot}(t)}{\mathrm{d}t}\right). \tag{5}$$

Finally, the conductivity compound of the current is found to be:

$$i_c(t) = i_{tot}(t) + R_L C\frac{\mathrm{d}i_{tot}(t)}{\mathrm{d}t}. \tag{6}$$

The knowledge of the value of the derivative $\mathrm{d}i_{tot}/\mathrm{d}t$ is essential to determine i_c in Eq. (6). This value is calculated numerically from measured values registered by oscilloscope and registered in the computer memory. Using of the approximation:

$$\frac{\mathrm{d}i_{tot,calc}(t_k)}{\mathrm{d}t} = \frac{i_{tot}(t_{k+1}) - i_{tot}(t_{k-1})}{t_{k+1} - t_{k-1}} \tag{7}$$

is effective.

4. RESULTS AND DISCUSSION

4.1. RC elimination

Reconstruction of the real curve tracing for the conductivity component of current, i_c, is possible due to application of the complex computational procedure. In first stage, the oscillogram of the curve tracing of the U_L recorded as the set of pixels is transformed into the system of double logarithmic scale axis $\log U_L$-$\log t$. During the development of each transient shape stored in computer as the oscillogram in the form of the set of (U,t), a polynomial approximation with exploitation of Loger Pro Vernier Software & Technology program was twice applied. Further the application of the cubic splines method [11], with use of SRS1 program from the SRS1 Software LLC, enabled to obtain smooth derivative. Fig. 3 shows the typical oscillogram of the transient obtained in the experiment for the hole conductivity measured for the layer of 1,5-dihydroxynaphthalene. For this layer the biasing voltage was U_B = 45 V, the thickness L = 12.7 μm and the resulting time constant RC for this transient was 110 μs. Fig. 4a presents the above mentioned handling of transients with use of spline method and then transformed to the system of double log axis, i.e. $\log U_B$-$\log t$, neglecting the influence of the time constant, RC. Obtained transient time was τ = 250 μs. In Fig. 4b the same transient as above is presented taking into account the influence of time constant RC. Resulting transient life-time was τ_{calc} = 130 μs, which is below the RC of the measuring set-up.

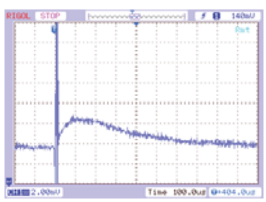
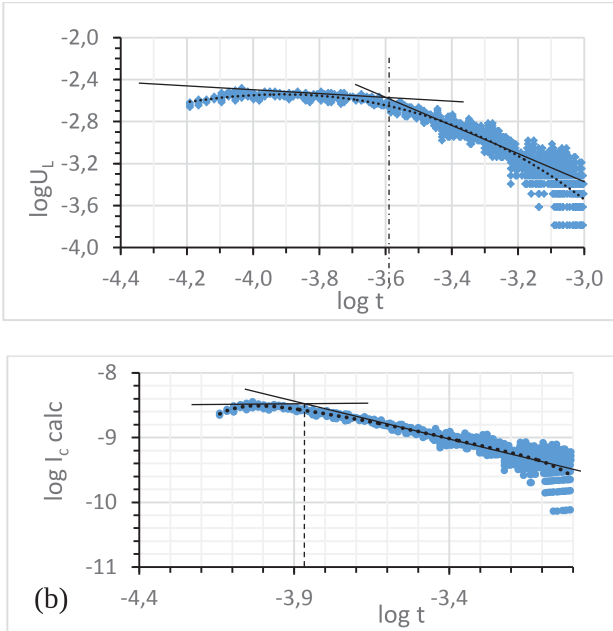


Fig. 3. Oscillogram of the transient shape of the hole mobility in the layer of 1.5-dihydroxynaphthalene, L = 12.7 μm, time constant of the measuring set-up is RC = 110 μs

(a)



(b)

Fig. 4. Determination of time of flight for the transient shown in the oscillogram seen in the Fig. 3 without taking into consideration the *RC* constant (a), and considering the influence of the *RC* constant (b)

A series of measuring cycles in the biasing voltage range from 25V to 45V was made for a measured layer. Linear dependence for the inverse time of flight versus U_B for both alternative handlings of data, i.e. with elimination of the impact of the *RC* time constant and without this procedure, was obtained. However, the slopes of the linear dependence obtained in these manner were different, what was a reason for obtaining different values of mobility in both cases. In the handling method without additional analysis of the impact of the *RC* constant, $\mu = 1.7 \cdot 10^{-4}$ $cm^2V^{-1}s^{-1}$, but with additional analysis of the impact of the *RC* constant obtained value was: $\mu = 3.6 \cdot 10^{-4}$ $cm^2V^{-1}s^{-1}$.

5. CONCLUSION

Method to eliminate the effect of constant *RC*, described in the article, has been used for a layer 1,5-dihydroxynaphthalene where measured time of flight was comparable to the time constant, *RC*, of the experimental set-up. Simultaneously, the requirement of the proportionality of the inverse time of flight versus biasing voltage, U_B, for both ways of data handling (without eliminating the impact of *RC* constant, and with eliminating the impact of *RC* constant) were met. However the values of slopes of the straight lines differed twice, what led to the same difference in obtained hole mobility values.

It can be concluded that:

1. The method of separating the conduction current shape as a function of time allows to extend the effective range of measurements of transient currents up to the time comparable or even equal to the time constant *RC* of the measuring set-up.
2. Possibility of numerical handling of the experimental data for transient shape of the transient photocurrent should allow further studies of the material properties with use of TOF. It can be applied to obtain distribution of traps (in the manner described in [12].

ACKNOWLEDGEMENTS

Great thanks to prof. B. Marciniak from Jan Długosz University of Częstochowa for valuable discussions.

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ELIMINACJA WPŁYWU STAŁEJ RC W POMIARACH FOTOPRĄDÓW PRZEJŚCIOWYCH WARSTW ORGANICZNYCH

Streszczenie

Zastosowanie metody eliminacji wpływu stałej RC obwodu pomiarowego do analizy wyników pomiaru fotoprądów przejściowych płynących w cienkiej warstwie niskocząsteczkowego materiału organicznego umożliwia eliminację wpływu składowej prądu przesunięcia związanej ze stratami dielektrycznymi i uzyskanie rzeczywistego przebiegu prądu przewodzenia w funkcji czasu. Pozwala to na wyznaczenie prawidłowej wartości czasu charakterystycznego nawet dla cieńszych warstw, dla których daje się zrealizować pomiar charakterystyki stałoprądowej *U-I* w zakresie prądów ograniczonych ładunkiem przestrzennym. Otwiera to możliwość pełnej charakteryzacji własności elektrycznych badanego materiału organicznego przy użyciu jednej komórki pomiarowej. Możliwość numerycznego przedstawienia przebiegu przejściowego fotoprądu powinna pozwolić na badanie własności materiału metodą TOF dla uzyskania rozkładu pułapek.