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Differential Thickness Layer Resistance Measurement method for measurements of contact resistance of organic semiconductor thin films

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ABSTRACT

The objective, basic theory and application of a new DTLRM (Differential Thickness Layer Resistance Measurement) method of contact resistance R_c (resistance of interface) and contact resistivity measurements are described. The method was developed for ultrathin films of high-ohmic organic semiconductors. The method is based on measurements of total resistance $R_{T,1}$, $R_{T,2}$ between two opposite planar contacts on two samples of differing thickness L_1, L_2 prepared from the same organic semiconductor. The important requirements are that both the opposite contacts are ohmic, that linear dimensions of the contacts are much larger than the film thickness, and that the actual measured data are consistent in the sense of condition $1 < R_{T,2}/R_{T,1} < L_2/L_1$. The DTLRM method was verified on zinc phthalocyanine samples with Au and Pt contacts. If the basic assumptions are fulfilled, the DTLRM method can be applied to a broad range of high-ohmic thin films.

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1. Introduction

Thin films of organic semiconductors based on phthalocyanines have been used for various electronic applications in recent years. These are, e.g., active layers of sensors detecting the presence of various gases (NH_3, NO_2, H_2, ...) [1–4], large-surface solar cells [5–7], data storage devices [8], or UV light sensors [9]. These semiconductors can be characterised as high-ohmic materials and are applied mostly in the form of thin or ultrathin layers. The functional principle of the sensors detecting the presence of gases consists in the measurement of the change of the conductivity of the active layer due to adsorption of gas molecules on its surface. Also the UV sensor is based on the change of the layer conductivity due to incident radiation. As a rule, the conductivity change of organic material is detected using a pair of surface metallic contacts. Their quality may significantly influence the resulting properties of the whole device. The basic measure of the contact quality is the value of electric resistance R_c (Ω) of the metal-semiconductor interface (contact resistance = interfacial resistance). To compare different interfaces, the contact resistance is related to a unit area of contact interface S_c (m^2). Hence we refer to a specific contact resistance (specific interfacial resistance = interfacial resistivity) ρ_c ($\Omega\, m^2$) ($\rho_c = R_c \cdot S_c$). The contact resistance is always in series with the active layer resistance of the organic semiconductor and can, under certain circumstances, decrease the total sensitivity of the mentioned sensors. In the case of solar cells, it can even diminish their overall sensitivity. The assessment of contact resistance can thus be very important e.g. for optimisation of the choice of the contact metal for particular application. The

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total resistance R_T (Ω) measured between the contacts can be affected not only by the contact resistance R_c, but also by numerous other contributions, which can be connected with the contacting the active semiconductor layer. The obtained value of R_T depends also on the resistance of the contact metal R_m (Ω) or on the resistance of the contact probe R_p (Ω) (R_m and R_p can be neglected in most cases), on the shape and surface S_c of the contacts ($R_c = \rho_c/S_c$), on the thickness L (m) and resistivity ρ (Ω m) of the layer under the contacts, to name but a few. Additional layers (e.g. oxidic, etc.) that may have been formed during preparation of the contacts can also contribute to the total resistance R_T. The dominance of a particular contribution in the total resistance of the device depends also on the direction of the current flow through the layer: transverse (vertical) or lateral (horizontal).

As a rule, during our measurement the current flows through the layer laterally. Therefore, we are primarily interested in the properties of the active layer between the contacts, i.e. in its resistance per square R_{ps} (Ω) (sheet resistance, sheet resistivity). To measure and evaluate R_{ps}, it is then sufficient to eliminate the influence of the resistance of the whole contact regions (see, e.g., measurement of R_{ps} on a stripe structure according to the DLSRM method [10]).

Our goal, on the contrary, is to assess only the contact resistance R_c on organic semiconductors. Hence, in this case, the selected method has to eliminate or at least minimise all other influences. In general, this is a very difficult task which has to be solved individually in each particular case.

The methods of contact assessment have been developed mainly for inorganic semiconductors. Most of these methods used in that case are characterised by lateral passage of current through the layer; this is because the layers formed by isoplanar technologies are well accessible only from one side. Beside the resistance of the material forming the active layer between the contacts, the dimensions of the material under the contacts play a very important role, too. If the layer under the contacts is sufficiently thick, compared to linear dimensions of the contacts, we have to face at least a bending of the current lines under the contact towards lateral directions between the contacts (current bending) and a spreading of the current line into the bulk (current spreading). On the contrary, if the layer is significantly thinner than linear dimensions of the contacts, we have to expect a thickening of current lines towards the inner edges of the contact (current crowding). Consequently, the effective contact surface can diminish if the transfer length L_t (m) [11,12] is at least 1.5 times shorter than the contact dimension in the current-flow direction.

It is important that, in case of lateral passage of current through the sample, we cannot reliably determine the contact resistance from the measured total resistances between the contacts, but only the resistance of the whole contact area. In practice, somewhat misleadingly, even in this case the term "contact resistance" is used; let us therefore denote it R_{CA} (Ω) (Resistance of Contact Area). To obtain a qualified estimate of the contact resistance R_c in the sense of its definition, in such cases it is necessary to analyse the behaviour of the current under the contact in greater detail. Several theoretical models were proposed for this purpose: KMM (Kennedy and Murley Model) [13], TLM (Transmission Line Model) and ETLM (Extended Transmission Line Model) [14]. There is also a variant of this method with circular geometry [15,16]. Perhaps the best known and most widespread method of measuring the "contact resistance" is the Transfer Length Method (TLM) [11,12,17]. It consists in forming a sequence of several (more than three) rectangular contacts at different mutual distances; they are formed on the semiconductor insulated from the substrate. The current flows through the semiconductor longitudinally between the first and last contact, and the voltage between the individual contacts is measured. From the dependence of the total resistance R_T between the contacts on the contact distance L, one can determine the contact resistance R_{CA}, sheet resistance R_{ps} of the semiconductor and the Transfer Length L_T (distance $L = -2L_T$ for which $R_T(-2L_T) = 0$). Then, to determine the corresponding contact resistivity ρ_{CA}, one often (if 1.5 L_T [11,12] $\leqslant$ contact length d (m) in the direction of current flow through the layer) uses, instead of the true contact surface $S_c = w \cdot d$, the effective contact surface $S_{c,eff} = w \cdot L_T$, where w (m) is the contact width and $\rho_{CA} = R_{CA} \cdot S_{c,ef}$. For relatively thick layers of low-ohmic inorganic semiconductors, in which the material resistivity is relatively low in comparison to organic semiconductors, one can expect in rare cases that the principal contribution to the measured "contact resistance" R_{CA} will be approximately equivalent to R_C (layer-metal resistance). However, this cannot be expected in the case of high ohmic ultrathin films of organic semiconductors, where the resistivity of the material is by several orders of magnitude higher. If our objective consists in obtaining the most accurate measurement of R_c (not only R_{CA}), in particular in these materials, it is more advantageous to refrain from the above mentioned methods based on lateral passage of current through the layer with contacts placed on one side. For completeness, let us add that the so-called Kelvin structure CBKR (Cross-Bridge Kelvin Resistance) [12,18] in the "four-terminals" or "six-terminals" variant makes it possible to determine the contact resistance R_c (close value) even in inorganic semiconductors. Extrapolation of this method to ultrathin layers of high-ohmic organic semiconductors with the sheet resistivity of order of 10^9 Ω would of course require using two electrometers in differential arrangement in order to measure the voltage response. In this case, the voltage drop on the metal-layer interface compared to that on the high-ohmic layer might be so small that we would subtract two approximately equal numbers with a potentially large error.

The methods based on transverse passage of the current [11,19] are in principle simpler, but the transverse passage of current requires preparation of contacts from both sides (opposite contacts). That is why this is rather exceptional case in isoplanar technologies of inorganic semiconductors and this method is rarely used for inorganic semiconductors. In any case, we must not only limit the spreading effect by proper methodology or accepting its influence, but we must also know the resistivity and the thickness

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